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ORIGINAL REPORT

EXOSKELETON GAIT TRAINING AFTER SPINAL CORD INJURY: AN EXPLORATORY STUDY ON SECONDARY HEALTH CONDITIONS

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Objective: **To explore changes in pain, spasticity, range of motion, activities of daily living, bowel and lower urinary tract function and quality of life of individuals with spinal cord injury following robotic exoskeleton gait training.**

Design: **Prospective, observational, open-label multicentre study.**

Methods: **Three training sessions per week for 8 weeks using an Ekso GT robotic exoskeleton (Ekso Bionics). Included were individuals with recent (<1 year) or chronic (>1 year) injury, paraplegia and tetraplegia, complete and incomplete injury, men and women.**

Results: **Fifty-two participants completed the training protocol. Pain was reported by 52% of participants during the week prior to training and 17% during training, but no change occurred longitudinally. Spasticity decreased after a training session compared with before the training session ($p < 0.001$), but not longitudinally. Chronically injured participants increased Spinal Cord Independence Measure (SCIM III) from 73 to 74 ($p = 0.008$) and improved life satisfaction ($p = 0.036$) over 8 weeks of training. Recently injured participants increased SCIM III from 62 to 70 ($p < 0.001$), but no significant change occurred in life satisfaction. Range of motion, bowel and lower urinary function did not change over time.**

Conclusion: **Training seemed not to provoke new pain. Spasticity decreased after a single training session. SCIM III and quality of life increased longitudinally for subsets of participants.**

Key words: exoskeleton; spinal cord injury; rehabilitation; pain; spasticity; SCIM III.

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LAY ABSTRACT

This report from a European multicentre, prospective, observational, open-label, exploratory study examines the effects of gait training using an exoskeleton (Ekso Bionics) after spinal cord injury on spasticity, pain, range of motion, bowel and lower urinary tract function, activities of daily living and quality of life. Exoskeleton gait training seemed to be well-tolerated in spinal cord injury participants with neuropathic and nociceptive pain, but pain did not change during 8 weeks of training. Compared with testing prior to a single training session, spasticity decreased after training when calculating a sum-score for multiple lower extremity muscle groups. The results indicate a benefit in terms of independence measure SCIM III as well as quality of life over time. Bowel and lower urinary tract function did not change overall. Future studies could investigate these parameters compared with traditional gait training for spinal cord injury, as well as testing more intensive training protocols.

Spinal cord injury (SCI) gives rise to a large number of secondary health conditions, including pain (1, 2), spasticity (2, 3) decreased range of motion (ROM) (3), decreased independence (4), bowel (5) and bladder dysfunction (6), and decreased quality of life (QoL) (7). Among individuals with SCI, these issues should be addressed with high priority (8, 9), as many of the secondary health conditions have been shown to be independently associated with decreased QoL (10, 11).

Exoskeleton training has been developed as a rehabilitation tool and is approved for the rehabilitation of individuals with SCI. Gait function has often been the focus of studies, but indications of improvements in pain, spasticity, bowel and bladder function have also been reported (12–14). However, further studies are needed. Several commercial exoskeletons are currently available (15). The exoskeleton used for this study was the Ekso GT robotic (Ekso Bionics, Richmond, CA,

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USA) exoskeleton. A characteristic of this exoskeleton is, among others, that initiation of a new step can be controlled by the user via sensors in the foot-plates that capture the weight transfer between the left and right legs. Power from the on-board motors controlling leg movement can be adjusted to accommodate the user's needs. An assistive device, walker or crutches, are always used for balance.

The safety and feasibility of the training protocol for this study and changes in outcomes of gait and balance have been published separately (16). The initial publication documented that the training was safe with no serious adverse events and that the protocol was feasible for all of the subgroups of included participants, i.e. recently and chronically injured individuals with paraplegia and tetraplegia, as well as those with complete and incomplete injury. There was progression over the 8 weeks in the time walking in the exoskeleton and the number of steps taken during the training sessions. The training was light to moderate in intensity. Lastly, there were indications of improvements in gait function and balance outside of the exoskeleton for individuals with incomplete SCI.

