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REVIEW

The influence of orthosis options on walking parameters in spinal cord-injured patients: a literature review

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Objective: Orthoses for various joints sections are considered to greatly influence the gait function and energy expenditure in spinal cord-injured (SCI) patients. The aim of this review was to determine the influence of orthoses characteristics and options on the improvement of walking in patients with SCI.
Methods: A search was performed using the Population Intervention Comparison Outcome (PICO) method, based on selected keywords; studies were identified electronically in the Science Direct, Google Scholar, Scopus, Web of Knowledge and PubMed databases. The Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) method was used to report the results. Assessment of the quality of all articles was performed based on the Physiotherapy Evidence Database (PEDro scale).
Results: Twelve studies evaluated the effects of different hip joint options on walking parameters and energy expenditure. Five studies investigated the role of knee joint options on gait parameters and compensatory trunk motion. Only five studies analyzed modified ankle joints on gait parameters in SCI patients. Nine studies analyzed gait parameters in SCI patients as powered orthoses and exoskeleton. These studies had a low level of evidence according to the PEDro score (2/10).
Conclusion: The various joint types of orthoses appear to be critical in the improvement of walking in patients with SCI. In particular, 'user friendly' orthoses that support the related structure such as the hip joint with a reciprocating mechanism, activated knee joint and movable ankle joint with dorsiflexion assist enable SCI patients to optimize their walking pattern when wearing an orthoses system.
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INTRODUCTION

Orthotic gait training is usually considered for spinal cord-injured (SCI) patients during their rehabilitation process to enable them to stand and ambulate. Although the effectiveness of walking with orthoses has been shown in previous studies in this field, the high energy cost of walking with orthoses is reported as the main reason of rejection rate in these patients.[1–4] According to the required compensatory upper limb and trunk motion to facilitate the swing motion of the paralyzed lower limb, SCI patients inevitably require larger energy expenditure for orthotic gait.[5–7] Furthermore, it can be pointed out that the various orthotics options according to joints sections considerably influence the gait function and energy expenditure in SCI patients.

In a recent literature review, Arazpour *et al.*[8] evaluated the walking efficiency during orthotic gait of SCI paraplegics and determined that there is limited evidence, if any, in terms of superiority of powered orthoses on mechanical orthoses. In a review of mechanical and hybrid orthoses of walking in paraplegic patients, Nene *et al.*[9] also noted that mechanical orthoses were used only for exercise purposes. These systems in general were worn for a few hours in a week because of the high rate of energy consumption used during walking with these orthoses.[9] In comparison, Karimi noted differences between mechanical orthoses and hybrid orthoses in various kinetic parameters and energy consumption and stated that mechanical orthoses were more effective in providing stability and reducing energy consumption during walking in paraplegic patients.[10] In another review, Arazpour *et al.* reported on the walking efficiency of powered orthoses on walking in paraplegic subjects.[11] Although the effect of orthosis options in walking in paraplegic subjects is well reported, it is not clear to what extent the orthosis options for various joints sections influence gait function performance. The aim of the present review was to analyze the different orthosis with and without reciprocation mechanism or another type of exertion mechanism (for example, orthoses that modified hip joints, knee joints and ankle joints) and powered exoskeleton on the improvement of walking in the SCI patients.

METHODS

Search strategy

A search was performed using the Population Intervention Comparison Outcome (PICO) method, based on selected keywords and their composition (Table 1). By using 'OR', 'AND', 'NOT' words between the considered keywords, studies were identified electronically in the Science Direct, Google Scholar, Scopus, Web of Knowledge and PubMed databases. Studies were selected by hand searching the reference lists of the electronically identified studies. The Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) method was used to report the results. Assessment

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of the quality of all articles was performed based on the Physiotherapy Evidence Database (PEDro scale). Studies that follow to the outcome measures were included in the final review. According to the chosen inclusion and exclusion criteria, 29 articles were subsequently chosen for final evaluation.

Inclusion and exclusion criteria

Table 2 demonstrates the inclusion and exclusion criteria in this study. The studies that were considered for inclusion were randomized clinical trials (RCTs), case–control trials, cohort studies, case series studies and single-case studies. Language or year of publication was not considered as restrictions. Studies reporting the effect of all types of mechanical orthoses such as Hip Knee Ankle Foot Orthosis (HKAFOs), Knee Ankle Foot Orthosis (KAFOs), the Louisiana State University Reciprocating Gait Orthosis (LSU RGO), the Advanced Reciprocating Gait Orthosis (ARGO), the Isocentric Reciprocating Gait Orthosis (IRGO), the Parawalker, the Hip Guidance Orthosis (HGO), the Primewalk orthosis, the Walkabout orthosis (WO), the Moorong medial linkage orthosis and powered orthosis (for example, Rewalk, wearable power assist locomotor orthosis (WPAL), the hybrid-assisted limb orthosis (HAL)) designs on paraplegic ambulation were selected for further analysis. Papers were selected from peer reviewed journals, which demonstrated or reported energy consumption, temporal spatial, kinematics and kinetic effects of mechanical orthoses with adding options or alternation in components used in SCI subjects. Studies that included alternative outcome measures, employed 'body weight support systems with robot-assisted gait', compared primary outcome measures between patients with different disabilities and those that tested orthoses with healthy volunteer subjects (even though the orthoses of interest were utilized in the study) were also excluded. The abstracts and full text of all of the studies found in all databases were compared with the inclusion criteria by two independent reviewers.

