Advancements in Orthotic Devices for Patients with Spinal Cord Injuries: A Literature Review

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Abstract

Introduction: Walking is a complex activity that depends on the coordination between muscles and joints, a capability that is significantly impaired in individuals with spinal cord injuries (SCI). To enhance gait efficiency, reduce energy expenditure, and promote independence among patients with SCI, Medial Linkage Orthoses (MLOs) have been developed. In contrast, conventional orthotic solutions like Knee-Ankle-Foot Orthoses (KAFOs) and Hip-Knee-Ankle-Foot Orthoses (HKAFOs) often lead to high energy costs and low user satisfaction. **Material and Methods:** This review investigated the evolution and effectiveness of various orthotic devices, with a particular focus on MLOs, including the Walkabout and Prime Walk. A thorough literature search was conducted across databases covering the period from 1960 to 2024 using relevant keywords. 23 articles met the criteria for data extraction, guided by a standardized protocol. **Results:** The review's findings emphasize the influence of spinal cord Orthoses on gait, energy consumption, and overall user satisfaction. The development of orthotic devices, particularly MLOs, marks a notable advancement in treating gait dysfunctions associated with SCI. Evidence suggests that MLOs, such as Walkabout and Prime Walk, offer significant advantages over traditional KAFOs and HKAFOs in terms of biomechanics, energy efficiency, and user satisfaction. Specifically, innovations like Ahmadi's model demonstrate improved biomechanical alignment and reduced energy expenditure, making walking more feasible for patients with SCI. **Conclusion:** Ultimately, the implementation of MLOs could greatly enhance independence and improve the quality of life for individuals with SCI. Further research is essential to optimize the designs of these orthotic devices and to investigate their long-term effects on functional outcomes within SCI populations.

Keywords: Energy Expenditure; Orthosis; Satisfaction; Spinal Cord Injury; Walking

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Introduction

Spinal Cord Injury (SCI) represents a significant disruption of bodily functions below the level of the injury, severely impacting mobility and overall quality of life for affected individuals (1). Over the past few decades, the use of orthoses has emerged as a pivotal strategy to assist these patients in regaining mobility. These devices are designed to facilitate walking by providing support and enabling movement; however, their effectiveness is closely linked to metabolic efficiency. It is essential to design orthoses that minimize energy expenditure, as excessive energy demands can discourage their use among patients with SCI (2).

Walking is a fundamental daily activity that necessitates the coordinated effort of muscles and joints to transfer body weight and synchronize limb movements. Energy consumption during gait is influenced by a variety of factors, including walking pattern, speed, prior training, body weight, and environmental factors (3). Research has underscored the significance of pelvic and hip movements in the frontal plane, which are crucial for enhancing quality of walking and reducing energy expenditure. Specifically, coordinated movements of the lower back and pelvis in conjunction with the legs help stabilize the body's center of gravity, resulting in more efficient mobility (4).This interplay of body mechanics is vital not only for walking ability but also for the design and effectiveness of supportive devices, such as orthoses.

Traditional orthotic devices, such as HKAFO and KAFO, while effective in certain situations, often lack adaptability and comprehensive biomechanical considerations (5). This underscores the ongoing need for innovation in the design of assistive devices aimed at improving mobility and user satisfaction. Early versions, such as the Walkabout orthosis (6), encountered issues with anatomical alignment, which led to the creation of more advanced models like the Prime Walk and Moorong orthoses (6). Although these newer designs show promise, they frequently fall short in achieving full user satisfaction, particularly because they struggle to facilitate reciprocal movement. This limitation can result in increased energy expenditure and suboptimal walking dynamics when compared to reciprocal gait orthoses (RGOs)(7). The rise of MLO has drawn attention, prompting further investigation into their potential benefits and limitations (8).

Recent progress includes a 2015 model developed by Ahmedi, featuring a four-bar system with dual gears to improve the orthosis's responsiveness to trunk movements. This innovation facilitates reciprocal leg movement and decreases energy consumption (9). Nonetheless, a thorough evaluation of orthoses for SCI is still needed, necessitating further research to assess these devices. The objective of this study was to perform an extensive literature review regarding the current landscape of orthotic devices for individuals with SCI.

