



## Research article

## Effects of wearing a foot orthosis on ankle function in children with idiopathic toe walking during gait

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## HIGHLIGHTS

- Walking barefoot and wearing foot orthosis were analyzed in idiopathic toe walkers.
- When worn, foot orthosis improves idiopathic toe walking severity classification.
- Heel-to-toe gait is promoted when using foot orthosis.
- When worn, foot orthosis improves ankle kinematics, moment, and power.

## ARTICLE INFO

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## ABSTRACT

**Background:** Idiopathic toe walking (ITW) is a gait deviation characterized by forefoot contact with the ground, possibly enhancing the risk of falling and causing Achilles' tendon shortening and psychological discomfort. Between possible treatments, foot orthosis may limit ITW when worn. With these premises, the effects of a novel foot orthosis (A.Dyn.O.<sup>®</sup>) on ankle function were analyzed in children with ITW during gait.

**Methods:** Twenty-one children were recruited in the study after ITW diagnosis. At follow-up assessment after a habituation period of at least two weeks, participants walked in barefoot condition and while wearing A.Dyn.O.<sup>®</sup>. Kinetics and kinematics were derived from a multi-segment foot model using an optoelectronic system. Gait spatiotemporal parameters, ankle kinetic and kinematic and rockers timing were analyzed. Lastly, ITW severity was classified according to Alvarez classification. Differences between conditions were verified with paired t-test. Statistical parametric mapping was used to evaluate differences in the entire kinematic and kinetic waveforms.

**Findings:** Wearing A.Dyn.O.<sup>®</sup>, step cadence was reduced, step length, stance phase and stride duration increased; physiological heel rocker was present, thus postponing the timing of ankle and forefoot rockers; ankle dorsiflexion angular excursion, range of motion, maximal dorsiflexor and plantarflexor moments together with maximal power absorption and production were all amplified.

**Interpretation:** While wearing it, A.Dyn.O.<sup>®</sup> limited gait deviations typical of ITW and improved ITW severity classification for most of the participants. These findings suggest that the use of A.Dyn.O.<sup>®</sup> may assist ITW treatment, preventing children from toe walking and thus limiting its side effects.

## 1. Introduction

Toe walking is a gait deviation characterized by initial forefoot ground contact and excessive ankle plantarflexion during the entire gait cycle (GC). It is observed in structural pathologies, neurological or neuromuscular disorders and in autism spectrum disorders [1]. Although toe walking may be adopted temporarily during typical gait development [2], the

persistence of this walking pattern after three years of age, without the presence of any known etiology, is called Idiopathic Toe Walking (ITW). Some authors have described children presenting ITW as able to walk with a normal pattern, if asked to do so [3]. Therefore, it is possible to describe children diagnosed with ITW as otherwise typically developed children who usually walk on their toes rather than assuming a regular heel-to-toe gait.