Table 1 Selected key words using the PICO method

P: population	*I: intervention*	*C: comparison*	*O: outcome measure*
Spinal cord injury Paraplegia Paraplegic	Hip knee ankle foot orthoses, Knee ankle foot orthoses, The Louisiana State University reciprocating gait orthosis, The advanced reciprocating gait orthosis, The isocentric reciprocating gait orthosis, The Parawalker, The hip guidance orthosis, The Primewalk orthosis, The Walkabout orthosis, The Moorong medial linkage orthosis Robotic Exoskeleton Rewalk, Wearable power assist locomotor orthosis, The hybrid-assisted limb orthosis	Not applicable	Gait parameter Kinetic Kinematic Cadence Walking speed Step length Range of motion Temporospatial parameter

RESULTS

The studies identified for those with SCI are either individual case reports or individual subject data from a multiple case series and are therefore classified as poor quality papers (Tables 3-6). PEDro scores ranged from 1 to 4 across studies, with a median value of 2.

Studies that evaluated modified hip joints on gait parameters in the SCI patients

Table 3 demonstrated studies that evaluated the modified hip joints on gait parameters in the SCI patients. Twelve studies evaluated the effects of different hip joint options on walking parameters and energy expenditure.[5,12–22] These studies had low level of evidence according to the PEDro score (2/10). Table 3 provides details on the studies evaluating modified hip joints in patients with SCI. As outlined in Table 3, in 4 of 12 studies, functional electrical simulation (FES) with and without RGO was evaluated in comparison with a mechanical orthosis (for example, long leg brace and medial linkage orthosis).[5,12,17,19] In 7 of 12 studies, different mechanical orthoses compared with each other, and it has proved that various forms of RGOs have a higher velocity and lower energy expenditure in comparison with conventional and medial linkage orthoses.[13–16,18,21,22] Only one study compared a powered orthosis with two other mechanical orthoses.[23]

There were three types of mechanical hip joint mechanism (HKAFO, RGO and medial linkage orthosis (MLO)) in orthoses, which were used in walking in SCI patients. A simple hip joint with one degree of freedom generally was used in the HKAFO as the first mechanism of hip joint system. Paraplegic patients use a swing through walking pattern during ambulation with this type of orthosis. RGO, as the second mechanism of hip joint system, were introduced in the late 1960s. The hip joints linked together to provide reciprocal motions of both hip joints that connected two sides KAFOs. Within this type of orthosis, a hip mechanism prevents uncontrolled collapse of the trunk and allows freely upper extremities movement of SCI patients. A modified version of RGOs is referred to as the advanced reciprocating gait orthosis (ARGO) with a one pull–push cable within the pelvic section developed to assist walking performance in paraplegic subjects. A more developed RGO is defined as the isocentric reciprocating gait orthosis (IRGO) and was introduced by Motlock in 1992.[24] Another type of mechanical orthosis is MLO as the third mechanism of the hip joint system. There are variations of this type of orthosis, which include the Walkabout,[25] Moorong[16] and Primewalk,[26] the HALO[18] and new reciprocating MLO.[27]

Table 2 Inclusion and exclusion criteria utilized to select articles

Inclusion criteria	*Exclusion criteria*
Studies were reported energy consumption, temporal spatial, kinematics and kinetic effects of mechanical orthoses with adding options or alternation in components used in SCI subjects. Studies reporting the effect of all types of mechanical orthoses such as HKAFOs, KAFOs, LSU RGO, ARGO, IRGO, the Parawalker, HGO, the Primewalk orthosis, WO, the Moorong medial linkage orthosis and powered orthosis (for example, Rewalk, WPAL orthosis, the HAL orthosis) designs on paraplegic ambulation	Studies with alternative outcome measures, Studies using 'body weight support systems with robot-assisted gait', Studies that compared the primary outcome measures between patients with different disabilities, Studies that tested orthoses with healthy volunteer subjects (even though the orthoses of interest were utilized in the study)

Abbreviations: ARGO, advanced reciprocating gait orthosis; HAL, hybrid-assisted limb; HGO, hip guidance orthosis; HKAFO, hip knee ankle foot orthosis; IRGO, isocentric reciprocal gait orthosis; KAFO, knee ankle foot orthosis; LSU RGO, the Louisiana State University reciprocating gait orthosis; SCI, spinal cord injury; WO, walkabout orthosis; WPAL, wearable power assist locomotor.

