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Is the Intermediate Assessment of Shod Walking Necessary on Patients with Orthopedic or Neuro Orthopedic Pathologies?

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Abstract
Ankle-foot-orthoses are a medically prescribed intervention that can make significant improvement to persons with pathological gait. Clinical gait analysis usually observes barefoot walking and if applicable, with orthoses. The effect of shoes as an intermediary between barefoot walking and walking with ankle- foot-orthoses is therefore generally overlooked. Also, little is known about the biomechanical effect of shoes on pathological gait. This study aims at bridging this gap in current literature and quantifying the isolated influences of footwear to improve the decision-making process of orthopedic intervention.

Barefoot, shod and if applicable, orthotic gait of up to 292 patients aged 2-63 years with orthopedic or neuro-orthopedic conditions were retrospectively analyzed. Initial Contact was analyzed by means of sagittal-plane videos. Temporospectral parameters as well as sagittal plane kinematics of the ankle and knee at specific instances in the stance phase were investigated using marker-based instrumented 3D- analysis.

The overall improvement in the quality of Initial Contact was attributed more to shoes than ankle-foot- orthoses. Step length and speed were significantly increased by shoes but not by the addition of orthoses ($p<0.01$). Cadence remained unchanged by shoes but decreased significantly due to orthoses. Ankle kinematics improved with both shoes and orthoses. Only minimal effects on knee kinematics were observed in both interventions.

Shoes being an important walking aid in pathological gait should be included in clinical gait assessment, especially when testing orthotics. Had their effect not been investigated, would improvements in pathological gait have been incorrectly credited solely to ankle-foot-orthoses.

Keywords: Gait Analysis, Shoes, Ankle Foot Orthosis, Kinematics, Children, Adults, Pathology

Abbreviations

- **AFO**: Ankle Foot Orthosis
- **FC**: Forefoot Contact
- **HC**: Heel Contact
- **IC**: Initial Contact
- **LHC**: Low Heel Contact
- **PC**: Plan Contact

Introduction

It is well established that shoes increase the functionality of locomotion by increasing ankle stability and comfort whilst protecting the foot from pain, uncomfortable environments or injury [1-3]. The biomechanical effects of different kinds of shoes on various aspects of physiological walking such as spatiotemporal parameters, kinematics and kinetics have also been well documented [1-9]. It has been shown that shoes increase walking speed [6-8], step length [2, 6], stride length [2, 3, 10], stride time [2, 8] and stance time [2, 6, 7] and activity in the M. Tibialis anterior [6]. There is also an increase in range of motion at the ankle at push off [1] and in the knee flexion [6]. Cadence and single support time have in contrast been proven to decrease during shod walking [4, 6, 7]. Effinger et al. however reported minimal changes in kinematics and kinetics when wearing shoes [10].

On the other hand, persons with orthopedic or neuro-orthopedic disabilities in general exhibit altered gait patterns [11]. Although shoes are predominantly worn during ambulation, little is known about the effect of shoes on the pathological gait of children and [12-16].

Ankle-foot-orthoses (AFOs) are a medically prescribed intervention that can make a significant contribution to improving gait and posture by influencing ground reaction forces and gait metrics such as walking speed, stride length, balance and postural control. They also attempt to normalize kinetics and kinematics [17-26]. Although AFOs are worn in conjunction with shoes, most studies investigating the effects of AFOs on pathological gait are based on comparison with barefoot walking and not on walking with shoes [1, 16, 23, 25, 28-32]. This is to say that the effect of shoes as an intermediary between barefoot walking and walking with AFOs is generally ignored. To the best of our knowledge, only two research groups have taken this effect into account [14, 15]. Hesse et al. reported significant improvements in speed, stride length, initial double stance duration and gait line in 19 hemiparetic patients by wearing only shoes, but even more marked improvements in these parameters as well as cadence when using orthotics [15]. Discovered et al. reported improvements in several gait parameters during walking with AFOs compared to barefoot walking in 15 hemiplegic children. But it was concluded that significant improvements were attributed due to the effect of wearing shoes only and not to the additional usage of AFOs [14].