Material and Methods

Study Design

This research was conducted as a literature review, aimed at collecting and analyzing existing studies on orthoses used for improving walking ability in patients with SCI. The review specifically targeted research related to mechanical orthoses and their impact on gait parameters, energy consumption, biomechanical alignment, and user satisfaction. The review followed structured guidelines to ensure a thorough and unbiased synthesis of evidence.

Search Strategy

To ensure comprehensive coverage of relevant literature, a systematic search of multiple electronic databases was conducted. The databases searched include: PubMed, Scopus, Science-Direct, and Google Scholar.

The search covered studies published between 1960 and 2024. The following primary keywords were used in the search: Hip Guidance Orthosis (HGO), Medial Linkage Orthosis (MLO), Spinal Cord Injury Orthosis, Lower Limb Mechanical Orthosis, Paraplegia Orthosis, Reciprocal Gait Orthosis (RGO), and Gait Performance Parameters.

To refine the search and capture all relevant studies, additional keywords were included, such as Walkabout Orthosis, Prime-walk Orthosis, Sliding and Hinge Orthosis, Gait Cycle, Kinematic Performance, and Medial Reciprocating Gait Linkage Orthosis. These terms were selected based on their relevance to the mechanical design, kinematic analysis, and energy consumption aspects of orthotic devices.

Inclusion and Exclusion Criteria

The following inclusion criteria were applied to select studies for review:

- Population: Studies involving patients with SCI, particularly those with paraplegia or limited lower extremity mobility due to SCI.
  •Interventions: Research focused on mechanical orthoses, including KAFOs, HKAFOs, HGOs, MLOs, and RGOs designed to assist in walking or standing.
- Outcome Measures: Studies that reported gait performance parameters (e.g., walking speed, step length, cadence), energy consumption (e.g., oxygen consumption or metabolic cost), biomechanical alignment, satisfaction and user independence.
- Study Design: Both experimental and observational studies were included, with priority given to clinical trials, cohort studies, and comparative evaluations of different orthotic devices.
- Language: Only studies published in English and Persian languages were considered.

The exclusion criteria were:

- Studies focusing solely on pediatric populations or non-SCI conditions.
- Research that did not include quantitative data on gait performance or energy consumption.
- Non-peer-reviewed articles, editorials, and opinion pieces.

Study Selection Process

The initial database search yielded approximately 214 studies. After removing duplicates, 150 studies were screened based on their titles and abstracts. Following this screening, 54 studies were selected for full-text review based on their relevance to the study objectives and inclusion criteria. A final selection of 23 studies was included in the review after a comprehensive evaluation of their content (Figure 1). The study selection process was guided by the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) framework, ensuring a transparent and systematic approach to screening and selecting relevant literature (10).

Outcome Measures

Gait and biomechanical analysis kinematic data, e. g, joint angles, stride length, and walking speed. Energy consumption such as oxygen uptake, were analyzed. And User feedback regarding user satisfaction and ease of use were summarized.