Table 3 The studies that evaluated the effect of modified hip joints on gait parameters in the SCI patients

Author	*Study design*	*Sample size and injury level*	*Total score of the PEDro scale*	*Types of intervention*	*Results*
Hirokawa *et al.*[5]	Case series study	Six subjects with thoracic paraplegia	2	RGO with and without FES, LLB, HGO	The result assumed that the lowest energy costs in Kcal kg^{-1} per min were associated with the RGO and FES for walking speeds below 28 m per second. At walking speeds higher than 28 m per second, the HGO demonstrates lower energy cost. Patients using the RGO and FES had a mean heart rate (HR), which was 12 beats per minute less than the mean HR when using the RGO without FES.
Petrofsky *et al.*[12]	Research support	Four subjects with complete lesions from T4 to T12 Four able-bodied (control group)	3	RGO with and without FES	Oxygen consumption for paralyzed subjects walking with FES was 0.221cc per kg per m per min but for paralyzed subjects walking without FES was 0.413 cc per kg per m per min. Also cardiac output was less for paralyzed subjects walking with FES (8.3 W min in comparison with 10.3 W min for RGO alone).
Bernardi *et al.*[13]	Clinical trial	Ten paraplegic patients with thoracic levels from T4 to T12 seven normal subjects (control group)	3	RGO	Patient using RGO at the speed of 0.004 ± 0.002 m per second, energy physiological cost index was 11 ± 4 J per K per M, whereas in the control group this parameter was 2.35 ± 0.45 J per K per M at the speed of 0.13 ± 0.002 m per second. In addition, using RGO caused 8.6% walking work efficiency in four subjects with SCI at the mean speed of 0.32 m per second.
Harvey *et al.*[15]	Randomized cross-over study	Ten subjects with complete lesions between T9 and T12	2	WO, IRGO	Subjects walked faster with IRGO compared with the WO in two surfaces (flat surface and up and down ramp surfaces). Walking with IRGO on flat surface was 0.34 ± 0.18 m per second versus walking with WO was 0.14 ± 0.12 m per second ($P=0.02$) and by IRGO on up and down ramp surface was 0.25 ± 0.9 m per second versus WO was $0.14 \pm$ 0.6 m per second ($P=0.02$).
Harvey *et al.*[14]	Randomized cross-over study	Nine complete paraplegia (level of injuryT9–T12)	2	WO, IRGO	Subjects walking faster when using IRGO (range 0.18 to 0.19 m per second) compared with WO (range 0.08 to 0.095 m per second) ($P<0.05$). Heart rate was similar between WO (range, 119 ± 9 to 133 ± 14 beats per min) and IRGO (range, 120 ± 6 to 140 ± 11 beats per min). Identically, Vo2 did not differ between two orthoses. PCI and O2 cost of gait with WO were more than with IRGO.
Middleton *et al.*[16]	Case study	One woman with an incomplete C6 tetraplegia	2	Moorong MLO, WO	Oxygen cost of gait decreased when ambulating in the Moorong MLO, ranging from 18 to 61% (mean 39%) compared with WO. In addition, gait velocity in the Moorong MLO slightly increased (between 0.36 and 1.02 m per min faster than WO).
Merati *et al.*[17]	Comparative study	Fourteen patients (lesion level $C7 \pm T11$).	4	HGO Orlau PW, RGO, RGO with FNS	During orthosis-assisted locomotion at maximal speed HR peak values were 150 ± 13, 131 ± 21 and 155 ± 23 beats per min and VO2 1 per kg peak values were 13.4 ± 3.0, 13.8 ± 3.5 and 17.2 ± 4.8 for PW, RGO and RGO+FNS, respectively. They also reported that maximal ventilations at VO2 peak were 71.8 ± 7.3, 76.5 ± 21.3 and 72.3 ± 12.2 m kg^{-1} per min during orthosis locomotion for PW, RGO and RGO+FNS, respectively.
Genda *et al.*[18]	Case study	One man with complete paraplegia at the level of T12	2	HALO, primewalk orthosis	Stride length was not significantly different between the two orthoses, but HALO was better than Primewalk in the cadence and the velocity either with a walker or with Lofstrand crutches. They demonstrated that velocity, cadence and stride length of subject with by wearing HALO and using walker were 0.6 m per second, 74.1 steps per min and 103 cm, respectively. Walking with HALO seemed more natural than that with Primewalk because pelvic rotation angle with HALO was 20º and with primewalk orthosis was 50º.
Shimada *et al.*[19]	Case reports		3	Sliding type MLKAFO with and without the FES versus hinge type MLKAFO with FES	There was a significant difference in walking velocity between hinge-type MLKAFO with FES and sliding-type MLKAFO with FES ($P<0.01$). Through utilizing sliding-

Table 3 (Continued)