The aim of this study is twofold; one is to bridge the huge gap in current literature on the effect of shoes on pathological gait patterns, focusing on the foot strike pattern at initial contact (IC), temporospectral parameters such as speed, step length and cadence as well as ankle and knee kinematics at specific points in the stance phase. The second aim is to then compare the effects of walking with AFOs against shoes. Both aims will be accomplished by retrospectively evaluating the entire database of patients with orthopedic and neuro-orthopedic disorders. We hypothesize that the effect of shoes on certain gait metrics will be significant enough so as to lessen the additional effect of AFOs.

Methods

Experimental Setup

The gait lab is fitted with an instrumented 3D marker-based system (Qualisys AB, Gothenburg, Sweden) comprising eleven Onus 400 infrared cameras (3D), mounted at a height of either 1.8m or 2.5m, synchronized with two Onus 210C video overlay cameras (2D), mounted at 0.5m. Sampling frequencies of the 3D and 2D cameras are 100Hz and 50 Hz respectively. Patients are referred to the lab for either a pedobarographic only, a video-analysis (2D) or a 3D-analysis, the latter including synchronized videos by default.

Patients included children and adults with an orthopedic or neuro-orthopedic diagnosis. They wore minimal, tight-fitting clothing to ensure high quality data not only for video analysis but also for good marker tracking. In a 3D-analysis, markers and clusters based on the CAST model were attached on the skin (Fig. 1) [33]. Overground walking at a self-selected speed was captured for at least four trials in a 2D-session and eight trials in a 3D-session over the 13m long walkway.

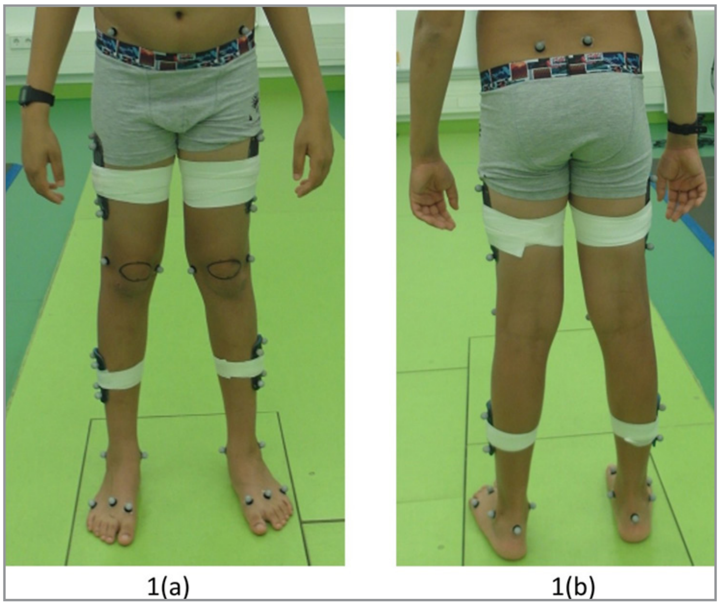

Figure 1: Ventral (a) and dorsal (b) view of the marker-based lower body CAST model [36]. Bilateral anatomical landmarks: anterior and posterior superior iliac spine, lateral and medial epicondyle, apex of lateral and medial malleolus, dorsal aspect of fifth, second and first metatarsal heads, upper ridge of the calcaneus posterior surface. Clusters were also placed bilaterally on the mid-thigh and mid-shank laterally.

Participants
The entire database of about 854 patients at the gate laboratory, Olga hospital, Stuttgart was screened retrospectively. Clinical gait analysis was performed in accordance with standard operating procedures of the gait lab and in compliance with ethical guidelines. Signed, informed consent was obtained from the patients or, in case of a minors, from the accompanying parent or guardian. Data was captured by a physiotherapist and lab engineer, both with a minimum of 5 years' experience in pediatric clinical gait analysis.

Patients referred to the lab for a pedobarographic were excluded from this study since they were examined only in the barefoot condition. This left patient referred to the lab for a 2D or 3D analysis. This comprised of some patients who had already been fitted with AFOs and did not wear only shoes. They were also excluded from this study. The next set of patients to be excluded were those with a bilateral physiological IC. From the remaining patients, those wearing shoes with an additional intervention on the shoe such as a wedge or additional full-length sole to counter were also excluded from the study.