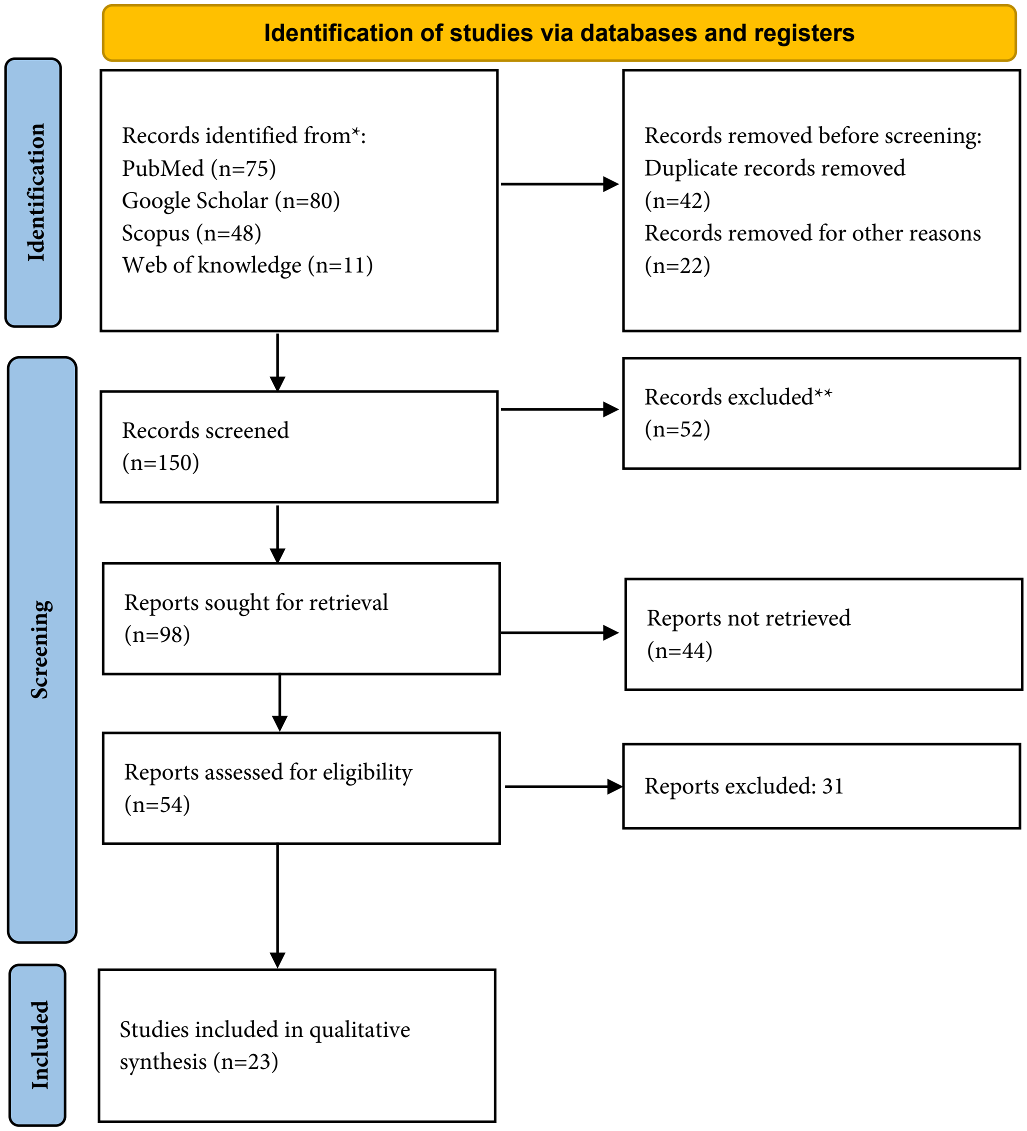

Figure 1. Flowchart of the articles selection using the PRISMA

Results

The results of this review provide a detailed comparison of various orthoses used for patients with SCI, with a focus on MLOs and their performance in terms of gait, energy consumption, and user satisfaction. The study compared traditional orthoses like KAFO and HKAFO with more advanced devices like the Walkabout, Prime-walk, and MLO design.

Types of Orthoses and Gait Performance

The reviewed studies showed that orthoses designed with reciprocal gait mechanisms, such as MLOs(11, 12) and some RGOs(7, 13), significantly improved the walking performance of patients with SCI compared to traditional devices like KAFOs and HKAFOs(14).

KAFOs were reported to provide stability during standing and walking, but the lack of natural hip movement resulted in a very slow walking speed (15), short step length(14), and high energy consumption. The use of KAFOs also required significant upper extremity strength due to the reliance on crutches or walkers (14).

HKAFOs, which add a hip joint to the KAFO structure, provided some improvement in reciprocal gait but were still associated with high energy demands and limited mobility (5).