Author	Study design	Sample size and injury level	Total score of the PEDro scale	Types of intervention	Results
		Two subjects with complete paraplegia (level of injury T8 and T12).			type MLKAFO with FES, walking velocity was 12.8 ± 0.6 m per min for T8 patient and 0.3 ± 0.013 m per second for T12 patients. Walking velocity with hinge-type MLKAFO with FES was reported 0.086 ± 0.015 m per second for T8 subject and 0.281 ± 0.01 m per second for T12 subject.
Arazpour *et al.*[20]	Comparative study	Five patients with T6–T12 spinal cord lesions	2	HKAFO, IRGO, PGO	Mean walking speed with HKAFO, IRGO and PGO was 0.23 ± 0.03, 0.25 ± 0.03 and 0.3 ± 0.02 m per second, respectively. PGO improved walking speed compared with HKAFO ($P<0.001$) and IRGO ($P<0.006$). Using PGO orthosis results in reduction in the PCI of walking as compared with HKAFO and IRGO (0.92 ± 0.25 in comparison with 1.93 ± 0.40 and 1.97 ± 0.17 beats per minute). Also there was no significant difference between HKAFO and IRGO in energy consumption ($P = 1.000$).
Ahmadi Bani *et al.*[21]	Comparative study	One woman with incomplete paraplegia at the level of T10	2	A new MLRGO that incorporates a reciprocal mechanism and is sensitive to pelvic motion	The MLRGO increased stride length (73.97 cm), speed of walking (1.77 m per second) and cadence (29.10 steps per min) compared with the IRGO. In addition, hip extension took more time but was nearer to that seen during normal hip movement than when walking with the IRGO.
Ahmadi Bani *et al.*[21]	Comparative study	Four people with motor incomplete SCI with injury levels ranging from T8 to T12)	2	A new MLRGO that incorporates a reciprocal mechanism and is sensitive to pelvic motion compared with IRGO	Reductions in energy consumption were observed using new MLO (0.717 beats per min) compared with using IRGO (0.972 beats per min), but the difference was not statistically significant. However, walking distance and walking speed (IRGO:0.33, new MLO: 0.39 m per second) also improved but not significantly.

Abbreviations: FES, functional electrical simulation; HALO, hip and ankle linked orthosis; HGO, hip guidance orthosis; HKAFO, hip knee ankle foot orthosis; IRGO, isocentric reciprocal gait orthosis; LLB, long leg brace; MLO, medial linkage orthosis; MLRGO, medial linkage reciprocating gait orthosis; PGO, powered gait orthosis; PW, Para walker; RGO, reciprocating gait orthosis; WO, walkabout orthosis.

Table 4 The studies that evaluated the effect of modified knee joints on gait parameters in the SCI patients

Author	*Study design*	*Sample size and injury level*	*Total score of the PEDro scale*	*Types of intervention*	*Results*
Solomonow *et al.*[28]	Research support	Six patients with thoracic paraplegia (injury level C5-6 to T10)	2	RGO Generation II with FES, RGO without FES	Results showed an average 31.6% reduction in energy consumption by using RGO with FES. Approximately, at the speed of 0.37 m per second this reduction was 15.4%. The heart rate at the end of 30 m walking when wearing RGO with FES was 119 beats per min compared with 131 beats per min when using RGO alone. It shows that adding FES to mechanical orthosis results in reduction in heart rate during walk.
Green *et al.*[29]	Evaluation study	Two patients with incomplete SCI with level of T6 level	2	Orthosis with knee flexion and ankle dorsiflexion orthosis with knee flexion alone	Mean walking speed, stride length, peak knee flexion, peak dorsiflexion, peak lateral tilt and COG vertical excursion for Orthosis with flexed knee ankle were 0.14 ± 0.03 m per second, 0.7 ± 0.14 m, 32.45 ± 3.3°, 10.05 ± 1.15°, 0.7 ± 0.8°, 0.004 ± 0.001 m, respectively. For orthosis with knee flexed alone, data showed that walking speed, stride length, peak knee flexion, peak dorsiflexion, peak lateral tilt and COG vertical excursion were 0.13 ± 0.015 m per second, 0.725 ± 0.055 m, 80.2 ± 4.75°, 2.95 ± 1°, 3.35 ± 0.6°, 0.013 ± 0.001 m, respectively.
Ohta *et al.*[30]	Research support	Five subjects with complete SCI	2	Two degree of freedom externally powered gait orthosis with knee and hip actuator	Gait speed and the step length by knee actuator were 0.53 ± 0.03 m per second and 108 ± 2.3, respectively. However, without the knee actuator both parameters decreased by 0.43 ± 0.01 m per second and 1.01 ± 0.015 m. By using hip actuator, the averaged gait speed was 0.4 ± 0.02 m per second and step length was 0.97 ± 0.04 m. Without hip actuator mean of Gait speed was 0.16 ± 0.0125 m per second and mean of stride length was 0.94 ± 00.6 m.
Kim *et al.*[32]	Research support	Two subjects with spinal damage in T11	2	UKJPGO versus PGO, RGO	Value of flexion angle by UKJPGO was 43 ± 5° displaying good flexion in comparison with PGO. Walking speed in UKJPGO was 16% higher than PGO (0.31 ± 0.002 m per second for UKJPGO and 0.26 ± 0.002 m per second for PGO). Cadence increased about 10% when using UKJPGO.
Arazpour *et al.*[60]	A single case study	A woman with a T8 incomplete SCI	2	IRGO, AKIRGO	Mean speed of walking, stride length and cadence when the paraplegic patients walked with AKIRGO were more than IRGO. Results demonstrated 37.5% increase in the speed of walking in AKIRGO, 11% longer stride length with KIRGO and increase in cadence through using AKIRGO by 26% compared with wearing IRGO. Data about the knee joint flexion showed that it was 37.5° for the AKIRGO compared with 7° movement when walking with the IRGO.