The objective of the present study was to explore changes in pain, spasticity, range of motion (ROM), Spinal Cord Independence Measure (SCIM III), bowel and lower urinary tract (LUT) function, and quality of life (QoL) in individuals with SCI following robotic exoskeleton gait training with Ekso GT, in order to guide future randomized controlled trials (RCT) and explore areas of potential benefit from exoskeleton training.

METHODS

This study followed individuals with SCI over an 8-week training period with an exoskeleton from Ekso GT (Ekso Bionics, Richmond, CA, USA) as an adjunct to therapy. Changes in pain, spasticity, ROM, SCIM III, bowel and LUT function and QoL, over the training period and at a follow-up were documented, in addition to spasticity pre- and post-training.

Study design

The study was a prospective, observational, open-label, multicentre study. The 9 European SCI rehabilitation centres were located in Denmark, Germany, the Netherlands, Norway, Spain, Sweden and Switzerland.

Training protocol and participants

The training protocol consisted of 24 robotic exoskeleton gait training sessions (TSs) of 1 h, 3 times per week for 8 consecutive weeks. Prior to commencing the study, researchers and therapists from the 9 centres joined a 2-day kick-off meeting. The study protocol and all tests were reviewed systematically, to ensure that all therapists agreed on performance of the tests and data collection. Participants were recruited as a convenience sample at each centre and screened and included according to the eligibility criteria listed in Table I (16).

Participant characteristics were collected according to the International SCI Core Data Set Version 1.1 (17, 18). The following 2 groups were defined; "recently injured" (Time since injury, TSI ≤1 year) and "chronically injured" (TSI >1 year). The rationale for this division in analysis was that some degree of neurological recovery would be expected in the early phase after injury, whereas this is less likely to happen in the chronic phase (19–21).

The training frequency of 3 times per week was based on general recommendations of training frequency and duration frequencies of (3–5 times per week with duration of 20–60

Table I. Eligibility criteria (16)

Inclusion criteria	Exclusion criteria
A traumatic or non-traumatic SCI with either motor complete (AIS A or B) with NLI from C7 to L2 (inclusive) or motor incomplete (AIS C and D) with NLI from C1 to L2 (inclusive), as determined by the ISNCSCI	Previous training with an exoskeleton and other types of robotic assisted gait training
Age 15–65 years at time of entry to the trial (some centres 18–65 years)	Spinal instability
More than 30 days since injury (TSI)	Acute deep vein thrombosis
Body height 157–188 cm OR max hip width 42 cm, upper leg length 51–61.4 cm and lower leg length 48–63.4 cm	Severe, recurrent attacks of autonomic dysreflexia requiring medical intervention
Maximum body weight 100 kg	Heterotopic ossification in the lower extremities resulting in restrictions of ROM at the hip or knee
Sufficient upper extremity strength to use a front-wheeled walker	Two or more pathological fractures in the last 48 months in a major weight-bearing bone in the lower extremity (femur or tibia)
Sufficient range of motion to achieve a reciprocal gait pattern and to perform sit-to-stand transition in the device	Hip subluxation
Medically stable and cleared by a physician for full weight bearing locomotor training	Cognitive deficits that limit the participant to understand instructions and safely participate in a training programme, evaluated by investigator
Standing orthostatic tolerance trial by standing for 15 min, fully supported in a standing-frame, while measuring blood pressure regularly	Spasticity assessed with the Modified Ashworth Scale = 4 in lower extremity muscles
	Skin integrity issues in areas in contact with the device
	Concurrent neurological injury or any other issue that in the opinion of the investigator would confound the results
	Pregnancy

AIS: American Spinal Injury Association [ASIA] impairment scale; SCI: spinal cord injury; NLI: Neurological Level of Injury; ISNCSCI: International Standards for Neurological Classification of SCI.

min) (22) and has commonly been used in similar exoskeleton studies (23). A 1-h session was estimated to be feasible from clinical experience at the included sites.

The study did not control for other types of training that individuals attended.

Assessments

The included tests and time-points are specified below. All tests for changes over time were performed before training at baseline and at the end of the 8-week training period, i.e. training session 24 (TS24). Pain and spasticity were, in addition, also assessed midway before training at session 12 (TS12). Assessments were repeated, at a follow-up session 4 weeks after the final training session, in order to assess whether potential changes were retained. Pain and spasticity were furthermore assessed immediately after the training session (details below).