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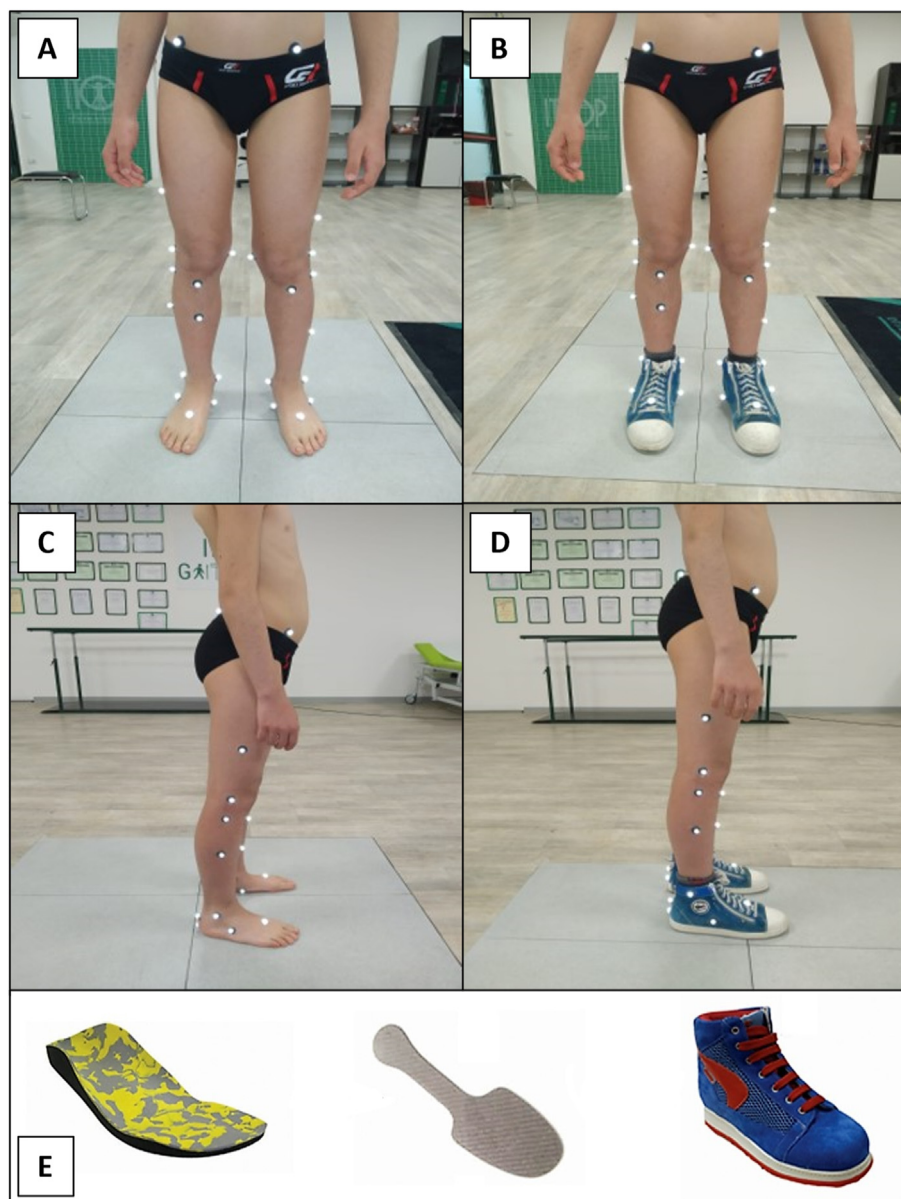
Although ITW may resolve spontaneously [4, 5, 6], it has been hypothesized that persistent toe walking may have effects on health status [7], thus making its correction preferable. Moreover, ITW could have negative psychological effects both on parents and children [8]. Nevertheless, at present a limited number of clinical trials analyzing health-related long-term effects of ITW is present. A recent review [9] found only one randomized controlled trial with a timeframe of minimum six months that analyzed the effectiveness of two different interventions [10]. The authors of the review concluded that at present there are insufficient findings on the effectiveness of ITW treatments.

Due to the unknown ITW etiology, treatments focus on increasing ankle dorsiflexion range of motion varying according to the case severity and the child's age [11]. Treatments comprise several strategies: conservative therapies, as passive or active stretching of plantarflexor muscles, dorsiflexor strengthening exercises, motor control exercises [12]; plantarflexion inhibition strategies, as Botulin toxin A injections or casting [10]; and orthoses, covering the ankle-foot (AFO) or only the foot (FO) [13]. Findings on the effectiveness of interventions in reducing toe walking are inconsistent and do not support devising clear and univocal guidelines for ITW management

[9]. Moreover, possible limitations and side effects must be considered: children's active adherence is needed with conservative therapies; some children reported pain in the calf muscles after Botulin toxin A injections, while visible AFOs and casts may have a social impact for children and families [11]. Therefore, at the time being, the choice of a correction strategy could be driven by its feasibility and potential to reduce side effects while limiting toe walking and constraints to the activity of daily living.

Among conservative treatments, FOs may be a feasible option as they promote an active modification of toe walking by the child, instead of passively limiting it, as casts and rigid AFOs do, while having less obtrusive appearance compared to them. Previous studies on FOs only measured gait spatio-temporal parameters [13, 14] which do not provide insights on ankle joint function. At present, studies investigating ankle biomechanics in children with ITW walking with foot orthosis are still missing.

Recently [15], an Antiequinus Dynamic foot orthosis (A.Dyn.O.<sup>®</sup>) was developed to treat ITW. A.Dyn.O.<sup>®</sup> is a modular solution that combines a custom-made insole, a carbon fiber flexible plate and a specific orthopedic shoe with the aim of exerting a downward force on the hindfoot, contrasting the toe-walking pattern without blocking the ankle (Figure 1E).