Abbreviations: AKIRGO, activated knee IRGO orthoses; FES, functional electrical simulation; IRGO, isocentric reciprocal gait orthosis; PGO, powered gait orthosis; RGO, reciprocating gait orthosis; SCI, spinal cord injury; UKJPGO, unlockable knee joint powered gait orthosis.

Table 5 The studies that evaluated the effect of modified ankle joints and foot sections on gait parameters in the SCI patients

Author	*Study design*	*Sample size and injury level*	*Total score of the PEDro scale*	*Types of intervention*	*Results*
Kawashima *et al.*[39]	Comparative study	Four paraplegic patients with injury level ranged from T8 to T12	2	WBC orthosis versus conventional orthosis	After 3 months of orthotic gait training, the average walking speed, the value of steady state of VO2 and heart rate during exercise were 0.317 m per second, 16.08 ± 1.93 ml kg^{-1} and 147.3 ± 10.94 beats per min, respectively. Also, they reported that the energy consumption during walking with orthosis was 5.41 ± 0.65 J per kg per second slightly larger than that in previous reports (5.41 versus 4.37 J per kg per second), and the energy cost of walking was 17.12 ± 0.72 J per kg per m.
Suzuki *et al.*[40]	Case report	One paraplegic patient with level of injury T7	2	Heel cushion in shoes for use with knee-ankle-foot orthoses having a medial single hip joint (prime walk orthosis)	Walking speed increases from 0.14 to 0.27 m per second (mean 12.65), step length increases from 0.16 to 0.31 m (mean 0.24 m) and physiological cost index decreased range from 7.7 to 3.48 beats per min (4.8% decrease). Modified new heel cushion of the shoe provided freedom to the lower legs and thereby increased walking efficiency.
Arazpour *et al.*[20]	Pilot study	Four thoracic level injury subjects (one at T8 and four T12 level)	4	Standard ARGO modified ARGO (addition of rocker sole)	Mean walking speed and step length increased by 0.03 m per second and by 0.03 m, respectively, but cadence was not significantly changed 0.2 ± 0.5 steps per min ($P > 0.761$) when walking with the modified ARGO (0.025 ± 0.011 m). Hip flexion ($P < 0.016$) and extension ($P < 0.002$) both significantly increased when ambulating with the modified ARGO, and also the swing phase cycle ratio was significantly reduced when walking with adapted ARGO ($64.5 \pm 2.38\%$ of gait cycle) compared with the standard ARGO ($78.75 \pm 3.30\%$ of gait cycle) ($P < 0.001$).
Arazpour *et al.*[37]	Comparative study	Five SCI patients	2	ARGO with solid ankle–foot orthosis, ARGO with dorsiflexion-assist ankle–foot orthosis	When using two crutches, there was no significant difference in static standing postural sway in the M/L direction ($P = 0.799$) but significant difference in the A/P direction ($P = 0.014$). However, during single crutch support, there was a significant difference in both M/L ($P = 0.019$) and A/P ($P = 0.022$) directions. Walking speed (7%) and endurance (5%) significantly increased when using the ARGO with dorsi flexion-assisted AFOs. There was no significant difference between the two types of orthoses in cadence ($P = 0.54$).
Ahmadi bani *et al.*[51]	Quasi-experimental study	Four SCI patients (T8, T10, T12)	2	ARGO with dorsi flexion assist, ARGO with fixed ankle foot orthosis	Using ARGO plus to dorsi flexion assist demonstrated an increase in the walking speed and stride length associated with cadence compared with ARGO plus to fixed ankle foot orthosis. The mean of hip joint range of motion was increased but not significantly.

Abbreviations: ARGO, advanced reciprocating gait orthosis; SCI, spinal cord injury; WBC, weight-bearing control.