Pain. Pain was assessed with the International SCI Pain Basic Data Set (version 2.0) (24) in 2 versions. The original version asked about levels of pain experienced during the last 7 days, prior to the training. The second version was modified by asking about pain experienced during the training, assessed immediately after the session. Every episode of pain was recorded, according to the International SCI Pain Basic Data Set, in terms of location, type and intensity. Participants could report up to 3 types of pain at each time-point. The type of pain was classified as either neuropathic or nociceptive.

Spasticity. The Modified Ashworth Scale (MAS) was used to assess spasticity. The following muscle groups were tested bilaterally: hip flexors and extensors, knee flexors and extensors, ankle dorsi-flexors and plantar flexors, 12 muscle groups in total. MAS assessments were performed immediately before training at baseline, TS12, TS24, and follow-up to assess changes over time. At TS12 and TS24, MAS was also tested immediately after the training session to assess changes pre-post a single training session. For statistical analysis, MAS was considered an ordinal scale. As a measure of overall spasticity, the sum-score of all 12 muscle groups was calculated for each person, at each time-point (0–60 scale). The calculated sum-score of MAS used in the analysis has not been validated, but a similar approach with a sum-score of spasticity has been described and used previously (25). If the MAS assessment triggered clonus, the measure was treated as a missing value, since the MAS scale does not include clonus, but rather describes increased tone or resistance against a passive movement. For calculation of the MAS sum-score, in case of clonus, all measures at other time-points for the same muscle were removed (list-wise deleting) to avoid an unbalanced sum-score when comparing different time-points.

Range of motion. ROM was measured by goniometry and assessed at baseline, TS24 and follow-up, bilaterally on the following lower extremity joint-movements: hip flexion, hip extension, knee flexion, knee extension, ankle dorsiflexion, and ankle plantarflexion. ROM was included, in order to assess potential mobility changes over time, as well as in conjunction with spasticity measures.

Spinal Cord Independence Measure. SCIM III (26, 27) was assessed for all participants at baseline, TS24 and follow-up. The subtotal-scores of Self-Care (0–20), Respiration and Sphincter Management (0–40), Mobility (0–40) and the total SCIM III-score (0–100) were used for analyses.

Bowel, lower urinary tract function and quality of life. The International SCI Basic Data Sets were used to assess bowel function (28), LUT function (29) and QoL (30).

All the International SCI Basic Data Sets were translated into the local language, according to recommendations (31). The International SCI Basic Data Sets can be found on the ISCoS homepage (http://www.iscos.org.uk/international-sci-data-sets).

Statistical analysis

Median and interquartile ranges (IQR) were used for descriptive statistics. Changes in paired, nominal data were analysed with McNemar's test. Repeated measures of intensity of pain, MAS, ROM, SCIM III and QoL were analysed with Wilcoxon signed-rank test and Bonferroni corrected for multiple comparisons of the repeated measures. Non-parametric statistics (McNemar's test and Wilcoxon signed-rank test) were also used for the analysis of change in MAS before and after a single training session at TS12 and TS24, the International SCI Bowel and Lower Urinary Tract Function Basic Data Sets. Significance level was set to $\alpha = 0.05$. Statistical analysis was performed with IBM SPSS Statistics version 22 (IBM Corp. Released 2013. Armonk, NY, USA).

Statement of ethics

All applicable institutional and governmental regulations concerning the ethical use of human volunteers were followed during the course of this research. All the necessary approvals were obtained in each centre, including local ethics committee approvals. All participants received oral, as well as written information about the study, before written consent was obtained. The study followed the guidelines of the Declaration of Helsinki. The study was registered at ClinicalTrials.gov (identifier: NCT02132702).

RESULTS

The study was performed from April 2014 to March 2016. A total of 52 participants completed the training. Participant characteristics are shown in Table II. A training session was up to 1 h and the median (IQR) was 31.5 min (24.5–39.0 min) over the 8 weeks of training (16).

