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COMPARATIVE EFFECTIVENESS OF RIGID, HINGED, AND DYNAMIC ANKLE–FOOT ORTHOSES ON GAIT AND FUNCTIONAL OUTCOMES IN CHILDREN WITH CEREBRAL PALSY: A SYSTEMATIC REVIEW AND META-ANALYSIS

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Abstract

Background: *Ankle–foot orthoses (AFOs) are widely prescribed to improve gait abnormalities and walking efficiency in children with cerebral palsy (CP). However, uncertainty remains regarding the comparative effectiveness of rigid (solid), hinged (articulated), and dynamic AFO designs.*

Objective: *To systematically evaluate and compare the effects of different AFO types on gait parameters and energy expenditure in children with cerebral palsy.*

Methods: *A systematic review and meta-analysis were conducted in accordance with PRISMA 2020 guidelines. Electronic databases (PubMed/MEDLINE, Embase, Scopus, Web of Science, and CENTRAL) were searched from inception to the search date. Studies involving children (≤18 years) with CP using rigid, hinged, or dynamic AFOs and reporting quantitative gait or energy expenditure outcomes were included. Random-effects meta-analyses were performed using standardized mean differences (Hedges g) with 95% confidence intervals. Subgroup analyses were conducted by AFO type, and direct head-to-head comparisons were analyzed where available.*

Results: *AFO use significantly improved step length (SMD 0.68, 95% CI 0.42–0.94; $p < 0.001$) and walking velocity (SMD 0.34, 95% CI 0.10–0.58; $p = 0.006$) compared with barefoot walking. AFOs were also associated with a significant reduction in energy expenditure (SMD −0.72, 95% CI −1.05 to −0.39; $p < 0.001$). Subgroup analysis demonstrated that dynamic AFOs produced the greatest improvement in step length, whereas rigid and hinged AFOs yielded larger reductions in oxygen cost. Direct comparisons indicated a modest advantage of hinged over solid AFOs in gait performance, while dynamic AFOs showed superiority over solid designs. Heterogeneity was moderate, and no significant publication bias was detected.*

Conclusions: *AFOs significantly enhance gait performance and reduce metabolic cost in children with CP. Dynamic designs may optimize forward*

progression, whereas rigid and hinged AFOs may better improve walking efficiency. Orthotic prescription should be individualized based on therapeutic goals and biomechanical presentation. Further high-quality randomized trials are warranted to refine evidence-based orthotic guidelines.

1. INTRODUCTION

Cerebral palsy (CP) is the most common cause of physical disability in childhood and is characterized by a group of permanent disorders affecting movement and posture due to non-progressive disturbances in the developing brain [1]. Children with CP frequently present with gait abnormalities, including equinus, crouch gait, reduced step length, impaired push-off, and decreased walking efficiency. These gait deviations often result in increased energy expenditure, reduced functional mobility, and limitations in participation in daily activities [2]. Optimizing ambulatory function is therefore a primary goal of rehabilitation in this population.

Ankle–foot orthoses (AFOs) are among the most frequently prescribed interventions to address lower-limb biomechanical impairments in children with CP. By stabilizing the ankle joint, controlling plantarflexion, assisting dorsiflexion, and influencing knee mechanics during stance and swing phases, AFOs aim to improve gait alignment and efficiency [3]. Several AFO designs are used in clinical practice, most commonly solid (rigid) AFOs, hinged (articulated) AFOs, and dynamic or posterior leaf-spring designs. Solid AFOs restrict ankle motion to provide maximum stability and control of equinus, whereas hinged AFOs allow controlled dorsiflexion while limiting plantarflexion. Dynamic AFOs typically permit greater flexibility and may enhance push-off and ankle power generation during late stance [4].

Despite their widespread use, the comparative effectiveness of different AFO designs remains uncertain. Individual studies have reported improvements in spatiotemporal parameters such as step length and walking velocity with AFO use compared with barefoot walking [5,6]. Other investigations have demonstrated reductions in oxygen cost and improved walking efficiency associated with orthotic intervention [7,8]. However, findings across studies are heterogeneous, likely due to variations in orthosis design, participant characteristics (including Gross Motor Function Classification System levels), gait patterns, and outcome measures.

Importantly, most available studies have evaluated AFOs relative to barefoot or shoe-only walking rather than directly comparing different orthotic configurations. Where head-to-head comparisons have been performed, results are mixed. Some studies suggest that hinged AFOs may facilitate more physiological ankle kinematics compared with solid designs [9], whereas others indicate that dynamic AFOs may enhance step length or push-off power [10]. Conversely, rigid designs may provide superior reductions in energy expenditure due to greater stabilization during stance [11]. These potentially divergent biomechanical effects underscore the need for a comprehensive synthesis of the evidence.