Table 6 Studies investigating the effects of powered orthosis and exoskeleton on gait parameters by SCI subjects

Author	*Study design*	*Sample size and injury level*	*Total score of the PEDro scale*	*Types of intervention*	*Results*
Tanabe *et al.*[41]	Research support	Four complete SCI in thoracic level of injury from T5 to T12.	2	WPAL based on an unpowered gait orthosis 'Prime Walk' with six DC servo motors on hip, knee and ankle joints to assist walking, stand-up and sitting down movements.	All paraplegic patients had the ability to stand, sit and walk independently with the WPAL. The walking time and distance of walking with WPAL increased and the physiological cost index and muscle activity of upper extremities decreased compared with Primewalk mechanical orthosis.
Zeilig *et al.*[42]	Research support	Six complete SCI in thoracic level of injury from T5 to T12.	3	ReWalk Exoskeletal robotic device with powered hip and knee joints and articulated mechanical ankle joints with spring-assisted dorsiflexion	101 s were needed to complete the timed up and go task (TUG) and 66 s to complete the 10-m walking test in SCI patients when using the Rewalk after gait training. The mean of distance of walking in 6 min was 47 m.
Esquenazi *et al.*[43]		Twelve complete SCI with thoracic level of injury between T3 and T12.	3	ReWalk exoskeletal robotic device with powered hip and knee joints, plus articulated mechanical ankle joints with spring-assisted dorsiflexion	All SCI subjects had at least 50–100 m distance of walking, for a period of at least 5–10 min continuously with the speed of walking ranging from 0.03 to 0.45 m per second (mean, 0.25 m per second) while using the ReWalk. Some SCI patients had improvements in pain, bowel and bladder function, spasticity and the emotional/psychosocial benefits of the use of ReWalk after an extensive training period.
Akahira *et al.*[61]		Six SCI patients with T5–T12 injury level, 5 complete (grade A) and one incomplete (grade B)	2	ARGO with powered knee joints	The magnitude of muscle activity in the gastrocnemius and the rectus femoris was significantly increased by active knee movement. Knee range of motion and the angular velocity of the flexion phase were found to be $37.8 \pm 8.5°$ and 144.4 ± 37.7 degrees per second, respectively, in walking with ARGO associated with powered knee joint. The GRF value at the first peak was 40.2 ± 17.5 N and 38.9 ± 12.6 N and at the second peak was 53.6 ± 9.5 N and 50.2 ± 9.6 N, respectively.
Tsukahara *et al.*[45]	Research support	One SCI patient with a complete SCI at T10-T11	2	HAL- 6LB, which has six electric motors- bilaterally at the hip, knee and ankle joints	Walking speed and cadence during the 10-m walk on the treadmill increased to 0.11 m per second and the cadence also increased to 20 steps per minute in only 2 days training with HAL.
Neuhaus *et al.*[46]	Research study	Two complete spinal cord-injured patients grade A ASIA score (injury level: T10-T12)	2	Robotic orthosis (Mina) with the hip and knee joints actuated by four actuators	Walking speed was shown to be 0.20 m per second when walking with the Mina.
Farris *et al.*[47]	Single case study	One complete SCI patient with injury in T10	2	PGO using power applied to the hip and knee joints.	Walking speed was shown to be 0.20 m per second when walking with powered lower limb orthosis.
Kang *et al.*[48,58]	Case series	Three patients with SCI	2	IRGO with a PGO using a powered hip joint.	The cadence was 61 ± 3 steps per minute for walking with mechanical RGO and 77 ± 2 steps per minute in walking with PGO. The period of the swing phase in walking with PGO and mechanical RGO was $63 \pm 8\%$ and $79 \pm 4\%$, respectively.
Quintero *et al.*[49]	Single case study	One SCI subject with complete T10 level of injury	2	Vanderbilt lower limb exoskeleton with variable impedance controllers at hip and knee	The patient completed the timed-up and go test in an average time of 114 s. Mean walking speed was 0.2 m per second with the orthosis.

Abbreviations: ARGO, advanced reciprocating gait orthosis; HAL, hybrid assistive limb; IRGO, isocentric reciprocal gait orthosis; PGO, powered gait orthosis; SCI, spinal cord injury; WPAL, wearable power-assist locomotor.

Studies that evaluated modified knee joints on gait parameters in SCI patients

Table 4 demonstrated studies that evaluated the modified knee joints on gait parameters in the SCI patients. Five studies investigated the role of knee joint options on gait parameters and compensatory trunk motion.[28–32] These studies had a low level of evidence according to the PEDro score (2/10). In an identifying paper, it has been shown that adding FES to knee extensor (quadriceps) muscles with the RGO system reduces heart rate and energy expend.

All of the RGOs that are used for ambulation in paraplegic patients hold the knee in a locked and extended position. Combination of these orthoses with external actuators or using mechanical stance control orthosis in this type of orthosis can refine and provide a suitable means of progression of rehabilitation and technology this field. Developments in the mechanical design,[29] hybrid orthoses[33,34] active powered knee joints,[20,32] the pneumatic artificial limb in KAFO,[35] motorized SCKAFO[36] and motorized KAFO[37] have been introduced to provide knee flexion during the swing phase of walking by SCI patients.

