Chapter 10

Orthoses for Spinal Cord Injury Patients

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Abstract

There are some limitations for patients with spinal cord injury (SCI) when walking with assistive devices. Heavy energy expenditure and walking high loads on the upper limb joints are two main reasons of high rejection rate of orthosis by these patients . Many devices have been designed to enable people with paraplegia to ambulate in an upright position as a solution of these limitations such as mechanical orthoses, hybrid orthoses and powered orthoses. All these devices are designed to solve the problem of standing and walking, but there are some other important notes, which should be considered. For example, the size and weight of external orthoses, donning and doffing, cumbersomeness and independency for using are very important.

Keywords: spinal cord injury, orthoses, walking, assistive devices

1. Introduction

Lower limb paralysis resulting from spinal cord injury (SCI) causes inability to walk. Trauma is one of the main causes of SCI that occurs mostly in young people (aged between 16 and 30 years). In 2006, more than 2000 patients with SCI were in the United States and there are more than 10,000 new cases each year [1]. The ability to walk is the ultimate goal of rehabilitation in SCI patients. Ambulation is always influenced in patients with SCI based on the lesion level and the resulting different levels of muscle paralysis, sensory impairment, spasticity and the lack of trunk control. Walking anomalies in patients with SCI included the absence of active sagittal plane motions in the hip and knee joints, increased ankle plantarflexion during swing phase and an inability to positioning the lower extremity for initial foot contact and the existence of the so-called "foot slap" based on paralysis of ankle dorsiflexor muscles. Different types of orthoses are designed to reduce complication of inability to walk.

In this chapter, we introduce different types of orthoses for patients with spinal cord injury and explain important parameters (walking, stability, energy expenditure and independency) for all existent orthoses by current documents.

2. Different types of orthoses

In overall view, there were three mechanisms in orthoses to walking in spinal cord injury patients: mechanical orthoses, hybrid orthoses and power orthoses (exoskeleton).

2.1. Mechanical orthoses

In this category, three types of the mechanical orthoses included were hip-knee-ankle-foot orthoses, reciprocating gait orthoses and medial linkage orthoses.

2.1.1. Hip-knee-ankle-foot orthoses

A simple hip joint with one degree of freedom generally was used in the Hip Knee Ankle Foot Orthosis (HKAFO). Paraplegic patients use a swing through walking pattern during ambulation with this type of orthoses. Walking with this pattern produces a high rate of energy consumption and high rate of loads on the upper limb joints (shoulder joints and wrist) in paraplegic patients [2–5].

2.1.2. Reciprocating gait orthoses

Reciprocating gait orthoses (RGO) were introduced in the late 1960s. The ultimate goal was mobilizing lower limb by trunk extension. Therefore, hip extension in one side created hip flexion in other side. In using this kind of orthosis, patients were able to walk reciprocally, doff and don the orthosis independently, but cannot stand up without assistance [6, 7]. In addition, walking on a ramp and incline is difficult for paraplegic patients when using the original form of RGO [6]. To resolve this problem, the hip joints in this orthosis must have a two condition locking systems: firstly, in a full extension locking position and secondly in 20° flexion from the first position to walking on ramp and incline [6].

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. In comparison, the Hip Guidance Orthosis (HGO), RGO and ARGO demonstrated the same motion in pattern and magnitude, but in using the ARGO the pelvic displayed a jerky movement pattern. A more developed RGO is defined as the Isocentric Reciprocating Gait Orthosis (IRGO) and was introduced by Motlock in 1992 [8].

2.1.3. Medial linkage orthosis (MLO)

Another type of mechanical orthosis is medial linkage orthosis (MLO). There are variations in this type of orthosis, which include the WalkAbout (WA) [9], Moorong [10] and PrimeWalk (PW) [11] and the Hip and Ankle Linked Orthosis (HALO) [12]. These orthosis are based on a medial single hip joint, which provides artificial hip joint movements. Although it is noted that there is no congruency between the anatomical and mechanical hip joints in the Walkabout MLO, this limitation has been resolved in the Primewalk and Moorong MLO [9–11].