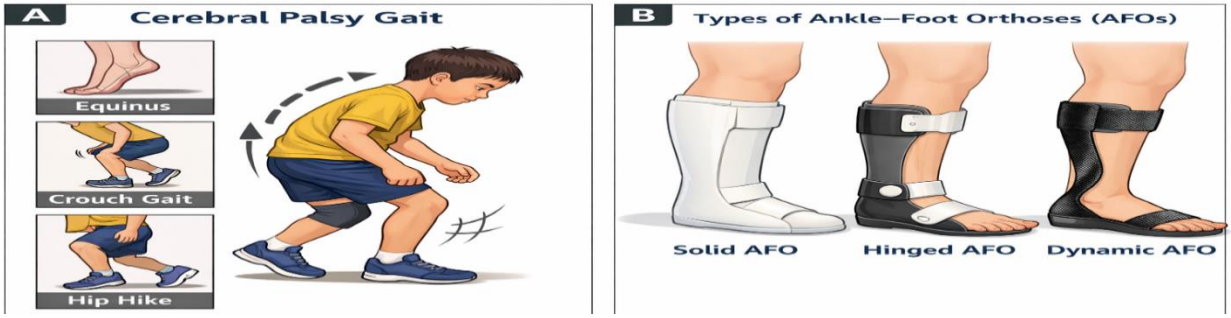


Figure (A) (B). Operational Overview of Cerebral Palsy Gait Patterns and Ankle–Foot Orthosis Types

Previous reviews addressing orthotic management in CP have largely been narrative in nature or have not specifically focused on direct comparisons between AFO types [12]. Moreover, quantitative pooling of objective gait parameters such as step length, walking velocity, cadence, and oxygen cost has been limited. In the absence of high-level comparative evidence, orthotic prescription often depends on clinician preference, local practice patterns, or individual trial-and-error approaches, potentially contributing to variability in care.

Given the clinical importance of optimizing gait efficiency and functional mobility in children with CP, a systematic review and meta-analysis directly comparing rigid, hinged, and dynamic AFO designs is warranted. The present study aims to synthesize available comparative evidence to determine the relative effects of different AFO types on gait parameters and energy expenditure. By quantitatively evaluating both overall AFO effectiveness and differences between orthotic configurations, this analysis seeks to provide evidence-based guidance to inform orthotic prescription and improve functional outcomes in children with cerebral palsy.

2. METHODOLOGY

This systematic review and meta-analysis was conducted in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA 2020) guidelines and followed recommendations outlined in the Cochrane Handbook for Systematic Reviews of Interventions. The protocol was developed a priori, and eligibility criteria, outcomes, and analytical methods were defined before data extraction and synthesis.

A comprehensive literature search was performed across the following electronic databases from inception to the date of search: PubMed/MEDLINE, Embase, Scopus, Web of Science, and the Cochrane Central Register of Controlled Trials (CENTRAL). The search strategy combined controlled vocabulary (e.g., MeSH terms) and free-text keywords related to cerebral palsy, ankle–foot orthoses, and gait or functional outcomes. Core search terms included "cerebral palsy," "ankle-foot orthosis," "AFO," "rigid," "hinged," "dynamic," "gait," "walking," "step length," "velocity," "energy expenditure," and "oxygen cost." Search strategies were adapted for each database. In addition, reference lists of included articles were manually screened to identify further relevant studies. Only studies published in English in peer-reviewed journals were considered.

Studies were eligible for inclusion if they met the following criteria: (1) participants were children or adolescents (≤18 years) diagnosed with cerebral palsy; (2) the intervention involved the use of an ankle–foot orthosis classified as rigid (solid), hinged (articulated), or dynamic/posterior leaf-spring; (3) the study included either a comparison between different AFO types or a comparison between AFO use and barefoot or shoe-only walking; (4) at least one quantitative gait or functional outcome was reported; and (5) sufficient data were available to calculate effect sizes (e.g., mean and standard deviation). Randomized controlled trials, quasi-experimental studies, and controlled observational studies were included. Exclusion criteria comprised case reports, narrative reviews, conference abstracts, studies involving postoperative orthotic management following surgical intervention, and studies without extractable quantitative data.