**Figure 1.** Top: marker placement for the barefoot and orthosis conditions (A–D). Bottom (E): representation of the A. Dyn.O.<sup>®</sup> orthosis. From left to right: foot orthosis, carbon fiber flexible plate, orthopedic shoe.

The aim of this study is to evaluate the effectiveness of the orthosis in restoring a physiological heel-to-toe gait pattern, by performing instrumented 3D gait analysis of children with ITW walking barefoot and while wearing it.

## 2. Methods

### 2.1. Participants

Twenty-one children aged between 5 and 10 and diagnosed with ITW were enrolled in the study, upon signed consent by their parents. The sample size was determined after a priori power analysis (effect size = 0.8, power  $1 - \beta = 0.82$ ,  $\alpha = 0.05$ ), based on a previous similar work [14]. The study received the approval of the local institutional review board (University of Rome “Foro Italico”, Rome, Italy). Participants were included in the study after the diagnosis of ITW. Children with any pathologies that may cause toe walking and children who underwent any alternative treatments to correct ITW were excluded. The diagnosis of ITW and prescription of use of A.Dyn.O.<sup>®</sup> orthosis was done by physiatrists of the Bambino Gesù Hospital in Rome. A first assessment was performed after two weeks to fine tune the orthosis after children got used to the device. After this, follow-up visits were scheduled approximately every 3 months to verify the need for orthosis replacement. Parents were instructed to have the children wearing the orthosis during the whole day, removing it only for sport activities and sleeping. At follow-up visits, physicians interviewed children's parents to assess the adherence to the treatment and the presence of any discomfort with the orthosis: all the children wore it regularly and no adverse effects were reported. Data for this study were collected from one of these follow-ups. Table 1 reports sex, age, and anthropometric measurements together with the period between the ITW diagnosis and the follow-up visit in which instrumented gait analysis was performed. ITW severity, classified during the same follow-up assessment, is also reported for both barefoot and FO walking (Table 1): the three classes (mild, moderate, and severe) are based on the presence or absence of the heel rocker, on early forefoot

rocker, and maximum plantarflexor moment in the early stages of stance phase [16]. Although passive range of motion of the ankle may determine the ability of the children to correct gait, it was not reported in the study as none of them presented limitations when passively assessed by physicians during examinations.

### 2.2. Experimental procedure

Testing sessions were performed during follow-up assessments: children were asked to walk at their preferred speed along a straight 10-meters walkway. A familiarization period of two weeks with the orthosis was set. Participants were recorded in barefoot condition and while wearing A.Dyn.O.<sup>®</sup>. An eight infrared cameras motion capture system (BTS SMART-DX, Quincy, USA, sampling rate 250 frame/s) and four force plates (BTS Bioengineering Corp, Quincy, USA, sampling rate of 1000 frame/s), placed in the middle of the walkway, were used to measure gait kinematics and kinetics. Trials were considered valid when foot strike occurred within the borders of the force plates. Trials recording continued until a minimum of six complete GCs in each condition (three for each side) were recorded. A total of 31 and 25 markers (Figure 1A–D) were placed on the children for static and dynamic trials, respectively, according to a 3D model following Lower body Plug-in Gait [17] model (pelvis and thigh) and a modified Oxford foot model [18] (versions 4 and 5 for shank and hindfoot). The design of the shoe used in combination with the orthosis allowed for palpation of anatomical landmarks except for those on the most posterior aspect of the calcaneus, identified as the most posterior point of the posterior profile of the shoe. The 3D model was then used to obtain ankle plantar-dorsiflexion angle. Concerning kinetics, the ankle moment was found to be equal using the two models during the propulsive action of the stance phase [19], thus Plug-in Gait model was used to obtain it during the entire stance phase. Ankle power was calculated as the product of ankle moment and ankle angular velocity.

The same two operators were positioned at the extremities of the walkway to engage children in games that comprised the walking task, with the aim of avoiding modification of the gait pattern.

**Table 1.** Participants' characteristics. F: Female; M: Male; 1: Mild; 2: Moderate; 3: Severe; # indicates one-class improvements; § indicates two-classes improvements.