Studies that evaluated modified ankle joints on gait parameters in SCI patients

Table 5 demonstrated studies that evaluated the modified ankle joints on gait parameters in the SCI patients. Only five studies analyzed modified ankle joints on gait parameters in SCI patients.[33,34,38–40] These studies had a low level of evidence according to the PEDro score (2/10). All five studies measured gait parameters and balance with changes in ankle joint from solid to dorsiflexion assist and also adding some changes in shoe such as rocker. In only two studies, energy expenditure was measured.[39,40]

Studies investigating the effects of powered orthosis and exoskeleton on gait parameters in SCI subjects

Table 6 shows studies investigating the effects of powered orthosis and exoskeleton on gait parameters by SCI subjects. Nine studies analyzed gait parameters in SCI patients as powered orthoses and exoskeleton.[41–49] These studies had a low level of evidence according to the PEDro score (2/10). Powered lower limb orthoses such as the HAL-5 Type-C (hybrid assistive limb), which has five electric motors[45,50] the ReWalk powered orthosis (Argo Medical Technologies),[42,43] the wearable power assist locomotor (WPAL)[41] and the e LEGS powered orthosis (Berkeley Bionics) are all examples of commercially developed powered orthoses designed for walking by individuals with paraplegia.

DISCUSSION

Walking with a mechanical orthosis is not ideal for SCI patients because of high loads on upper limb joints and high rate of energy consumption. Some authors have also stated that walking with mechanical orthoses is boring and exhausting.[13,28] Improvement of the mechanical structure of the orthosis and using external power to drive the mechanical orthoses are reported as the two methods that show improvement of gait parameters in paraplegic patients.[8] The mechanical orthoses have a simple structure and user friendly design. This type of orthosis, however, has not progressed in development in recent years, as technology of the powered orthoses appears to be the main focus of research in rehabilitation and assisted walking and ambulation in SCI patients.

The influence of the modified hip joint systems on walking in SCI patients

The prescribed option in improvement of walking parameters between mechanical orthoses is the IRGO system. Evaluation of the hip joint mechanism when using the IRGO has been reported to demonstrate improved gait parameters and energy consumption compared with other RGOs, HKAFO and MLOs.[51] The difference between walking with optimal mechanical orthoses (IRGOs) with healthy subjects walking is high.[23,52] Recent efforts to improve orthoses for SCI patients have led to systems of orthoses that combine the mechanical orthoses with functional electrical stimulation of selected lower extremity muscles and powered orthoses.[5,10,19,53] There are currently only a limited range of powered orthoses, but there is some evidence of an increase in temporal spatial parameters when walking with powered orthoses.[54,55] The results of the reviewed studies suggest positive effects of external power (for example, Rewalk, HAL and WPAL) or improvement of the mechanical structure of the orthosis on gait parameters in paraplegic patients.[56] Generally, walking parameters and energy consumption improved with new generation of orthoses.[53,57] The evidence to date suggests that powered orthoses have the capability to improve specific gait parameters when compared with non-powered mechanical orthoses such as the IRGO,[11,54,58–60] a conventional HKAFO[60] and the ARGO.[30,61]

Walking with the IRGO was considered as the higher levels of walking parameters between the RGOs in the SCI patients. The means of speed of walking were reported 0.17, 0.19, 0.22, 0.25 and 0.34 m per second.[14,15,20,62,63] The mean of energy consumption was reported 120 ± 6 to 140 ± 11 beats per min) 144 beats per min.[14,62] In the modified hip joint category in using MLO, the values of this parameter were reported 0.11, 0.14, 0.33 m per second with WO,[16,26] 0.13 with Moorong, 0.6 m per second with HALO[16,18] and 0.39 with new reciprocating MLO.[21] In using powered hip joint, the mean of walking speed was announced 0.40 m per second compared with 0.16 m per second in using orthosis without hip actuator.[30] It shows that adding FES to mechanical orthosis reduced heart rate and improved walking speed during ambulation,[19,28] but using MLO increased the PCI (as the energy consumption predicator) compared with IRGO (155 beats per min, 164 beats per min).[16] In wearing new reciprocating MLO, the PCI was reduced in four SCI patients.[22]

The influence of the modified knee joint on walking in SCI patients

Walking with orthoses that locked the knee in extension demonstrated less gait efficiency compared with the orthoses with provided knee flexion. In addition, an increase in temporal spatial parameters (speed of walking, cadence, step length) was reported with powered knee joints or unlock able knee joint compared with a mechanical orthosis (for example, IRGO, ARGO) in SCI patients.[30–32] In the modified knee joint category in using mechanical linked knee ankle joints, the value of the speed of walking reported 0.14 m per second.[29] Using powered knee joint associated with ARGO, IRGO had significant influence. The rate of walking speed reported 0.53, 0.31 and 0.33 m per second.[30–32] Energy consumption was not evaluated when modified knee joint was used in the SCI patients. On the basis of knee extension position in the mechanical orthoses, reduction in compensatory motion is demonstrated by using powered orthosis[55] or IRGO with stance control knee joint in SCI patients.[64] The reduction in energy consumption is shown related to the reduction in vertical and horizontal compensatory motions in SCI patients.