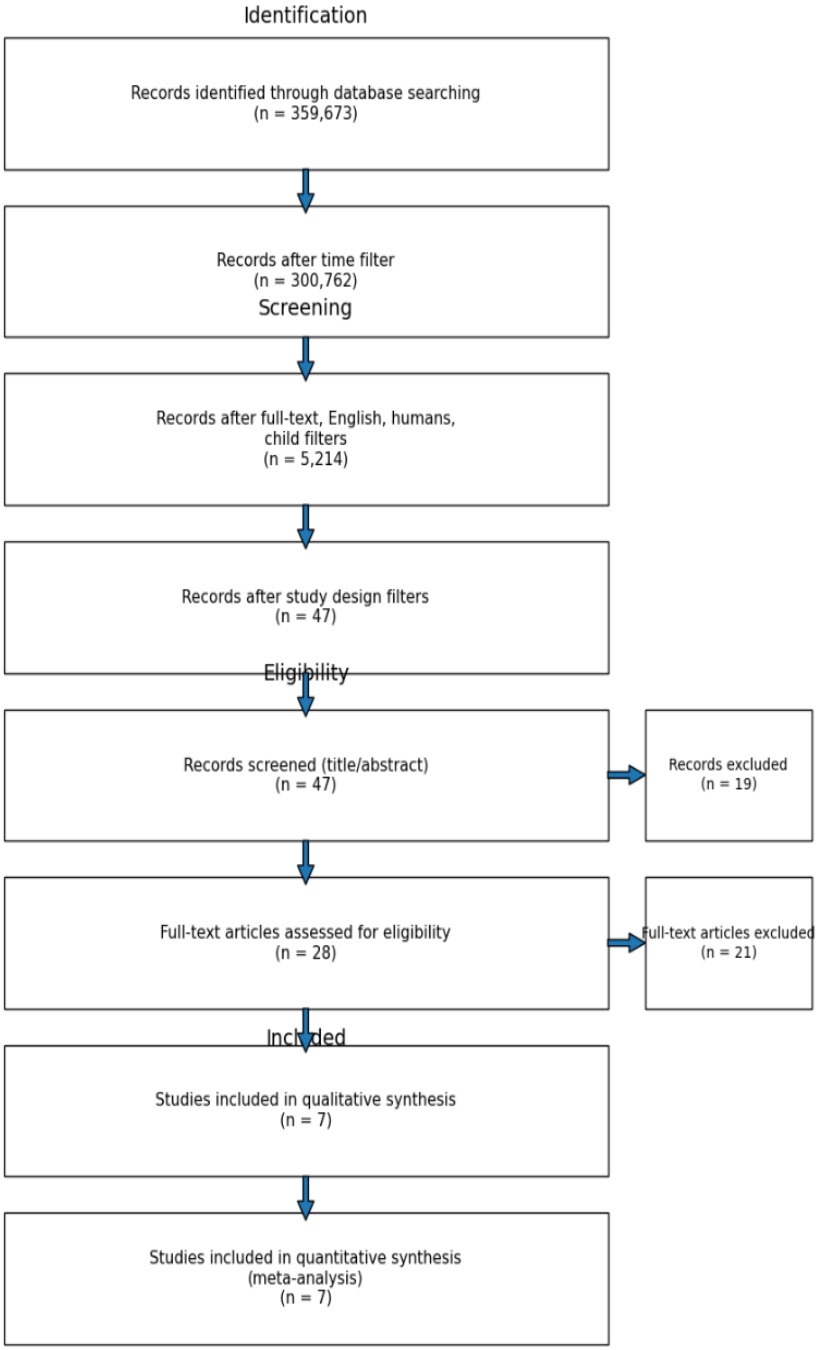


Figure (C) PRISMA Flow Diagram

Titles and abstracts were screened for eligibility, followed by full-text review of potentially relevant articles. Data extraction was conducted using a standardized form to collect study characteristics (author, year, country, study design), participant characteristics (sample size, age, cerebral palsy subtype, Gross Motor Function Classification System level), orthosis type, comparator, and

outcome measures. Primary outcomes included spatiotemporal gait parameters (step length, walking velocity, cadence), while secondary outcomes included energy expenditure (oxygen cost). When studies reported multiple AFO conditions, each relevant comparison was extracted separately.

Risk of bias was assessed according to study design. Randomized controlled trials were evaluated using the Cochrane Risk of Bias tool (RoB 2), and non-randomized studies were assessed using the ROBINS-I framework. Discrepancies in assessment were resolved through consensus.

Meta-analysis was performed using random-effects models (DerSimonian–Laird method) to account for anticipated clinical and methodological heterogeneity. Continuous outcomes were pooled using standardized mean differences (Hedges g) with 95% confidence intervals. Heterogeneity was quantified using the I^2 statistic, with values of 25%, 50%, and 75% interpreted as low, moderate, and high heterogeneity, respectively. Subgroup analyses were conducted based on AFO type (rigid, hinged, dynamic) to explore potential differences in effect magnitude. Direct head-to-head comparisons between orthotic designs were analyzed separately when sufficient data were available. Publication bias was evaluated using funnel plot inspection and Egger's regression test when at least 10 comparisons were available. Statistical significance was defined as $p < 0.05$ (two-tailed).