As shown in Fig. 2, inclusion criteria for this study were:

- Patients referred for a 2D or 3D-analysis
- Recording of barefoot walking and shod walking without elevation in shoes
- Pathological unilateral or bilateral IC during barefoot Walking

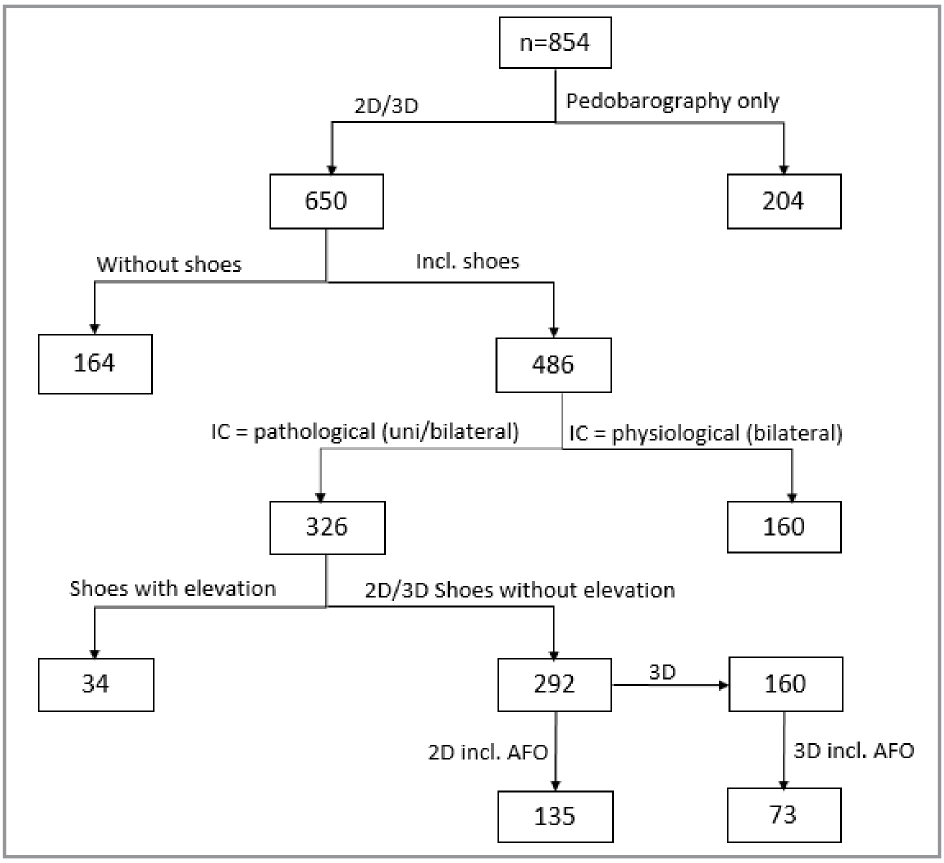

Figure 2: Inclusion and exclusion criteria applied to the database of 854 patients that resulted in 292 patients examined for the effect of IC on walking with shoes of which 135 patients on the additional effect of orthoses. A total of 160 patients were examined for the effect of ankle and knee kinematics as well as temporospatial data with shoes and 73 of them for the additional effect of orthoses.

IC was differentiated into heel contact (HC), low heel contact (LHC), plan contact (PC), and forefoot contact (FC). Of these, only HC is physiological; the rest classified as pathological. An LHC is defined as an IC where the forefoot is very close to the floor, the underlying cause being any impairment that contributes to excess plantarflexion [11]. If the patient had visited the gait lab on multiple occasions, only one session was selected. The session where a patient came for a 3D-analysis was prioritized over a 2D- only analysis. Two groups of patients were formed; one group that had only 2D-analysis where the effect of shoes on IC could be assessed by means of videos. The second group who were referred for 3D- analyses where temporospectral parameters and kinematics could be assessed.

As shown in Fig. 2, applying the above criteria resulted in 292 patients (2–63 years, 52% male, 48% female) in the 2D-analyses group and 160 patients in the 3D-analysis group. Please refer to Table 1 for the patient characteristics.

Table 1: Patients characterised into assessment of IC based on video analysis and assessment of ankle and knee kinematics as well as temporospatial data based on 3D analysis. Each of these two groups are sub-grouped into patients who also wore orthotics and were therefore assessed for this condition as well.