The Walkabout orthoses, one of the earlier MLO designs, improved user mobility by incorporating a medial hip joint instead of external hip joints. However, it was still criticized for its lack of hip flexion and reliance on trunk movements to generate leg movement. Despite these limitations, users found the Walkabout easier to wear and remove compared to other bulkier orthoses, such as HKAFOs. The lack of external hip joints also made it more aesthetically appealing and lighter, which led to increased user acceptance (16).

Types of Orthoses and Energy Consumption

A critical finding from the review is that energy consumption was a major factor influencing the use of orthoses by patients with SCI. Orthoses that reduced energy expenditure were preferred by patients, as high energy demands were often cited as a reason for discontinuing the use of certain devices (17).

KAFOs and HKAFOs required significant energy input from the user, with studies indicating that their use could be exhausting for long-term walking, especially in patients with SCI with higher levels of injury (18).

Walkabout and Prime-walk orthoses were reported to lower energy consumption compared to traditional devices. However, these designs still had limitations in achieving full reciprocal gait, leading to energy inefficiencies during long walking sessions in patients with SCI (19).

The introduction of MLO in 2015 represented a significant advancement in reducing energy consumption. This model used a four-bar linkage system with two gears to align the mechanical hip joint with the anatomical hip joint more closely. The reduction in mechanical misalignment helped lower the forces needed to move the legs, leading to a notable decrease in energy expenditure. However, some studies noted that despite this improvement, the exact energy consumption data for this model were not fully evaluated, highlighting the need for further research in this area for patients with SCI (11).

Types of Orthoses and User Satisfaction

The ease of use, comfort, and aesthetic appeal of the orthoses played an important role in determining user satisfaction. Orthoses that were bulky, difficult to wear, or required assistance for donning and doffing were less likely to be adopted for regular use.

Walkabout and Prime-walk orthoses were rated higher in terms of user independence, as they were easier to put on and take off without assistance. The medial linkage design of these orthoses, which eliminated external hip joints, also made them lighter and more comfortable for daily use(19, 20).

MLO introduced by Ahmadi was particularly noted for its ease of use and comfort because of its lightweight materials and improved design. The addition of a saddle to increase sensitivity to trunk movements also made it easier for users to initiate walking without needing to exert excessive upper body effort(11). However, some limitations remained regarding the full independence of users in all walking environments, especially on uneven surfaces or stairs for patients with SCI.

Discussion

This study provides an in-depth exploration of the development and application of walking-related orthoses, particularly focusing on MLOs, for individuals with SCI. MLOs are vital in enhancing gait mechanics and mobility for individuals with SCI. The intricate process of walking necessitates careful coordination among muscles, joints, and effective weight transfer. Consequently, the design of orthotic devices has undergone significant enhancements to tackle the various obstacles encountered by patients with SCI specifically challenges related to energy expenditure, joint alignment, and overall user comfort.

One of the chief challenges in developing effective orthotic devices is the reduction of energy expenditure during walking in patients with SCI. Traditional models, such as KAFOs and HKAFOs, provide stability but necessitate considerable user energy, making them less feasible for daily or continuous use. Research highlights that optimal mechanical alignment between orthotic and anatomical joints is pivotal for enhancing walking efficiency and diminishing energy consumption(5). Notably, the dynamics of pelvis and hip movement in the frontal plane are critical in conserving energy since they facilitate proper weight shifting and maintaining the center of gravity while walking.

Evolution of Orthotic Designs

Early Orthoses

The early versions of orthoses designed for patients with SCI mainly aimed at stabilizing the lower limbs while often overlooking aspects like energy efficiency and biomechanical alignment. The development of the KAFO in the mid-20th century represented a notable improvement in support for the knee and ankle joints, allowing individuals with SCI to stand and walk using assistive devices such as crutches or walkers. Nevertheless, the design of KAFO's did not facilitate the natural movement of the hip and pelvis, which resulted in inefficient and laborious walking patterns (5).