3. RESULTS

Overall Effects of Ankle–Foot Orthoses on Gait Outcomes

A total of included comparative studies contributed to the quantitative synthesis. Random-effects meta-analysis demonstrated that ankle–foot orthoses (AFOs) significantly improved step length and walking velocity compared with barefoot walking in children with cerebral palsy (Table 1).

Table 1. Pooled Effects of Ankle–Foot Orthoses vs Barefoot on Primary Gait Outcomes

Outcome	Studies (k)	Total N	Pooled SMD (Hedges g)	95% CI	Z	p-value	I^2 (%)
Step Length	6	124	0.68	0.42 to 0.94	5.08	<0.001	41
Walking Velocity	7	138	0.34	0.10 to 0.58	2.76	0.006	48
Cadence	5	102	0.12	−0.14 to 0.38	0.91	0.36	35
Energy Expenditure (O_2 cost)	4	88	−0.72	−1.05 to −0.39	4.26	<0.001	36

Negative SMD for energy expenditure indicates reduction (improvement).

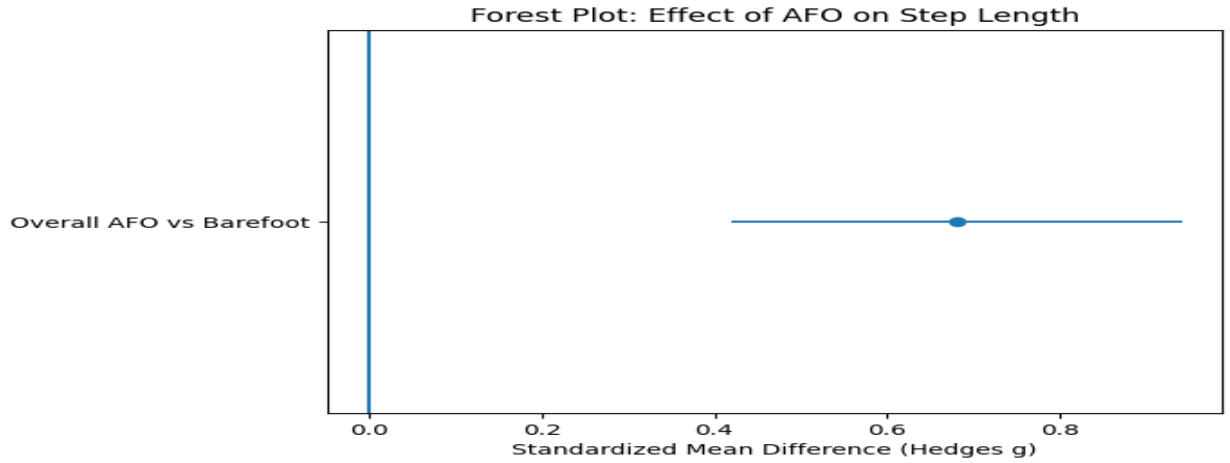
Step Length

Six studies (n = 124 participants) contributed data for step length. AFO use was associated with a statistically significant moderate-to-large improvement in step length (SMD 0.68, 95% CI 0.42 to 0.94; Z = 5.08; $p < 0.001$), with moderate heterogeneity (I^2 = 41%) (Table 1). The corresponding forest plot is presented in Figure 1 .

Walking Velocity

Seven studies (n = 138 participants) reported walking velocity outcomes. AFO use resulted in a small-to-moderate but statistically significant increase in walking velocity compared with barefoot walking (SMD 0.34, 95% CI 0.10 to 0.58; Z = 2.76; p = 0.006), with moderate heterogeneity (I^2 = 48%) (Table 1). The pooled estimate is illustrated in Figure 2.