Participant	Sex	Age [y]	Mass [kg]	Stature [m]	Treatment time [month]	Alvarez [15] classification	
						BAREFOOT	A.Dyn.O. <sup>®</sup>
S01	F	10	28.9	1.35	1	2	1 <sup>#</sup>
S02	M	6	20.8	1.18	1	2	1 <sup>#</sup>
S03	F	10	40.8	1.40	1	2	2
S04	M	5	18.9	1.15	79	3	1 <sup>§</sup>
S05	M	8	28.3	1.34	21	3	1 <sup>§</sup>
S06	M	9	32.3	1.39	8	2	1 <sup>#</sup>
S07	M	7	22.4	1.27	18	1	1
S08	F	7	37.1	1.40	33	2	1 <sup>#</sup>
S09	M	12	39.1	1.60	6	2	1 <sup>#</sup>
S10	F	8	38.1	1.39	12	2	1 <sup>#</sup>
S11	F	11	56.5	1.55	26	2	2
S12	M	9	44.8	1.34	4	2	1 <sup>#</sup>
S13	F	12	77.0	1.57	9	3	1 <sup>§</sup>
S14	M	11	43.5	1.52	8	1	1
S15	M	10	28.5	1.37	8	3	2 <sup>#</sup>
S16	F	5	20	1.13	6	1	1
S17	M	10	33.5	1.36	12	2	1 <sup>#</sup>
S18	M	8	29	1.28	6	3	1 <sup>§</sup>
S19	M	5	30	1.27	12	2	2
S20	F	7	23	1.21	30	2	1 <sup>#</sup>
S21	M	6	22	1.18	30	1	1
Group		8.3	34	1.34	16		

### 2.3. Data analysis

Kinetic and kinematic data were obtained using Vicon Nexus 2.10 (Vicon, Oxford, UK). Raw data were filtered using a low-pass fourth order Butterworth filter with a cut-off frequency of 12 Hz. Foot contact and foot off were identified as the time instants in which the ground reaction force vertical component reached values above and below the 5% of the participant's body weight, respectively. If the second foot contact of the GC occurred outside the borders of the force plates, it was detected by visual inspection of heel and toe markers trajectories. GCs were time normalized to obtain 100-points waveforms.

GCs intra-participant and intra-condition consistency was calculated using the Linear Fit Method [20], to use mean waveforms in data analysis. Consistency was verified analyzing the right and left limb together. The linear relationship assumption was proved valid [21] (mean  $R^2 > 0.5$ ) within and between participants (Table 2), for each condition, thus mean data were used for the other analyses. Precisely, children's means were calculated as the mean of children's trials while conditions' mean was computed as the mean of participants' means.

Kinematic analyses are graphically described in Figure 2. Maximal ankle angular excursions on the sagittal plane were measured during the four arcs of motion described by Perry et al. [22], i.e., plantarflexion and dorsiflexion during stance phase, plantarflexion at terminal stance phase and initial swing phase, and dorsiflexion during swing phase. Range of motion was calculated as the difference between maximum and minimum value of ankle angle. Heel, ankle, and forefoot rockers timings were identified using maximal ankle plantarflexion and dorsiflexion angles

**Table 2.** Within and between participants ankle kinematic consistency analysis. This method compares a set of waveforms with their mean, precisely (i) for each subject GCs waveforms were compared to the subject mean waveform; (ii) at group level the mean waveforms of each subject was compared to the group mean waveform.  $R^2$ : Mean strength of the linear relationship within and between subjects' waveforms;  $a_{0SD}$ : Standard deviation of the scalar offset within and between subjects' waveforms  $a_{1SD}$ : Standard deviation of the amplitude scaling factor within and between subjects' waveforms.

Participant	BAREFOOT			A.Dyn.O. <sup>®</sup>		
	$R^2$	$a_{0SD}$ [deg]	$a_{1SD}$	$R^2$	$a_{0SD}$ [deg]	$a_{1SD}$
S01	0.59	2.77	0.13	0.95	1.44	0.07
S02	0.71	1.87	0.09	0.67	0.60	0.05
S03	0.84	1.78	0.04	0.94	2.69	0.02
S04	0.89	1.98	0.07	0.60	3.04	0.11
S05	0.85	1.94	0.05	0.85	1.03	0.07
S06	0.88	0.96	0.08	0.85	2.99	0.06
S07	0.79	1.76	0.08	0.91	4.21	0.06
S08	0.71	0.66	0.11	0.93	2.74	0.04
S09	0.88	1.24	0.07	0.88	3.16	0.06
S10	0.91	3.25	0.04	0.88	2.40	0.02
S11	0.88	2.93	0.09	0.83	0.97	0.06
S12	0.89	3.34	0.07	0.98	3.53	0.09
S13	0.72	3.00	0.08	0.96	0.78	0.04
S14	1.00	1.31	0.08	0.87	1.52	0.05
S15	0.81	1.50	0.10	1.0	2.26	0.05
S16	0.91	1.50	0.05	0.94	0.63	0.05
S17	0.69	12.6	0.83	0.88	2.76	0.05
S18	0.78	4.02	0.08	0.88	4.23	0.05
S19	0.76	6.58	0.05	0.69	2.80	0.12
S20	0.61	3.60	0.09	0.87	5.20	0.04
S21	0.76	5.85	0.07	0.86	0.80	0.16
Group	0.73	4.79	0.08	0.82	3.32	0.05