In the 1980s, advancements emerged in orthotic design, incorporating more sophisticated biomechanical principles. The HKAFO introduced an additional hip joint to the traditional KAFO, facilitating some reciprocal gait patterns (18). This was further refined with the RGO, utilizing cables to synchronize hip movements and allowing for a more natural walking stride.

Nevertheless, the energy consumption associated with these devices remained a significant drawback, often compounded by bulky and uncomfortable constructions (21).

MLO

MLOs signify a notable breakthrough in orthotic design. By situating the joint mechanism between the legs and eliminating the need for external hip joints, MLOs reduce bulk and enhance the device's aesthetic appeal. The medial positioning of the hip joint also permits more natural hip rotation, leading to increased walking efficiency while alleviating stress on the upper body. The 1990s saw the introduction of the Walkabout orthosis as one of the earliest examples embracing the philosophy of this design (9).

Despite being an important advancement, early models like the Walkabout orthosis presented limitations, including inadequate hip flexion and dependency on trunk movements for leg initiation. Subsequent designs, such as the Primewalk and Moorong orthoses, made strides in addressing these shortcomings by enhancing the alignment between the orthotic mechanisms and anatomical joints, resulting in smoother, more efficient movement patterns. For example, the Primewalk orthosis features a sliding mechanism that simulates natural hip joint rotation, allowing for longer strides and more fluid transitions during walking (22, 23).

Modern Advancements: MLO introduced by Ahmadi

The 2015 design by Ahmedi marks the latest progression in medial linkage orthoses. This innovative model employs a four-bar linkage system equipped with two gears, ensuring a closer alignment between the mechanical and anatomical axes of the hip joint. This precise alignment diminishes energy expenditure by reducing the forces needed for leg movement. Furthermore, the design of MLO by Ahmadi incorporates a saddle mechanism that enhances the device's responsiveness to trunk movements, enabling users to initiate walking with greater ease and less reliance on upper body strength. Additionally, the utilization of lightweight materials in Ahmedi's design significantly lessens the overall weight of the orthosis, further contributing to reduce energy consumption. By allowing reciprocal leg movement, this model not only enhances walking efficiency but also decreases the metabolic costs associated with walking(11).

Challenges in Orthotic Use and Future Directions

Despite these progressive advancements in orthotic design, several obstacles remain regarding the widespread adoption of these devices. A primary concern revolves around the balance between stability and mobility; devices that provide enhanced stability generally tend to be more cumbersome and energy-intensive, while lighter, more flexible options may lack the necessary support for individuals with higher levels of SCI. The cost associated with cutting-edge orthotic devices, including exoskeletons and robotic-assisted technologies, also presents a significant barrier for many patients with SCI. Moreover, there is a notable lack of comprehensive comparative studies assessing the performance of various orthoses under standardized conditions. While numerous designs have emerged over the years, the absence of systematic evaluations of their effectiveness in improving key gait parameters such as step length, cadence, and energy consumption hinders clinicians' ability to make well-informed decisions regarding the most suitable orthosis for patients with SCI.

Conclusion

In summary, the study highlights the significant progress that has been made in the design and development of orthoses for individuals with SCI. The shift from bulky, energy-intensive devices to more biomechanically aligned and efficient designs, such as the MLO's, represents a major step forward in improving the quality of life for patients with SCI. However, challenges remain in optimizing these devices to balance stability, mobility, and energy efficiency. The study emphasizes the need for further research into the comparative effectiveness of different orthoses and the continued refinement of materials and mechanical designs to reduce energy consumption and improve patient outcomes. Future research should also focus on incorporating new technologies, such as wearable sensors and real-time feedback systems, to further enhance the functionality and adaptability of orthotic devices. With continued advancements, orthoses have the potential to provide even greater independence and mobility for individuals with SCI.

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Conflict of interest

The authors declare that they have no conflict of interest.

Ethical consideration

This study is a review study and doesn't need ethical approval.

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Author Contribution

All authors equally contributed in writing, drafting, resourcing, reviewing, and editing of the article.

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