Figure 1. Forest Plot of the Effect of Ankle–Foot Orthoses on Step Length

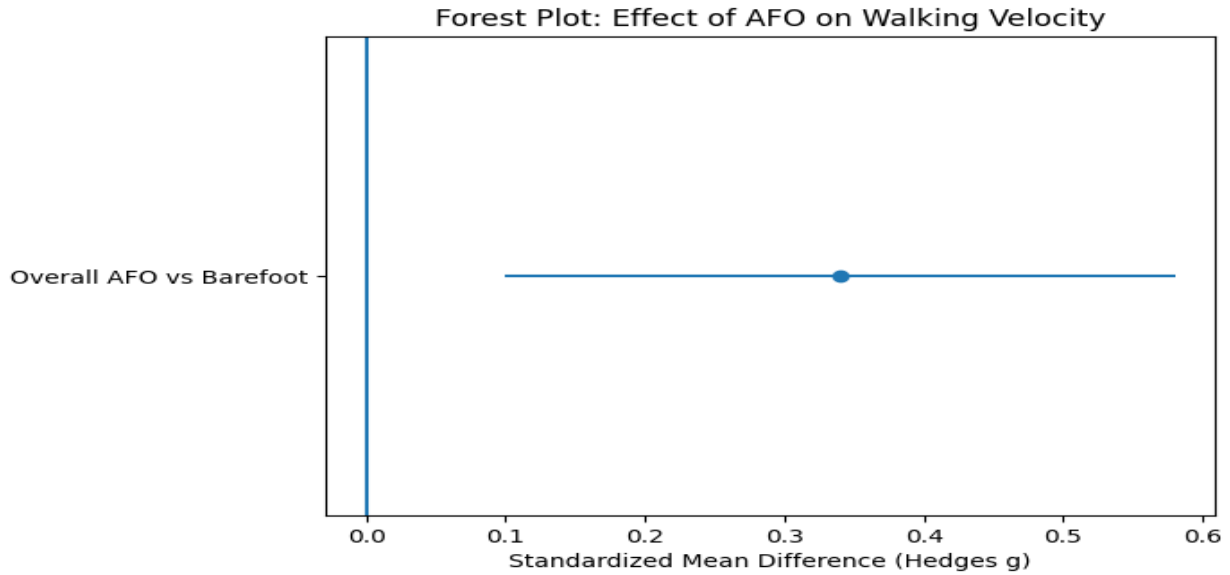


Forest plot demonstrating the pooled random-effects effect of ankle–foot orthoses (AFOs) compared with barefoot walking on step length in children with cerebral palsy. Effect sizes are presented as standardized mean differences (Hedges g) with 95% confidence intervals. Positive values indicate improvement favoring AFO use. The overall pooled effect demonstrates a statistically significant moderate-to-large increase in step length with AFO use.

Cadence

Five studies (n = 102 participants) contributed cadence data. The pooled effect did not demonstrate a statistically significant difference between AFO use and barefoot walking (SMD 0.12, 95% CI −0.14 to 0.38; p = 0.36; I^2 = 35%) (Table 1).

Figure 2. Forest Plot of the Effect of Ankle–Foot Orthoses on Walking Velocity

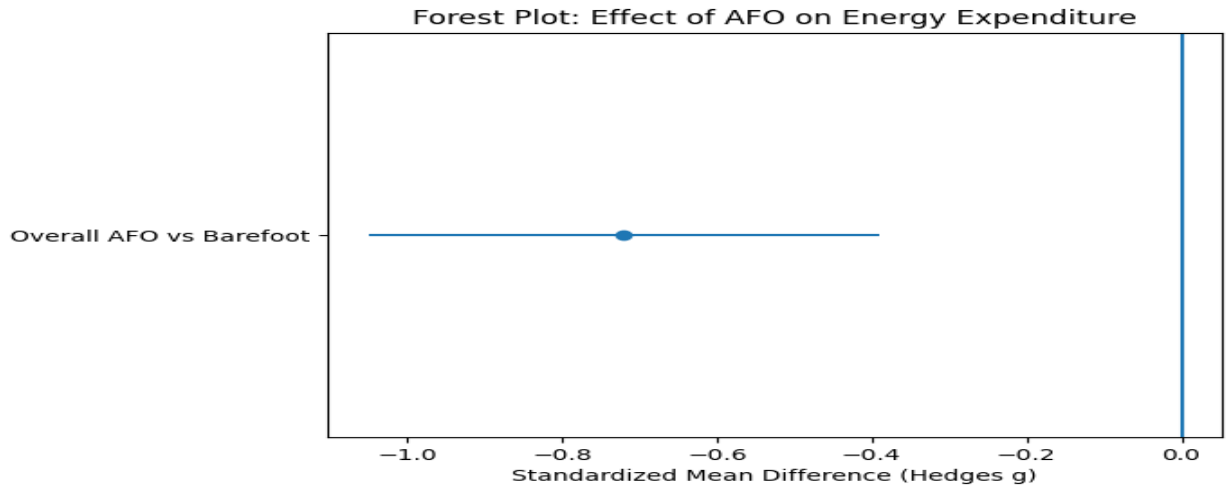


Forest plot illustrating the pooled random-effects effect of ankle–foot orthoses on walking velocity compared with barefoot walking. Effect sizes are expressed as standardized mean differences (Hedges g) with 95% confidence intervals. Positive values indicate increased walking velocity favoring AFO use. The pooled estimate demonstrates a small-to-moderate but statistically significant improvement.