Pain

Fig. 1A shows the number of participants who reported presence of pain in the week prior to training and Fig. 1B shows the number of participants who reported presence of pain during the exoskeleton training session. Pain in the week prior to training and during training (TS1, TS12 and TS24) was not always present, and thus was not reported by the same participants. Presence of pain in the previous week, at all 4 time-points (TS1, TS12, TS24, follow-up), was reported by 21 participants (40%), pain at 1, 2 or 3 time-points was reported by 15 (29%) and no pain at any time was

Table II. Participant characteristics, $n = 52$

Characteristics	
Age, years, median (IQR)	35.8 (27.5–52.6)
Sex, *n* (%)	
Men	36 (69.2)
Woman	16 (30.8)
BMI, kg/m^2, median (IQR)	24.1 (22.0–26.2)
Time since injury, year, *n* (%); median (IQR)	
Recently injured (TSI ≤1 year)	25 (48); 0.3 (0.2–0.4)
Chronically injured (TSI >1 year)	27 (5); 5.5 (2.1–10.8)
Spinal cord injury aetiology, *n* (%)	
Sport/leisure	16 (30.8)
Assault	2 (3.8)
Transport	17 (32.7)
Fall	7 (13.5)
Other traumatic cause	1 (1.9)
Non-traumatic spinal cord dysfunction	9 (17.3)
NLI and severity of injury at baseline, *n* (%)	
C1–C4 AIS A, B, C	0 (0)
C5–C8 AIS A, B, C	4 (7.7)
T1–S5 AIS A, B, C	29 (55.8)
All AIS D	19 (36.5)
Grouping of neurological injury, *n* (%)	
Motor complete tetraplegia C7–C8, AIS A and B	3 (5.8)
Motor incomplete tetraplegia C2–C8, AIS A and B	11 (21.2)
Motor complete paraplegia T1–L2, AIS A and B	22 (42.3)
Motor incomplete paraplegia T1–L2, AIS C and D	16 (30.8)

IQR: interquartile range; NLI: neurological level of injury; BMI: body mass index; AIS: American Spinal Injury Association Impairment Scale; TSI: time since injury.

reported by 16 (31%). Pain during all TSs was reported by 2 participants (4%), 4 participants (8%) had pain at 2 of the TSs and 13 (25%) reported pain at 1 of the 3 TSs where pain was surveyed.

There was no statistical difference, in either recently or chronically injured participants, from TS1 to TS24, or to follow-up of interference of pain on day-to-day activities, overall mood, ability to get a good night's sleep or in the number of pain problems experienced in the previous week.

Seven participants reported neuropathic pain during training at TS1, TS12 and TS24, while 15 reported nociceptive pain, with an overlap of 4 participants who experienced both types of pain. Locations for nociceptive pain were; lower back ($n = 7$), upper back ($n = 1$), shoulder ($n = 3$), hip ($n = 2$) and knee ($n = 2$). Locations of neuropathic pain during training were; thigh and lower extremity ($n = 4$), lower back and hip ($n = 3$).

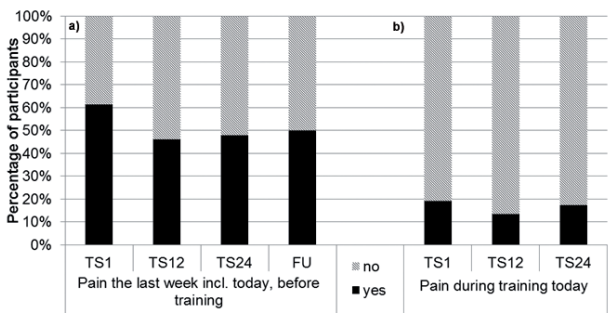

Fig. 1. Presence of pain in the last week and pain during exoskeleton training, $n = 52$. TS: training session; FU: follow-up.

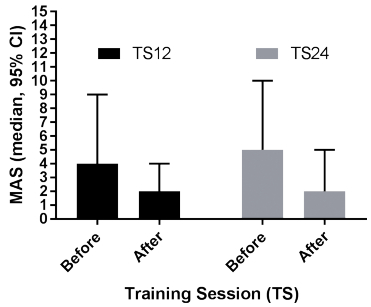

Fig. 2. Modified Ashworth Scale (MAS) before and after a single training session, $n = 51$. CI: confidence interval.