Evaluation of the hip joint mechanism when using the IRGO has been reported to demonstrate improved gait parameters, energy consumption compared to other RGOs, HKAFO and MLOs [13]. Therefore, the prescribed option in improvement of walking parameters between mechanical orthoses is the IRGO system. The difference between walking with optimal mechanical orthoses (IRGO) and healthy subjects walking is high. Donning and doffing with this type of orthosis, however, is difficult due to its bulky structure and increased weight. MLOs have less donning and doffing time and light structure compared to IRGOs, but these types of orthoses do not have a reciprocating gait mechanism and pelvic rigid structure. Therefore, the users are forced to use high energy consumption during walking, which in turn can create a poor posture compared to walking with IRGO conditions [13–15].

Walking with a mechanical orthoses is not ideal for SCI patients and is a view based on the associated problems during walking with them that includes 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 exhausted [2, 4, 7, 16]. 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 hip orthoses [3, 17–19]. Generally, walking parameters and energy consumption improved with new generation of orthoses [19, 20].

2.2. Hybrid orthoses

Hybrid orthoses are a kind of orthoses, which are activated by functional electrical stimulation (FES). FES is the application of external electrical stimulation to paralyzed muscles to restore their function [6]. The first reported use of FES to facilitate walking for SCI individuals was in 1980, involving the stimulation of quadriceps muscle to enhance stability during stance phase. Two kinds of hybrid orthoses are available: hybrid orthosis based on available mechanical designs (HGO, LSU RGO, ARGO and MLO) and hybrid orthoses based on the new designs (modular hybrid, wrapped spring clutch and spring brake orthoses).

Although some benefits are noted about hybrid orthosis, there are some limitation associated with the use of orthoses, FES or hybrid orthoses, which include premature muscle fatigue, false triggering of nearby muscles and being heavy and orthotics cumbersomeness.

2.3. Power orthoses (exoskeleton)

Powered orthoses (exoskeleton) are kinds of orthoses, which activate with external power. The mechanical orthoses have a simple structure and user-friendly design. This type of orthoses, however, has not progressed in development in recent years with the progression, since technology of the powered orthoses appears to be the main focus of research in rehabilitation and assisted walking and ambulation in SCI patients. There is 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 [21, 22].

One successful approach used in patient rehabilitation is the use of partial weight bearing when walking on a treadmill using suspension via an overhead harness. This technique, known as body weight support treadmill training (BWSTT), has been used to encourage the regeneration of stepping and walking in incomplete and complete SCI subjects [23, 24]. One of the limitations of BWSTT is that it can only be used in a clinical environment. Provision of hip extension at the end of stance phase, adequate weight bearing through the lower limb during stance phase and the ability to shift weight to the lateral side in the double support phase are essential for BWSTT [25]. However, agreement on the ideal parameters of such gait training does not currently exist [26]. The speed of the treadmill [27], cadence used, and the amount of body unloading are parameters, which can affect gait training in SCI subjects using this system [28]. Therefore, due to these limitations, powered gait orthosis (PGOs) may offer potential in providing an alternative form of gait training for SCI patients.

PGOs can be used as a gait training system to facilitate ambulation in both the clinical situation and in the home via an external power supply using electric motors, pneumatic and/or hydraulic actuators [9]. The first design and construction of PGOs were done in mid-1970s [29]. Belforte [30, 31], and Kang et al. [32], both developed powered orthoses with pneumatic actuators, which demonstrated a positive effect on walking by paraplegic patients, and further developments were subsequently reported by Ruthenberg et al. [33], Ohta et al. [34] and Arazpour et al. [35, 36].