Group		Nr. of patients	Nr. of males	Nr. of females	Age(yr.) ± 1SD
Effect on IC by	shoes	292	153	139	16.4 ± 10.8
	shoes and	135	69	66	14.1 ± 8.7
Effect on ankle and knee kinematics by	shoes	160	87	73	16.3 ± 8.8
	shoes and	73	39	34	13.8 ± 7.5

Data Analysis

Referring to the 2D-analyses group, the sagittal video camera was used to classify the position of the foot at IC for barefoot, shod and if applicable orthotic walking condition. For the 3D-analyses group, marker trajectories were filtered at 6 Hz using a 2nd order low-pass Butterworth filter in Visual3D™ v2020.11.2 (HAS-Motion, Canada). Two consecutive gait cycles from each of the 8 trials were analyzed. The Visual3D segment optimization procedure was used to compute the joint angles with 6 degrees of freedom. Kinematics were time normalized to 101 data points of the gait cycle and their means calculated. The temporospectral parameters including step length, walking speed and cadence, as well as ankle dorsiflexion/plantarflexion and knee flexion/extension were analyzed in MATLAB™ 2021a (The MathWorks, USA). Visual observation of the kinematics was carried out. Average dorsiflexion and knee flexion at IC as well as maximum dorsiflexion and minimum knee flexion during stance phase of 8 gait cycles were determined per patient.

The kinematic values and the temporospectral data were tested for normal distribution using the Kolmogorov-Smirnov and Shapiro-Wilk tests. According to the tests, the kinematic data were not normally distributed. Hence the Wilcoxon test was applied. Since the temporospectral data were normally distributed, a paired t-test was used here. The significance level was set at $\alpha < 0.01$. The SPSS™ program v29 (IBM, USA) was used for statistical analysis.

Results

Initial Foot Contact

As shown in Fig. 3, pathological IC during barefoot walking (in blue) was found in 474 feet of the 292 patients investigated using videos. Of these, 173 feet had a FC, 224 PC, and 77 LHC. The effect of wearing shoes was a 72% decrease in FC, a 21% decrease in PC and a slight increase in LHC by 6% (depicted in red). The total number of HC rose from 0 during barefoot walking to 166 when walking with shoes. The most common foot contact during both conditions was the PC.

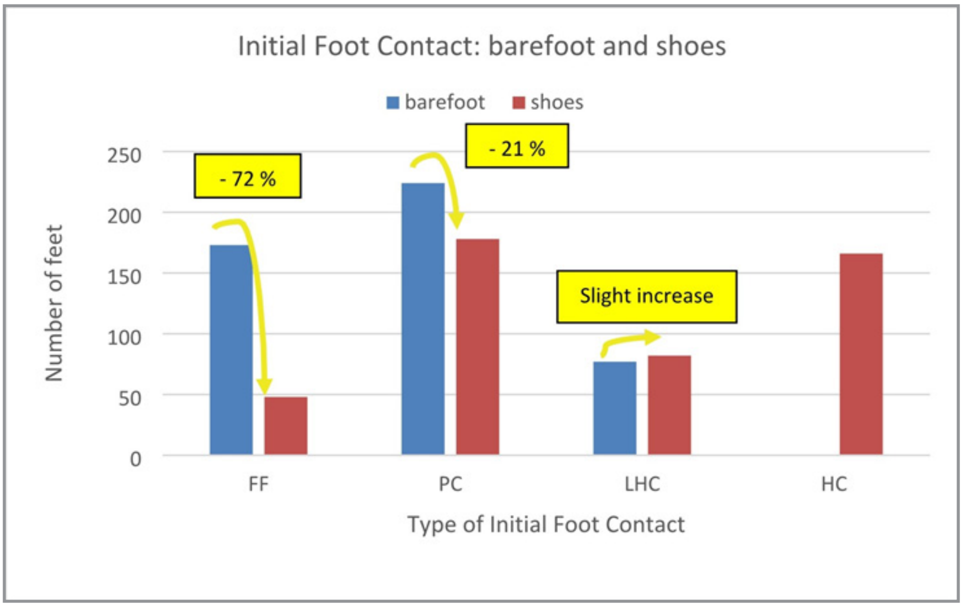

Figure 3: Comparison of initial foot contact during barefoot walking and walking with shoes; FC = Forefoot Contact, PC = Plan Contact, LHC = Low Heel Contact, HC = Heel Contact

Figure 4 shows the sub-group of 135 patients who were additionally fitted with unilateral or bilateral AFOs. Here we see the changes in IC from barefoot walking (blue) to shoes as an intermediary (red) and then with AFOs (green). When considering FC, an improvement of 69% was seen from barefoot to shod walking, similar to that seen in the entire group. In comparison, wearing AFOs brought about only a further 10% improvement in FC. PCs decreased slightly by 9% by wearing shoes and by 33% when AFOs were included. Following a similar trend to the entire group, LHC increased slightly from condition to condition. The most common IC during barefoot and shod walking was PC whereas HC was the most frequently established when walking with orthotics.