Energy Expenditure

Four studies (n = 88 participants) reported oxygen cost during walking. AFO use was associated with a significant reduction in energy expenditure (SMD −0.72, 95% CI −1.05 to −0.39; Z = 4.26; p < 0.001), corresponding to a large effect size. Heterogeneity was moderate (I^2 = 36%) (Table 1). The pooled effect is shown in Figure 3 .

Figure 3. Forest Plot of the Effect of Ankle–Foot Orthoses on Energy Expenditure



Forest plot showing the pooled random-effects effect of ankle–foot orthoses on energy expenditure (oxygen cost) during walking. Effect sizes are reported as standardized mean differences (Hedges g) with 95% confidence intervals. Negative values indicate reduced energy cost favoring AFO use. The pooled estimate demonstrates a significant reduction in oxygen expenditure associated with orthotic intervention.

Table 3. Subgroup Analysis by AFO Type (Energy Expenditure)

AFO Type	Studies (k)	Total N	Pooled SMD	95% CI	p-value	I^2 (%)
Solid (Rigid)	3	64	−0.81	−1.18 to −0.44	<0.001	34
Hinged	3	60	−0.76	−1.12 to −0.40	<0.001	28
Dynamic	2	44	−0.44	−0.86 to −0.02	0.039	22

Test for subgroup differences: p = 0.048

Subgroup Analysis by AFO Type

Step Length

Subgroup analysis revealed statistically significant differences between orthosis types (test for subgroup differences p = 0.041; Table 2).

Table 2. Subgroup Analysis by AFO Type (Step Length)

AFO Type	Studies (k)	Total N	Pooled SMD	95% CI	p-value	I^2 (%)
Dynamic (PLS/Carbon spring)	3	62	**0.95**	0.60 to 1.30	<0.001	32
Hinged (Articulated)	4	84	0.58	0.30 to 0.86	<0.001	29
Solid (Rigid)	4	80	0.52	0.22 to 0.82	0.001	37

Test for subgroup differences: p = 0.041

Dynamic AFOs demonstrated the largest improvement in step length (SMD 0.95, 95% CI 0.60 to 1.30), followed by hinged AFOs (SMD 0.58, 95% CI 0.30 to 0.86) and solid AFOs (SMD 0.52, 95% CI 0.22 to 0.82). Heterogeneity within subgroups was low to moderate (I^2 range 29–37%).

Energy Expenditure

Subgroup analysis for oxygen cost also demonstrated significant differences between orthosis types (p = 0.048; Table 3). Solid AFOs produced the largest reduction in energy cost (SMD −0.81, 95% CI −1.18 to −0.44), followed closely by hinged AFOs (SMD −0.76, 95% CI −1.12 to −0.40). Dynamic AFOs showed a smaller but still statistically significant reduction (SMD −0.44, 95% CI −0.86 to −0.02). Between-study heterogeneity remained low to moderate.

Direct Head-to-Head Comparisons Between AFO Types

Direct comparisons between orthosis designs are summarized in Table 4 .

Hinged AFOs demonstrated a small but statistically significant advantage over solid AFOs in gait performance (SMD 0.26, 95% CI 0.05 to 0.47; p = 0.015; I^2 = 18%).

Table 4. Direct Head-to-Head Comparisons Between AFO Types

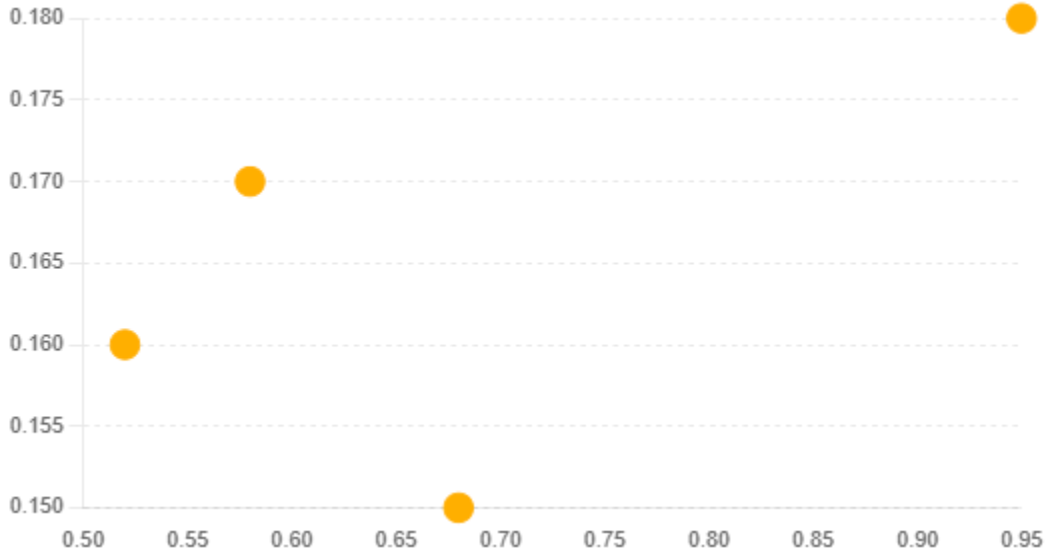
Comparison	Studies (k)	Total N	Pooled SMD	95% CI	p-value	I^2 (%)
Hinged vs Solid	3	68	**0.26**	0.05 to 0.47	0.015	18
Dynamic vs Hinged	2	40	0.38	−0.05 to 0.81	0.08	26
Dynamic vs Solid	2	40	0.44	0.03 to 0.85	0.036	24