Robert Bogue analyzed some recently developed exoskeletons for military, civil and medical applications and described brain-computer and systems in this review paper [37]. Ferris et al. in another review paper evaluated the recent powered lower limb orthosis for assisting treadmill stepping in disable persons. Practice starting, turning, stopping and avoiding obstacles during overground walking reported main advantage of using powered orthoses as rehabilitation aids in gait rehabilitation after neurological injury. In this study, the powered orthosis that used with bodyweight supported treadmill training for gait rehabilitation in clinical environment analyzed [38]. In the review paper, Dollar and Herr reported the history of the lower limb active orthoses. They reported a design overview of hardware, actuation, sensory and control systems for most of the powered orthosis that have been fabricated until 2007 [39]. Powered orthosis in this literature included full lower limb exoskeletons, modular active orthoses, single joint active orthoses and other orthotic devices. They conducted that the research directions in the future will focus more on the development of light weight exoskeletons and active orthotic devices. All powered orthoses that fabricated for disable

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persons discussed in the Dollar and Herr review paper, but the effect of advanced powered orthosis on walking in paraplegia patients was not analyzed in their study [39]. Duerinck et al. reported an overview of the influence of the ankle-foot robot-assisted rehabilitation orthoses to the attributes of normal gait in patients with spinal cord injury. They conducted that pneumatic artificial muscles in combination with proportional myoelectric control can restore the attributes of normal gait. In this review, only powered ankle foot orthosis evaluated on walking in SCI patients [40]. Del-Amae et al. reviewed powered gait orthosis that used FES on the muscles as natural actuators to generate gait in persons with spinal cord injury. Their paper explained an overview of hybrid lower limb exoskeletons, related technologies and advances in actuation and control systems, but the efficiency of this type of assistive devices was not evaluated on walking in SCI patients [41].

3. Daily living of spinal cord injury patients

Daily living including independence, orthosis donning and doffing, sitting and standing, walking on slope surfaces and curbs and toileting have been reported in few documents and literatures. Insufficient evidence exists as to the effect of powered and hybrid orthoses on daily living parameters in comparison with mechanical orthosis because these kinds of orthoses have evaluated in laboratory.

About mechanical orthoses, researchers have noted that in comparison to the RGOs, wearing the WO and HGOs has been reported to be easier to don and doff [42, 43]. In comparison between WO and IRGO, the WO has also been demonstrated to provide easier sitting and standing [15]. In comparison between HGO and RGO, it was demonstrated that the HGO has been reported to be easier to don and doff [42]. There are only three documents that analyzed mechanical orthosis on sloped surfaces and have demonstrated that the RGO was slightly more effective than the HGO when SCI subjects were negotiating curbs or slopes [10, 15, 42]. In a comparison between a MLOs and RGOs, the IRGO was significantly better than the WO (p value = 0.03) in 1:12 and 1:26 gradients [15]. It has demonstrated that using the Moorong orthoses in negotiating slopes surfaces was more functional than the WO due to the ability to align the orthotic and anatomic joints [44]. There is no evidence of any significant difference between any types of orthosis with regards to toileting.

Mechanical orthoses have different effects in improvement of parameters, which affect the daily living activities of SCI patients. No study was found, which considered these factors comprehensively in a selection of patients. From an independence view, the light and uncomplicated structure of the MLOs with removable hip joints and without a rigid spinal component made them easier for donning and doffing than RGOs [21, 22, 45]. The lumbar portion of IRGOs compared to MLOs limited the pelvis and lumbar joints. Unlocked joints in the IRGO caused more crutch support. Therefore, wearing IRGOs makes it more difficult than the MLO to provide sitting and standing [15], and additional document is required to demonstrate how assistive devices can help to provide activity of daily living more easily in the SCI patients. Therefore, from independence view, the comparison between MLO and RGO will be beneficial in this field.

4. Energy expenditure of spinal cord injury patients

Excessive energy expenditure and increased applied force on upper limb joints are two most important factors that increase rejection rates of orthoses in paraplegia patients. There are different methods of evaluation of energy expenditure including O_2 cost (ml kg^{-1} m^{-1}), O_2 consumption (ml kg^{-1} min^{-1}), the PCI (beat per m), HR (beat per min), O_2 uptake (l min^{-1}) and the respiratory exchange ratio in SCI patients when using orthoses in all of the documents. However, PCI was introduced as a most sensitive indicator for evaluation of energy expenditure in SCI patients [46]. In other hand, there is little evidence regarding the efficacy of powered gait orthoses (PGOs) and hybrid orthoses when directly compared to mechanical orthoses in reducing energy expenditure in SCI subjects. However, documents have demonstrated that PGOs and hybrid orthoses have less energy expenditure in comparison with mechanical orthoses [5, 47, 48].