during stance phase. If present, heel rocker starts at ground contact, while the ending point was selected as the timing of maximal plantarflexion during stance phase. Ankle rocker starts after heel rocker and lasts until maximum dorsiflexion angle in stance phase. Forefoot rocker lasts from maximal dorsiflexion until the end of stance phase [16, 23]. Concerning ankle kinetics, peak values were computed for: plantarflexor and dorsiflexor moment and power generation and absorption during stance phase. ITW severity (Table 1) was defined according to Alvarez classification [16].

Regarding gait spatiotemporal parameters, swing phase and stride ( $t_{stance}$ ,  $t_{swing}$  and  $t_{stride}$ , respectively) duration were calculated through the identification of gait events. Precisely,  $t_{stance}$  was defined as the time between ground contact and toe-off of the same foot;  $t_{swing}$  was defined as the time between toe-off and ground contact of the same foot;  $t_{stride}$  was defined as the time between two ground contacts of the same foot. Step length ( $l_{step}$ ) and width ( $w_{step}$ ) were calculated using the spatial distance (anterior-posterior and medio-lateral, respectively) between heel marker positions at the instants of two consecutive contralateral ground contacts. Walking speed ( $s_{walking}$ ) was estimated using the anterior-posterior distance covered by pelvis marker over a gait stride and  $t_{stride}$ . Cadence was defined as the number of steps per minute. The following parameters,  $s_{walking}$ ,  $l_{step}$ , and  $w_{step}$ , were normalized using acceleration of gravity and participants' leg length [24].

### 2.4. Statistical analysis

For all tests, significance level  $\alpha$  was fixed at 0.05. To compare mean ankle plantar-dorsiflexion, moment and power waveforms across barefoot and FO conditions, statistical parametric mapping (SPM) [25, 26] was used. After D'agostino-Pearson K2 normality test (Figure 3B, E, H), a non-parametric two-tailed paired t-test was used (Figure 3C, F, I). SPM investigates the difference (SPM{t}) between the conditions at each ith time node of the participants' mean curves and calculates a critical threshold at which only 5% (i.e.,  $\alpha$ ) of random curves would be expected to cross. When the SPM{t} trajectory crosses the threshold, producing areas called "supra-threshold clusters", the null hypothesis is rejected. Using Random Field Theory, SPM then calculates clusters p-value. SPM analysis was implemented using the open source spm1d code (v.M0.1, www.spm1d.org).

For all discrete variables, normal distribution was verified with Shapiro-Wilk test. Parametric and non-parametric [27] analysis of covariance was implemented according to variables' distribution, using the period of use of the orthosis as a covariate. These statistical analyses were performed using SPSS 23.0 software (Chicago, IL, USA).

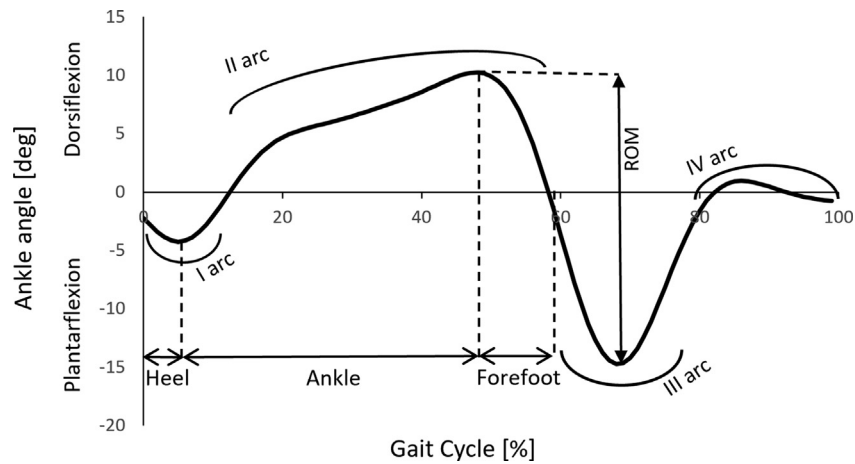
## 3. Results

In FO compared to the barefoot condition, participants presented longer step length, higher stance, and stride durations, together with lower step cadence (Table 3). This difference was true both for normalized [24] values and non-normalized ones.