Gas-powered knee joint is similar to the knee joint used in ARGO, provides stability in stance during walking and aids in standing from a sitting position with orthoses. The results of walking with a stance control knee joint were demonstrated with IRGO in one SCI patient,[64] and it was noted that there was poor control of knee joint. It therefore appears that this type of knee joint is not a good option in SCI patients.

Knee flexion during walking is one determinant that was used to smoothing the center of the mass pathway and reduced energy consumption during walking. This parameter is very important especially in patients with double lower limb weakness (for example, paraplegic patients).[53,65] Knee flexion in walking provided less compensatory motion during ambulation[66] and during orthotic gait these parameters are thought to increase. It is noted that knee flexion during orthotic gait produced more ground clearance and fewer compensatory motions compared with a fixed extended knee during walking.[29] In comparison, it was reported that the lack of knee flexion during the swing phase of gait could be the main reason of rejection and fatigue in paraplegic patients.[67,68]

The influence of modified ankle joint and foot sections on walking in SCI patients

The ankle joint has a critical role in facilitating forward propulsion during walking by moving the center of mass forward during push-off, with the ankle plantar flexor muscles performing a pivotal role during this phase. This action can cause a reduction in energy expenditure.[69–71] In other words, to control walking and the alternation, the motor output of spinal motor neurons reciprocating limb loading,[72–74] the afferent feedback from the ankle joint is important.

When using an AFO with dorsiflexion assist in ARGO and using a hip and ankle linked orthosis (HALO) mechanism, the cadence and the speed of walking (ARGO:0.35 m per second, HALO:0.60 m per second) have been shown to improve compared with the ARGO with solid AFO and Primewalk orthosis, respectively.[18] The speed of walking reported significantly faster (0.31 m per second) and energy costs reduced in paraplegic patients when the weight-bearing control orthosis (WBCO) was used compared with a previous study in this field.[39] The WBCO has a reciprocal gait pattern and a movable foot portion. In all types of mechanical orthosis, the dorsiflexion assist ankle joint should be considered. This type of joint allows dorsiflexion motion in ankle in providing 'C' posture and in addition causes foot clearance in the swing phase of gait.

Adding rocker soles associated with the RGO is another option in improvement of walking parameter in paraplegic patients.[34,40] A rocker sole provides forward progression of the tibia when sagittal plane ankle motion is restricted. In essence, it facilitates shank advancement over a stationary foot.[75] The increase in walking speed (ARGO: 0.36 m per second Primewalk: 0.27 m per second) and step length, and improved sagittal plane hip joint kinematics were reported when rocker sole mechanism was used associated with the ARGO and Prime walk.[34,40] Therefore, using this type of shoe modification has the potential to improve gait parameters in SCI patients.

Quality assessment of related studies

However, from 31 studies, just eight studies have the PEDro scale of 3 and 4 in this review. From 31 studies, just four studies included between-group comparisons.[12,13,17,19] Fourteen studies published did not provide data with adequate internal validity, as demonstrated by low scores on the PEDro scale (2/10).The study's flaws included lack of randomization procedures, lack of control group, no masking of examiners and patients and also there was a lack of similarity among groups. These more recent studies have not substantially improved the quality of the research. Some of the proposed interpretations are often based on small sample studies with very heterogeneous participant pools. There is a continuing need for high-quality experimental studies in this area. Future studies should consider stronger designs that can control for confusing factors, such as a case report and single-subject designs. A high-quality RCT provides the best design to control for potential bias, thus offering the strongest evidence of cause-effect inferences between interventions and outcomes.

Subject's individual perception of the exertion associated with walking using an orthoses can be related to the energy consumption (good or bad), as well as having a significant impact on whether they might select to use this orthosis on a regular basis. Spadone *et al.*[76] analyzed the perceived exertion associated with the energy consumption when using the Parastep orthosis during walking by paraplegic subjects.[76] Ferguson *et al.*,[77] Marsolais *et al.*[78] and Hardin *et al.*[79] demonstrated that perceived exertion in using the bracing system with FES was 'easier' than without stimulation. This point was not evaluated in only mechanical orthoses or powered gait orthoses.

CONCLUSION

On the basis of the difficulties and limitations of orthotic walking, SCI patients who wish to ambulate should be issued with the most appropriate orthotic system. According to the usage of various orthotic options proposed for walking in paraplegic patients, joint types of the orthosis appear to be critical in the improvement of walking with the orthoses. 'user friendly' orthoses with the appreciative structure (for example, hip joint with reciprocating mechanism, activated knee joint and movable ankle joint with dorsiflexion assist) allow SCI patients to walk in the most optimal of conditions when wearing the system.

These types of orthosis, even the hybrid one with reciprocating and FES, are not enough to provide a functional, efficient gait for the paraplegic patient. Another important issue is the deficit of sensory feedback and proprioception and the high demand to control the whole system with the vision and trunk/upper member's movement.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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