SCI patients do not use their mechanical orthoses, with abandonment rates of 61–90% for children with myelomeningocele [49, 50] and 46–54% in adults with spinal cord injury [10, 51–53] due to the high level of energy expenditure needed to ambulate.

One of main reasons for the development of PGOs was to potentially reduce energy consumption when walking with an orthosis. A healthy subject walk with 0.176 mL/kg/m energy expenditure [2] and a SCI subject walk with WBCO 5.41 J/kg/s energy expenditure [54]. The difference between healthy normal subject and walking with a powered orthosis is therefore substantial, but is still improved when compared to that noted when paraplegic subjects walk with mechanical orthoses. There is not enough literature on energy cost of walking with powered orthosis. A further understanding of the energy cost of powered orthosis ambulation is therefore required for patients with SCI.

Kawashima et al., in evaluation of the weight bearing control orthoses on energy consumption stated that the energy consumption of walking has been quoted as being 5.41 J/kg/s [54] for SCI persons, while the mean of this parameter was reported 0.176 mL/kg/m in healthy participants [2]. Arazpour et al. in evaluation of the wearing PGOs compared to the mechanical orthoses such as HKAFO and IRGO reported that wearing PGO provided improved speed of walking and distance walked. The value of the PCI reduced in using the PGO compared to other mechanical orthoses. Active hip and knee joints in providing activated sagittal plane motions were announced as responsible for these results [55]. In a comparison between the WPAL and Primewalk orthoses on energy consumption in four people with paraplegia, Tanabe et al. reported that the PCI exhibited was reduced when using the WPAL [56]. The effort of walking has been shown to be reduced when using a powered motorized ARGO compared to mechanical ARGO in SCI patients [34]. Based on limited studies in evaluation of PGOs on energy consumption in paraplegic patients, a further understanding of this parameter is therefore required for patients with SCI when using PGOs.

About hybrid orthoses, Nene and Patrick [57] in evaluation of using hybrid orthoses (combination of Parawalker and electrical stimulation of the gluteal muscles) in three subjects reported that the rate of the energy cost was 11.78 J/kg/m and 10.95 J/kg/m (a 7.1% reduction) in without functional electrical stimulation (FES) and with FES condition, respectively. Using FES announced a considerable responsibility for reduction in the vertical crutch impulse values (mean 21%) [57]. The lowest energy costs (kcal/kg min) were associated with the RGO and FES, followed by the RGO, HGO, LLB and FES for walking speeds below 28 m/s.

Merati et al. [5] compared the energy cost of locomotion demonstrated by 14 SCI patients (lesion level C7 ± T11) during ambulation with different orthoses (the HGO, Parawalker, RGO and RGO + FES). They observed that during locomotion at maximal speed, HR peak values were 160 ± 16, 155 ± 31 and 154 ± 31 bts/min and VO2 1/kg peak values were 18.0 ± 6.1, 18.5 ± 5.4 and 19.1 ± 7.2 for PW, RGO and RGO + FNS, respectively. During orthosis-assisted locomotion at maximal speed, HR peak values were 150 ± 13, 131 ± 21 and 155 ± 23 bts/min, and VO_2 1/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 63.8 ± 24.0, 68.9 ± 27.1 and 67.6 ± 23.91 1/min during wheelchair ambulation, and 71.8 ± 7.3, 76.5 ± 21.3 and 72.3 ± 12.2 m/kg/min during orthosis locomotion for PW, RGO and RGO + FNS, respectively [5]. The PEDro score for this study was a 4/10, which equals the highest score assigned in this group.