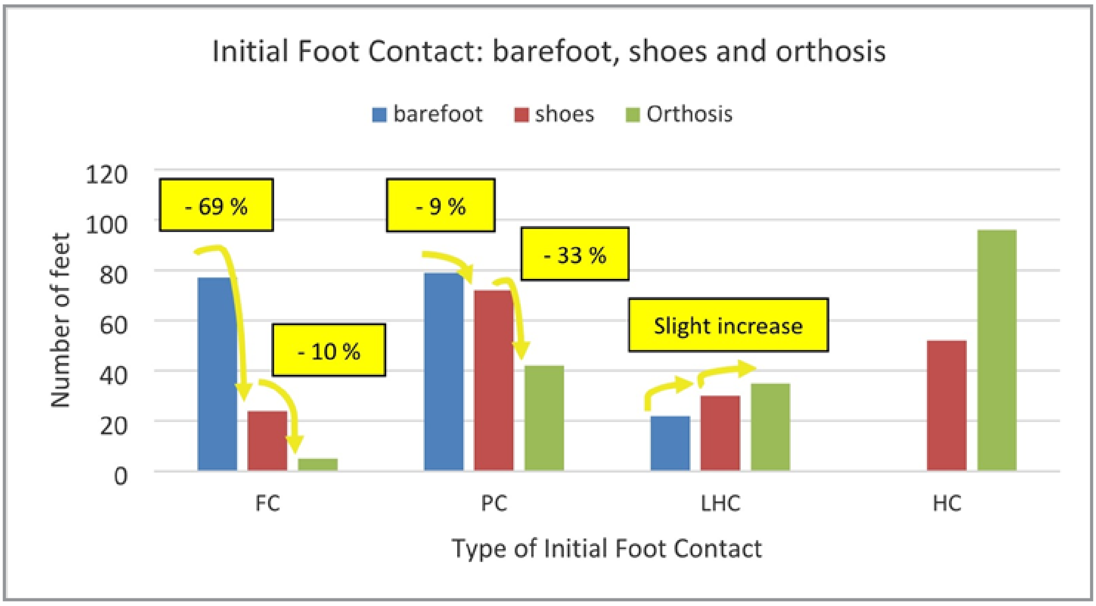

Figure 4: Comparison of initial foot contact during barefoot walking, walking with shoes and walking with orthoses. FC = Forefoot Contact, PC = Plan Contact, LHC = Low Heel Contact, HC = Heel Contact

Temporospatial Parameters

From the 3D-analyses of 160 patients, it was found that during barefoot walking, 259 feet had a pathological IC whereas in the sub-group of patients who additionally wore an orthosis there were 106 pathological ICs when walking barefoot.

As shown in Table 2, the effect of walking with shoes on the entire group of patients who had a 3D- analyses was a 6cm increase in step length and a 0.1m/s increase in speed, both changes being significant ($p < 0.001$). There was no change in cadence. When looking at the sub-group of patients who additionally wore AFOs, similar change in temporospectral parameters were seen from barefoot to shod walking namely a 5cm increase in step length, a 0.09m/s increase in speed and a slight decrease in cadence by 2 steps/min. Wearing orthoses brought about slight changes in step length and speed, and a significant increment of 3 steps/min in cadence.

Table 2: Effect of shoes and orthoses on temporospectral parameters; average step length (m), velocity (m/s) and cadence (steps/min). Ankle and knee kinematics at IC (dorsiflexion is positive and plantarflexion negative), maximum dorsiflexion and minimum knee flexion during stance phase are also given. Significant differences (p<0.01) are depicted with*.