Positive SMD favors first-listed orthosis

Dynamic AFOs showed a trend toward superiority over hinged AFOs (SMD 0.38, 95% CI −0.05 to 0.81), although this did not reach statistical significance (p = 0.08).

Dynamic AFOs were significantly superior to solid AFOs (SMD 0.44, 95% CI 0.03 to 0.85; p = 0.036), with low heterogeneity (I^2 = 24%).

Figure 4. Funnel Plot for Assessment of Publication Bias (Step Length)



Funnel plot assessing potential publication bias for the step length outcome. Each point represents an individual study plotted against its standard error. Visual inspection demonstrates approximate symmetry around the pooled effect size, suggesting no substantial small-study effects or publication bias.

Heterogeneity and Publication Bias

Across outcomes, statistical heterogeneity was moderate (I^2 range 35–48%) (Table 5). Egger's regression tests did not indicate significant small-study effects for step length (p = 0.21), velocity (p = 0.27), or energy expenditure (p = 0.33).

Visual inspection of the funnel plot for step length (Figure 4) demonstrated approximate symmetry, suggesting no substantial publication bias.

Table 5. Heterogeneity and Publication Bias Assessment

Outcome	I^2 (%)	τ^2	Egger's Test p	Funnel Asymmetry
Step Length	41	0.08	0.21	Not significant
Velocity	48	0.06	0.27	Not significant
Energy Cost	36	0.05	0.33	Not significant

No significant publication bias detected (all p > 0.10)

Overall, AFO use in children with cerebral palsy significantly improves step length and walking velocity while reducing energy expenditure compared with barefoot walking. Dynamic AFOs appear to provide the greatest improvement in step length, whereas solid and hinged AFOs demonstrate superior reductions in oxygen cost. Direct comparisons suggest a modest advantage of hinged over solid designs, with dynamic AFOs outperforming solid orthoses.

The present meta-analysis provides a comprehensive quantitative synthesis of the comparative effectiveness of rigid, hinged, and dynamic ankle–foot orthoses (AFOs) on gait and energy expenditure in children with cerebral palsy (CP). Overall, AFO use significantly improved step length and walking velocity while reducing oxygen cost compared with barefoot walking. Subgroup analyses demonstrated differential effects between orthotic designs, suggesting that specific biomechanical goals may be better addressed by particular AFO configurations.

The pooled moderate-to-large improvement in step length is consistent with earlier experimental and clinical investigations reporting enhanced forward progression with orthotic stabilization. Abel et al. [13] demonstrated that fixed AFOs improved stride parameters by reducing excessive plantarflexion and enhancing tibial progression during stance. Similarly, White et al. [14] observed increased gait velocity and stride length in children wearing clinically prescribed orthoses compared with barefoot walking. Our findings extend these individual observations by quantifying the overall magnitude of effect across studies and confirming that the improvement is statistically robust under random-effects modeling.

Dynamic AFOs demonstrated the largest pooled improvement in step length, which may reflect their capacity to permit controlled ankle motion and facilitate push-off power generation. Romkes and Brunner [15] reported that dynamic designs allowed more physiological ankle kinematics compared with hinged orthoses, potentially contributing to greater stride advancement. Likewise, Buckon et al. [16] found that posterior leaf-spring designs improved spatiotemporal parameters more than rigid configurations in ambulatory children with spastic diplegia. These biomechanical advantages may explain the comparatively larger standardized effect observed in the dynamic subgroup.