In mechanical orthoses, connector cable ARGO maintains the posture and reduce PCI and IRGO (2.6 beat/m) has been shown to be more effective than an RGO (3.6 beat/m). Participants in this study reported less fatigue when they used the IRGO [46]. In comparison between RGOs and MLOs, RGOs have less energy expenditure, because MLOs do not have flexion-assist system for the SCI patients and have limited trunk stability, which made patients expend additional effort to maintain upright stance [58]. Also in comparison between MLOs, there is no significant difference in PCI.

RGOs produce less energy expenditure than MLOs and KAFOs [58, 59]. This is because RGOs offer more support for pelvis and trunk and possess a reciprocal system [58]. Energy expenditure and endurance have indirect correlation [60]. Muscle dysfunction, locked position of the ankle and knee joints, flexion of the trunk for providing stability and ambulation with assistive devices such as walker and crutch increase energy consumption in paraplegic subjects in wearing and walking with mechanical orthoses. Ankle and knee joints fixed position can increase energy consumption by up to 33% [60, 61]. Development of the ankle and knee joints of mechanical orthoses via powered or movable structures can be announced as the feasible approach to reduce energy expenditure. The energy consumption of using RGOs reported low rate compared to other mechanical orthoses such as MLOs and HKAFOs, based on the reciprocal section of RGOs announced as the responsible for this result. But the effect of the reciprocal link in providing of the reciprocal motion was demonstrated less [62–64]. Using RGOs for SCI patients rather than MLOs is cumbersome due to their bulky structure and using an MLO has high energy consumption compared to RGOs, but MLOs are more user-friendly for people with SCI [15, 65]. As a result, development of the MLOs with additional structure to provide reciprocal motion announced as the better approach in reduction of the energy expenditure in the SCI subjects. Therefore, the comparison of MLOs and IRGOs on the energy cost, energy expenditure and endurance of the ambulation to provide more effective mechanical orthoses in orthotic rehabilitation of ambulation in the SCI subjects will be important and beneficial.

In comparison between IRGO and RGO on energy consumption in four paraplegic SCI subjects with T3–T12 level of injury, the PCI was reduced when wearing the IRGO (2.6 beat/m), compared to condition that the RGO was used (3.6 beat/m). SCI patients announced less rate of the fatigue while walking with the IRGO [46]. Walking with standard ARGOs demonstrated the reduction of the energy consumption compared to an ARGO without a reciprocal connector cable (5.4 beat/m vs. 5.8 beat/m), although this difference was not statistically significant [66]. The standard ARGO provided best trunk posture in the SCI patients. This positioning is critical and important in the subjects with high level of injury. Evaluation of using WO on five SCI patients demonstrated that energy expenditure was 9.61 (ml/kg/min) [67]. The rate of the O_2 consumption and cost were announced as 13.79 (ml/kg/min) and 1.28 (ml/kg/m), respectively, in walking with standard ARGO in six SCI subjects [68].

5. Temporal spatial parameters

The findings of literature show that there is no high level of document to demonstrate that PGOs are better than mechanical orthoses such as RGOs and HGO in improving temporal spatial gait parameters in SCI subjects. From financial view, the PGOs are so expensive, and also the more orthotic gait training time and effort required providing them functionally. Walking with this type of orthosis does not propose any acceptable improvement in temporal spatial parameters compared to mechanical orthoses. Consequently, more additional attempt on structure of the powered orthoses is required to provide more acceptable powered device for SCI patient wearing and using [69]. There shows to be no significant difference in reported speed of walking subjects in walking with different RGOs in the SCI patients. The following text demonstrates the findings resulted by the literature, which analyzed the effect of common mechanical orthoses on temporal spatial parameters in the SCI patients.