When analysing the participants individually, the pain reported during training had the same location and was of the same type as pain reported between TSs in the previous week. The only exceptions to this were 2 participants who reported pain in the hip and shoulder during their first training session, but did not report pain in the previous week.

Spasticity

Fig. 2 shows the MAS sum-score before and after a single training session at TS12 and at TS24. There was a significant reduction in spasticity on the MAS sum-score from pre- to post-training at both TS12 and TS24 sessions after Bonferroni correction ($p = 0.05/2 = 0.025$). The results at TS12 were a median (IQR) decrease from 4 (0–16) to 2 (0–10), $p < 0.001$ and at TS24 a decrease from 5 (0–14) to 2 (0–9), $p < 0.001$. In 8 participants, the movement of the ankle plantar flexors triggered clonus; thus, as it was not possible to rate on the MAS, the data-points were excluded from analysis. Statistical testing was done only on the MAS sum-score of the 12 muscle groups (6 muscle groups bilaterally), but all of the 12 muscle groups decreased on the MAS sum-score from before to after the training session at TS12 and TS24, calculated as rank scores.

No significant difference was found in MAS longitudinally from baseline to TS24 or follow up, in either the recently, or the chronically injured group.

Range of motion

No differences in ROM were detected between baseline, TS24 and follow-up.

Spinal Cord Independence Measure

The results of the SCIM III for recently injured and chronically injured participants are shown in Table III.

Table III. Spinal cord independence measure III

	Baseline Median (IQR)	TS24 Median (IQR)	Follow-up Median (IQR)	Baseline–TS24 *p*-value	Baseline–Follow-up *p*-value
Recently injured ($n=25$)					
Self-care	18 (14.5–19.5)	18 (16.0–20.0)	18 (16.0–19.0)	0.006	0.025
Respiration and sphincter management	30 (23.5–35.5)	33 (30.5–36.0)	34 (31.5–36.0)	0.001	<0.001
Mobility	16 (13.0–18.5)	19 (16.5–24.5)	19 (15.5–26.5)	<0.001	<0.001
Total score	62 (51.0–73.0)	70 (65.0–77.0)	73 (67.5–78.0)	<0.001	<0.001
Chronically injured ($n=27$)					
Self-care	18 (17.0–19.0)	18 (17.0–19.0)	18 (17.0–20.0)	0.280	0.189
Respiration and sphincter management	35 (30.0–37.0)	35 (33.0–38.0)	36 (33.0–37.0)	0.027	0.010
Mobility	19 (16.0–23.0)	19 (17.0–25.0)	19 (17.0–23.0)	0.064	0.297
Total score	73 (64.0–77.0)	74 (68.0–81.0)	74 (71.0–78.0)	0.008	0.014

IQR: interquartile range; TS24: training session 24.

The recently injured group improved significantly on the total SCIM III score, as well as on all sub-categories. The "Respiration and Sphincter Management" sub-category did not change on the bladder score, but increased on the bowel and use of toilet score.

The chronically injured group improved significantly on the total SCIM III score, with a median increase of 1 point. Out of all sub-categories scores, the "Respiration and Sphincter Management" was the only one with a significant increase. Within that sub-category, "Use of Toilet" had the largest change.

Bowel function and lower urinary tract function on the International SCI Basic Data Sets

Within the item "awareness of the need to defecate", improvements were seen in 6 out of 25 participants of the recently injured group and none worsened. The chronically injured did not change on this item. No significant differences over time were found on outcomes measuring either bowel or LUT function.

Quality of life

Results for recently and chronically injured participants are shown in Table IV. QoL in the recently injured group did not change significantly over time, whereas, satisfaction with life as a whole was found to increase significantly for the chronically injured group from baseline to TS24 ($p=0.03$), as well as to follow-up ($p=0.01$).

DISCUSSION

This study aimed to assess changes in pain, spasticity, ROM, SCIM III, QoL, bowel and LUT function, during a period of gait training using an exoskeleton. The main findings were short-term reductions in lower extremity spasticity and, for a subset of participants, there were improvements over time in SCIM III and QoL. There were no significant longitudinal changes on the other outcomes. The importance of early intervention is well established and there are no results from this study indicating that this training modality could not be initiated in the early phase of rehabilitation. To ensure this recommendation, further studies need to be carried out. Furthermore, also, the chronically injured participants (TSI >1 year) seemed to benefit on some parameters from the training, indicating that the exoskeleton training might be well-suited, both for persons with recent, and those with chronic, injuries.