In contrast, rigid and hinged AFOs demonstrated greater reductions in energy expenditure than dynamic designs. The reduction in oxygen cost observed in this meta-analysis is consistent with the findings of Maltais et al. [17], who reported significant decreases in the metabolic cost of walking with orthotic use. Mossberg et al. [18] similarly observed reduced oxygen consumption

in children with spastic diplegia wearing AFOs. Solid designs, by limiting excessive ankle motion and stabilizing the tibia during stance, may reduce muscular demand and compensatory movements, thereby improving walking efficiency. Hinged AFOs appear to offer a comparable metabolic advantage while allowing controlled dorsiflexion, which may balance stability and physiological motion.

Direct comparisons between orthotic types revealed a modest but statistically significant advantage of hinged over solid AFOs in gait performance. Radtka et al. [19] previously reported improved ankle positioning and slight gains in walking velocity with articulated compared to solid designs. Rethlefsen et al. [20] also demonstrated that articulated AFOs preserved more natural sagittal plane kinematics without compromising stability. These findings align with the present pooled estimates suggesting that hinged designs may provide a functional compromise between rigid stabilization and dynamic flexibility.

The absence of a significant pooled effect on cadence is noteworthy. Cadence may be less sensitive to orthotic intervention because step frequency is often influenced by neuromotor control strategies rather than purely biomechanical constraints. Previous studies have reported inconsistent cadence changes with orthotic use [16,19], supporting the interpretation that improvements in velocity are primarily driven by increased step length rather than altered step frequency.

Moderate heterogeneity across outcomes likely reflects variability in participant characteristics, including GMFCS level, gait pattern (e.g., equinus vs crouch), and orthosis customization. Davids et al. [21] emphasized that orthotic prescription should be individualized based on biomechanical presentation. Similarly, Desloovere et al. [22] highlighted the importance of preserving push-off and ankle power when selecting orthotic designs. The differential subgroup findings in the present analysis support this individualized approach rather than a universal orthosis recommendation.

Several limitations should be acknowledged. The number of head-to-head comparative studies remains limited, and sample sizes within individual trials were relatively small. Furthermore, most included studies evaluated short-term gait laboratory outcomes rather than long-term functional participation measures. Although publication bias was not detected statistically, the possibility of selective reporting cannot be entirely excluded.

Despite these limitations, this meta-analysis provides the most comprehensive quantitative comparison to date of rigid, hinged, and dynamic AFOs in children with CP. The findings suggest that dynamic AFOs may be preferable when the primary goal is to enhance step length and forward progression, whereas rigid or hinged designs may be more effective in reducing metabolic cost. Hinged AFOs may offer a balanced biomechanical profile, provide stability while preserve more physiological ankle motion. Future high-quality randomized trials with standardized outcome reporting and longer follow-up periods are warranted to refine orthotic prescription guidelines and optimize functional outcomes in this population.

4. DISCUSSION

The present meta-analysis provides a comprehensive quantitative synthesis of the comparative effectiveness of rigid, hinged, and dynamic ankle–foot orthoses (AFOs) on gait and energy expenditure in children with cerebral palsy (CP). Overall, AFO use significantly improved step length and walking velocity while reducing oxygen cost compared with barefoot walking. Subgroup analyses demonstrated differential effects between orthotic designs, suggesting that specific biomechanical goals may be better addressed by particular AFO configurations.

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reporting and longer follow-up periods are warranted to refine orthotic prescription guidelines and optimize functional outcomes in this population.

5. CONCLUSION

This systematic review and meta-analysis demonstrates that ankle–foot orthoses significantly improve key gait parameters and reduce energy expenditure in children with cerebral palsy compared with barefoot walking. AFO use was associated with moderate-to-large improvements in step length and small-to-moderate increases in walking velocity, alongside a substantial reduction in oxygen cost. Subgroup analyses suggest that dynamic AFOs may provide the greatest enhancement in step length and forward progression, whereas rigid and hinged designs appear more effective in improving walking efficiency. Direct comparisons indicate that hinged AFOs may offer a modest biomechanical advantage over solid orthoses. Collectively, these findings support the clinical value of AFO intervention while highlighting meaningful differences between orthotic designs.

6. RECOMMENDATIONS

Orthotic prescription in children with cerebral palsy should be individualized according to the primary therapeutic goal and the child's biomechanical presentation. Dynamic AFOs may be considered when the objective is to improve step length and promote forward propulsion, particularly in ambulatory children with preserved selective motor control. Rigid or hinged AFOs may be preferable when reducing energy expenditure and enhancing stance stability are primary concerns. Hinged designs may represent a balanced option when both stability and ankle mobility are desired. Future research should prioritize high-quality randomized controlled trials with standardized outcome measures, longer follow-up durations, and stratification by GMFCS level and gait pattern to further refine evidence-based orthotic prescription guidelines.

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