Parameter	Barefoot VS Shoes		Barefoot VS Shoes VS Orthoses		
	Barefoot	Shoes	Barefoot	Shoes	Orthoses
Step length (m)	0.48 ± 0.1	0.54* ± 0.1	0.49 ± 0.07	0.54 ± 0.08	0.55 ± 0.08
Speed (m/s)	0.91 ± 0.24	1.01* ± 0.23	0.95 ± 0.19	1.04 ± 0.20	1.03 ± 0.21
Cadence (steps/min)	110 ± 19	110 ± 17	113 ± 18	111 ± 17	108* ± 17
Dorsiflexion at IC (°)	-5.2 ± 9.5	-1.1* ± 7.9	-5.9 ± 8.4	-1.8 ± 7.2	3.3* ± 5.0
Max. dorsiflexion in stance (°)	11.7 ± 9.5	15.9* ± 8.5	12.1 ± 6.7	16.2 ± 6.6	14.8* ± 5.5
Knee flexion at IC (°)	20.5 ± 12.3	18.8* ± 13.4	19.4 ± 11.8	17.8 ±	18.3 ± 13.2
Min. knee flexion in stance (°)	11.2 ±12	10.2* ± 12.2	9.7 ± 10.3	8.7 ± 10.9	8.8 ± 10.3

Kinematics

Table 2 also details the effects of shoes and AFOs on ankle and knee kinematics. In IC, wearing shoes reduced the mean excessive ankle plantarflexion significantly from 5.2° to 1.1° in the main group of subjects and from 5.9° to 1.8° in the sub-group of subjects additionally fitted with AFOs. Wearing AFOs resulted in a mean dorsiflexion of 3.3, the effect being significant ($p < 0.01$). Mean maximum dorsiflexion in the stance phase increased in both the main group as well as the subgroup from 11.7° to 15.9° and from 12.1° to 16.2° respectively. When walking with AFOs, the knee flexion lightly decreased by the additional use of AFOs (16.2° to 14.8 °). Excessive knee flexion at IC and minimum knee flexion in the stance phase reduced in the both groups, the effect being statistically significant in the main group of subjects. Wearing AFOs resulted in a slight worsening of knee flexion at both events of the gait cycle.

Discussion

This study investigated barefoot versus shod walking and shod versus orthotic walking in a population of patients with a host of orthopedic and neuro-orthopedic disorders. We hypothesized that barefoot walking should not be compared directly to walking with AFOs since shoes themselves are an intervention that could have potential positive effects on pathological gait.

Type of Initial Contact

Barefoot Versus Shoes

Just wearing shoes reduced the number of pathological forefoot and plan ICs and improved the number of physiological heel contacts significantly, already improving foot strike at the beginning of the gait cycle. A reason for this improvement could be facilitated by the wedge of the shoe that can help perform or improve the heel rocker [34]. Since this is the first study of its kind to investigate this particular aspect in pathological gait, comparisons with other literature cannot be undertaken.

Shoes Versus AFOs

The addition of AFOs provided a further decrease in the number of forefoot and plan contacts and increase in heel contact thereby further improving the overall quality of IC. These results correlate with Hesse et al. who also reported an increase in the number of HC due to orthotics [15]. The foot can be held in a relatively fixed position due to the support device and cannot excessively plantarflexion during swing phase. This stabilizes the ankle joint and prevents the foot from hitting the ground in plantar flexion.

The results clearly indicate that IC is tremendously improved by AFOs compared to barefoot walking. But, had the effect of shoes not been investigated, would this improvement have been incorrectly credited solely to AFOs.

Temporospatial parameters

Barefoot Versus Shoes

The additional stability offered by shoes not just improved IC, but also improved temporospectral parameters. Here a significant increase in step length and speed was seen, cadence remaining relatively unchanged. The changes in step length and speed were similar to those demonstrated in other two studies on pathological gait [14, 15]. The increase in step length can be attributed to the natural presence of a wedge under the heel that increases the sole height of the shoes which in turn increases leg length by this amount [4, 6].

The unvarying cadence is contradictory to both Hesse et al. and Discovered et al. although both studies reported opposed results, the former showing a significant increase and the latter a significant decrease in cadence [14, 15]. One possible reason for conflicting results in all three studies could be due to the differences in the demography and sample size; Hesse et al. investigated 19 adults with cerebral palsy, discovered et al. studied 15 children with hemiplegia and the current study analyzed children and adults with multiple disorders.