Table IV. Quality of life

	Baseline Median (IQR)	TS24 Median (IQR)	Follow-up Median (IQR)	Baseline–TS24 *p*-value	Baseline–Follow-up *p*-value
Recently injured ($n=25$)					
Satisfaction with life as a whole[a]	5 (3.0–7.0)	6 (4.5–8.0)	6 (4.0–8.0)	0.101	0.079
Satisfaction with physical health[b]	6 (3.5–7.5)	7 (4.5–8.0)	6 (4.0–7.0)	0.129	0.363
Satisfaction with psychological health, emotions and mood[c]	7 (5.0–8.0)	5 (4.0–8.0)	7 (4.0–8.0)	0.073	0.636
Chronically injured ($n=27$)					
Satisfaction with life as a whole[a]	6 (5.0–7.0)	7 (6.0–9.0)	8 (7.0–8.00)	0.036	0.010
Satisfaction with physical health[b]	7 (6.0–8.0)	7 (6.0–8.0)	7 (4.0–8.0)	0.279	0.329
Satisfaction with psychological health, emotions and mood[c]	7 (6.0–9.0)	8 (7.0–8.0)	7.5 (5.75–8.0)	0.080	0.273

[a]Satisfaction with life as a whole refers to the question "Thinking about your own life and personal circumstances, how satisfied are you with your life as a whole in the past 4 weeks? Please use a scale ranging from 0 (completely dissatisfied) to 10 (completely satisfied)".
[b]Satisfaction with physical health refers to the question "How satisfied are you with your physical health in the past 4 weeks? Please use a scale ranging from 0 (completely dissatisfied) to 10 (completely satisfied)".
[c]Satisfaction with psychological health, emotions and mood refers to the question "How satisfied are you with your psychological health, emotions and mood in the past 4 weeks? Please use a scale ranging from 0 (completely dissatisfied) to 10 (completely satisfied)".
TS24: Training Session 24.

Pain

The prevalence of pain in the week prior to training (Fig. 1) was similar to frequencies reported in the literature (10). The pain experienced in the week prior to training and during training did not differ regarding type and location of pain. Relatively few participants experienced pain during training. This could indicate that the training did not provoke a new pain sensation and that the training was well tolerated. Kolakowsky-Hayner (13) reported lower back pain during training with Ekso during walking, but this did not affect participation. In our study, although reports of low back pain were documented as the most frequent location of pain, no individuals dropped out as a result of this (16). Case reports on improvements of pain after exoskeleton training have been published (12, 14, 32), as well as decrease in pain over time after training in the Lokomat (Hocoma AG, Zurich, Switzerland) (33), but changes over time in pain between training session were not found in our study. Differences in the findings in this study from previous findings could, however, be related to the method of pain assessment.

Spasticity

Spasticity did not change over the 8-week period, but decreased from before to after a training session at both TS12 and TS24. The sum-score values were in the lower end of the 0–60 sum-score scale. The reason for this was a high number of MAS ratings having a value of 0, i.e. no spasticity, since all values of the 12 muscle groups were included in the sum-score. This indicates a floor effect, which biased the analysis of the training effect on spasticity. However, when listed as rank scores, all of the individual 12 muscle groups tested had more ranks that decreased than increased in MAS score at both TS12 and TS24.

Decreased spasticity post-training could be useful for individuals with SCI who would like to participate in exoskeleton training or use it as a potential, future mobility device. If used on a daily basis, it could, potentially, be incorporated as part of a spasticity relief programme. Stampacchia et al. (25) found decreased spasticity, from pre- to post-training in 1 walking session in a study of 21 participants. Case reports of short-term improvements in spasticity of a few hours after training have also been published on the exoskeleton HAL (Hybrid Assistive Limb), Cyberdyne, Inc., Ibraki, Japan) (34). Thus, the results from the present study are in line with previous findings.