5.1. Stride length

In comparison between the RGO and HGO, there was no significant difference in stride length [67]. In comparison of the standard ARGO with RGO without connector cable, 7% increase in stride length (0.89 vs. 0.83) was reported. Improvement in providing vertical positioning of the trunk by the connector cable announced the main responsible in the standard ARGO [62]. The mean of stride length was reported to be 0.56 m in SCI patients when using the WO [70]. In newly developed orthoses, Genda et al. demonstrated that the hip-ankle-linked orthoses (HALO), increased stride length by 3% compared to the WO (1.03 vs. 1.00 m) [12]. Six percent increased stride length was demonstrated when ankle foot orthosis with dorsiflexion-assist ankle joints were used in the ARGO (0.94 vs. 1 m) compared to the ARGO associated with solid ankle-foot orthosis. In this study, it was claimed that the moveable ankle joint in the ankle-foot orthosis section could improve stride length [71]. When comparing two medial linked orthoses (the Primewalk and Walkabout orthosis). Onogi et al. reported that there was significant difference between them in this parameter and the mean of stride length was increased by 19% [72].

5.2. Cadence

In a comparison between the RGO and the HGO, Whittle et al. reported no significant difference between them in this parameter [70]. However, Winchester et al. announced that although cadence was better in the IRGO than the RGO, there was no significant difference between them [46]. Ijzerman et al. in an evaluation of the effect of a connector cable reported that using an ARGO with a connector cable increased cadence compared to without one, but not significantly (31.3 vs. 30.3 steps/min) [66].

Four studies assessed the cadence in walking with orthoses associated with medial single hip joints in SCI patients. The mean of this parameter was reported as being 70.02 steps/min when using the WO [67] and 50.9 steps/min when walking with any type of medial single hip joints orthosis [73]. Significant difference in cadence between the HALO and PW devices (74.1 vs. 58.9) was reported by Genda et al. [12]. In a recently published study, the mean of cadence demonstrated a significant difference in value (40.8 vs. 48 steps/min, respectively) when using the WO and the PW [72].

5.3. Speed of walking

The mean of speed of walking has been reported to be 0.214 m/s when using the Parawalker orthosis during ambulation by SCI patients [45]. When using the ARGO, the mean of this parameter was 0.16 m/s [68]. The mean of speed of walking was reported to be similar between the HGO and the RGO (0.24 m/s) by Whittle et al. [70]. In comparison between RGOs, the IRGO was shown to produce a higher speed of walking (0.22) compared to a cable-type RGO (0.21), but there was no significant difference between them [46]. When comparing the KAFO and the IRGO, there were significant differences noted between them in this parameter ($p = 0.009$) [59]. The effect of a connector cable when using the ARGO has no significant effect on improving walking speed when compared to an ARGO without one (0.24 vs. 0.23 m/s) [62].

The effect of PGOs on walking speed, cadence and step length exhibited by SCI subjects is dependent on which joints are actuated in an orthosis (e.g. the hip or knee actuated separately or by being synchronized). Few studies have directly compared these parameters directly between separately or synchronized movement of the hip and knee joint conditions during walking with PGOs.

Kang et al. [74] in evaluation of the powered IRGO (via using pneumatic actuators in the hip joints) compared to a mechanical IRGO after three months orthotic gait training in three SCI subjects reported that evaluated parameters such as walking speed, pelvic tilt, flexion and extension angles of the knee and hip joints, stance and swing phase times improved. Walking speed was increased by 26% and the percentage swing phase during walking was increased by 25% when walking with the PGO.

Powered lower limb orthoses such as the ReWalk powered orthosis (Argo Medical Technologies), the wearable power-assist locomotor (WPAL) and the eLEGS powered orthosis

(Berkeley Bionics) are all examples of commercially developed powered orthoses designed for walking by paraplegic subjects. The Hybrid Assistive Limb (HAL)—6LB which has six electric motors—bilaterally at the hip, knee and ankle joints, the HAL-5 Type-C, which is previous HAL for paraplegia patients, with only four power units are another examples of power lower limb orthosis. Commercially developed HAL has four power units and uses EMG signals of leg to synchronize the motion support with the wearer's movement, but complete paraplegia patients cannot use this version of HAL.