Shoes versus AFOs

The additional use of AFOs brought about only a slight 1cm increase in step length compared to walking with shoes. Contrary to the outcome reported by Discovered et al., walking speed in our group of patients slightly decreased by 0.01m/s compared to shod walking [14]. The difference can be attributed to the fact that their study included patients who were already familiar with the use of AFOs, whereas the current study also includes many patients on whom AFOs were being tested for the first time. They consequently walked somewhat cautiously, thereby dampening the overall effect on this intervention on speed. However, if we compare the effect of AFOs to barefoot walking in our study as routinely performed in other studies, we arrive at comparable outcomes [18].

Cadence decreased significantly by 3 steps/min compared to shoes. The change in temporospectral parameters compared to barefoot walking could also be the increased mass due to the shoe and the orthoses, which lead to an increased inertia of the leg during the swing phase [6, 35]. The small temporospectral differences between shoes and AFOs compared to barefoot walking and shoes prove that these parameters are strongly influenced by shoes compared to orthotics.

Kinematics

Barefoot versus shoes

Walking with shoes reduced the excessive plantarflexion at IC and produced a significant increase in maximal dorsiflexion in the stance phase, both results agreeing with Discovered et al. [14]. Although the knee flexion angle shows statistically significant changes at IC and during minimal stance phase flexion, the changes are in practice too small to be considered clinically significant.

Shoes Versus AFOs

Wearing AFOs allowed the foot to be better positioned in the swing phase which led to a significant improvement at IC by means of a dorsiflexion instead of plantarflexion and a much-improved heel-rocker. This agrees with other studies [14, 20, 24, 28]. Orthoses are made of stiffer material than shoes and the additional brace on the shin allows the foot to be held in a fixed position, allowing a better heel contact. The average peak dorsiflexion in the stance phase was unchanged. At push-off however, the plantarflexion as well as range of motion was now greatly reduced.

No significant differences were seen in knee kinematics which agreed with Ethelene et al. [28]. One reasoning for the reduced changes between conditions in the sub-group could be that this study encompasses an extremely diversified population of pathologies and gait deviation including varied degrees of stiff-kneed and crouch-gait patients.

After examining 14 able-bodied children for barefoot and shod walking, Effinger et al. concluded that shod assessment in most clinical studies is unnecessary [10]. Whilst this may be the case in physiological gait, the results of the current study indicate that shod assessment is a necessity in assessment of pathological gait.

Limitations

There are however, certain limitations in this study that must be mentioned. Certain pathologies can bring about greater improvements when walking with shoes as compared to barefoot walking. To this effect, it would be more effective to subgroup the database with respect to diagnosis, foot deformities or neurologic conditions such as spasticity or reduced proprioception. Another factor overlooked in this study is the effect of different types of shoes and AFOs on walking. Here it would be of great interest to further investigate if a certain type of shoe produced a better effect on walking, for example, shoes with a wedge. A detailed look into the effect of different types of AFOs (e.g. rigid versus hinged) is also worth investigating.

Conclusion

The aim of the retrospective study is encouraging the clinical gait community to incorporate the assessment of shod walking in addition to barefoot walking, especially when decisions pertaining to orthotic interventions are to be made. This study therefore emphasizes the need to assess shod walking as an in-between step, after barefoot walking and before testing orthoses to decide on the most effective orthotic intervention for patients and possibly prevent overprovisioning of orthotic care. Further work needs to be carried out into the evaluation of the effect of different kinds of shoes and orthotics compared to barefoot walking. Separating the sample population of patients into specific disorders as well as grouping into children and adults also needs to be investigated. A detailed look into the effect on the kinematics in other joints and planes of movement as well as into the kinetics is worth following up on.

Declarations

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Author Contributions

Sonia D'Souza is responsible for the conception, data acquisition and design of the study. Lisa Kava conducted the analysis and interpretation of the data in consultation with Wilfried Alt and Sonia D'Souza. Lisa Kava also wrote the first draft of the manuscript. All authors revised the manuscript critically and approved the final version to be published.

Data Availability Statement

The data that support the findings of this study are available from author Sonia D'Souza, upon reasonable request.

Declaration of Competing Interests

The authors declare no potential conflicts of interest with respect to the research, authorship and/or publication of this manuscript.

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Ethics Statement

An ethics approval was waived due to the nature of this retrospective study since it was based on data collected at the gate laboratory, Olga hospital in accordance with standard operating procedures for 3D clinical gait analysis. The data was collected in compliance with ethical guidelines. Informed consent and assent were obtained from patients or their guardians/parents with regards to collection, analysis and publication for this study.

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