The MAS was chosen as assessment method for spasticity. The MAS has several limitations as a measure of spasticity (35), but is still the most-used scale in the clinical setting (3). Furthermore, its use is recommended by the National Institute of Neurological Disorders and Stroke (NINDS) Common Data Element (CDE) (36). In a previous study, we found the MAS to be reliable, assuming that the scale is considered as an ordinal scale (37). The sum-score of MAS used in the analysis is not validated, but a similar approach with a sum-score of spasticity has been used previously (25). We argue that the sum-score could give an overall picture of the degree of lower limb spasticity. Future studies could consider adding other scales of spasticity alongside MAS to capture other aspects of spasticity.

ROM was included as an end-point, in conjunction to the spasticity tests. In case there would have been changes in ROM, this could potentially confound the MAS assessment, but no change in ROM was found.

Spinal Cord Independence Measure, bowel and bladder function

The improvements seen in SCIM III for the recently injured group could probably be attributed to early phase improvements following SCI, especially considering that this group was relatively newly injured, with a median (IQR) time since injury of 0.3 (0.2–0.4) years (Table II). Interestingly, the results also indicated improvements for chronically injured participants on the total SCIM III score, although to a smaller degree.

Respiration and sphincter management sub-score on SCIM III improved for both recently and chronically injured participants. There were signs of improvement in bowel function in the recently injured group on the SCIM III sub-score and in one item on the International SCI Bowel Function Basic Data Set, but not significantly, within the chronically injured group. It can be speculated that a reason for not capturing a potential effect on bowel and LUT function was that the amount of training and intensity was too low to elicit changes. A recently published study by Hubscher et al. (38) documented improvements in urinary incontinence and time needed for defecation, assessed by the same questionnaires as in our study, following 80 daily locomotor training sessions using body-weight-supported treadmill training.

There were, however, improvements on the SCIM III subscale "Use of Toilet". We speculate whether this could be related to an improved balance function, since these participants also improved the Timed Up and Go test and the Berg Balance Scale in the same study period, as described previously (16). This could be a direction for future research. Previous studies on changes in bowel and bladder function after exoskeleton training has been documented in case reports (13, 14).

Quality of life

Chronically injured participants experienced an improved QoL "satisfaction with life as a whole" over the study period. This result was maintained throughout the follow-up period. Adriaansen et al. (10) reported a median value of 7 on the item "satisfaction with life as a whole", a value of 6 on "satisfaction with physical health" and 7 on the item "satisfaction with psychological health" in a study on individuals with chronic SCI. Similar values on QoL were found in our study. Improvements in QoL have previous also been reported in case studies using the exoskeletons ReWalk (ReWalk Robotics Ltd, Yokneam, Israel (39) and HAL (32).

The recently injured group did not show any changes in QoL values in the present study. One explanation could be that QoL is known to improve in the years following the injury (7) and the recently injured group was only a few months post-injury.

The strengths of the current study include the heterogeneous sample of participants with SCI, including participants with complete and incomplete injury, tetraplegia and paraplegia, recently and chronically injury and both sexes, across different rehabilitation centres and countries, reflecting the heterogeneous nature of the SCI population. However, this also limits the possibility to detect changes in the subgroups, since this would need a larger study population to fully explore all subgroup differences. Future studies could investigate whether more frequent and intense training protocols would elicit changes in, for example, pain, bowel and LUT function. The comparator in randomized trials has often been body-weight-supported treadmill training, but also comparison with daily clinical routine treatment or even functional electric stimulation would be worth exploring, since the latter can be incorporated into exoskeletons.

The study was a non-controlled, non-randomized study with a sample of convenience, which does not allow conclusions to be drawn on causality of the findings in relation to the intervention of exoskeleton gait training. The results should be interpreted as indicators and can be used only to guide the direction of future studies.

Conclusion

The results of this study indicate that both recently injured and chronically injured participants can benefit from exoskeleton training. The exoskeleton training seemed to be well-tolerated in participants with pain and did not provoke new types of pain sensations. Spasticity decreased from before to after a training session, but did not change over time and there was no change in ROM. There was increase on SCIM III for both recently and chronically injured participants. Furthermore, the QoL score increased in chronically injured participants. No significant changes were detected in bowel and LUT function. Future studies assessing bowel and LUT function could investigate a longer training period and higher frequency of training.

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