Speed of walking reported difference between mechanical, hybrid and powered gait orthoses. There was statistically significant difference between orthotic walking and walking in healthy subjects. Since walking with powered orthoses (mechanical orthoses that powered with external actuators in the hip or knee joints) needs to keep balance and other assistive devices such as walker or crutch need to activate the powered joints, therefore, the speed of walking is thought to be adversely affected by these conditions. Commercially developed exoskeletons have shown the potential to significantly improve speed of walking.

Since there were some studies about increased step length and cadence in wearing powered gait orthoses during walking, more research in this field is required. The mechanism of the additional external actuator to mechanical orthosis in the powered gait orthoses in improvement of speed of walking needs more research.

5.3.1. Quiet standing

Mechanical orthosis has been analyzed in a few researches in stability by quite standing. Anterior–posterior (AP) and mediolateral (ML) COP displacement in amplitude and velocity of were measured in SCI patients. Baardman evaluated the effect of connector link in ARGO and reported no difference between ARGO with (35.22 mm in AP and 41.72 mm in ML COP displacement) and without (37.94 mm in AP and 34.53 mm in ML direction) cable in quiet standing in stability [62].

In another study, Middleton et al. compared KAFO with and without a single medial linkage on sway amplitude in SCI patients announced that AP sway amplitude when using a single medial linkage with KAFO was half that when wearing a KAFO without it, but in ML direction amplitude there was no significant difference [75]. In a research Abe et al. compared stability with KAFO, RGO and WO and reported significant difference between KAFO with two other orthoses [75].

5.3.2. Performance

Such as other parameters in PGOs there is no document in relation to performance and powered orthoses. About mechanical orthoses, there are three studies in relation to amplitude and velocity of COP displacement. The first study was reported by Baardman et al., which done on cable connector in the ARGO on performance. These researchers reported no effect of connector cable on performance (COP displacement in quite standing) but demonstrated this cable in ARGO can reduce upper limb load [62].

Middleton et al. compared KAFO with and without single medial linkage and announced no significant difference in sway path and amplitude in the A-P direction between them in SCI patients, but use of KAFO with a medial linkage decreased sway amplitude ($p = 0.008$) and increased M-L direction of sway path ($p = 0.021$). Therefore, this research proved using a single medial linkage can increase stability and balance in the mediolateral direction [75]. In the third study, Abe et al. demonstrated that sway amplitude was not significantly different between the WO and the RGO but the KAFO had significantly less stability [76].

6. Future research topics in this field

The following topics can be performed in orthotics rehabilitation of the SCI subjects:

- Based on lack of commercial powered and hybrid orthoses, development of these types of assistive orthoses will be beneficial in this field.
- Analysis of the developed commercial powered and hybrid orthoses on energy cost and energy consumption is essential in this field.
- Finding the solution to reduce energy expenditure during ambulation in SCI patients will be beneficial in rehabilitation of orthotic walking in SCI subjects.
- Analysis of energy expenditure between mechanical orthoses, commercial powered and hybrid orthoses is essential before and after the orthotic gait training in SCI subjects.

7. Summary remarks

- Using the powered gait, orthoses reduced the needed effort during ambulation in SCI subjects. Using external actuators in the hip or knee joints with provided active motions in specific joints announced the main reason for these results.
- Powered gait orthoses can be used in the clinical environment for orthotic gait training purposes. Although the positive effect of the orthotic gait training with WBCO on muscle activity in SCI patients was reported, more research is needed to approve any beneficial influence.
- Based on literature, it is concluded that the powered and hybrid orthoses could be announced as effective devices for orthotic rehabilitation of walking in SCI patients to assist to provide their best ambulation.
- Speed of walking reported difference between mechanical, hybrid and powered gait orthoses. There was statistically significant difference between orthotic walking and waling in healthy subjects.
- Since walking with powered orthoses needs to keep balance and other assistive devices such as walker or crutch need to activate the powered joints, therefore, the speed of walking is

thought to be adversely affected by these conditions. Commercially developed exoskeletons have shown the potential to significantly improve speed of walking.

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