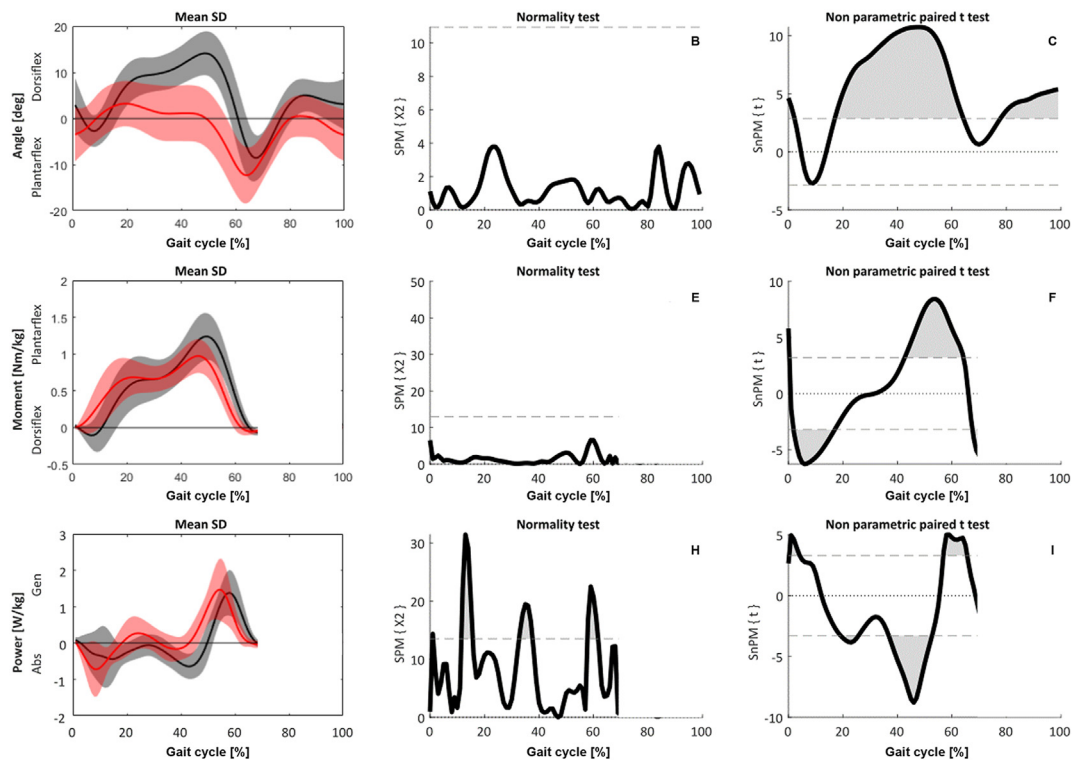
According to Alvarez classification (Table 1), in barefoot condition, four children were classified as mild, twelve as moderate and five as severe ITW. Wearing the orthosis, nine out of twelve children with moderate ITW changed their class to mild ITW, while the others did not exhibit any changes. Out of the five severe cases, four improved their classification to mild and one to moderate ITW.

Ankle plantar-dorsiflexion peak values during the four consequent arcs of motion [22] and RoM are reported in Table 4 together with timing of ankle and forefoot rockers. In FO condition, dorsiflexion excursion increased during the second and the fourth arc of motion, while plantarflexion decreased during the third arc. Range of motion significantly increased in FO condition. Kinetic analysis showed increased peak





**Figure 2.** Graphical representation of kinematic parameters. Representative sagittal component of ankle angle in orthosis condition and graphical representation of the four consecutive ankle arcs of motion, the three rockers (heel, ankle, forefoot) and the range of motion (ROM) calculation.



**Figure 3.** First column: mean waveform with standard deviation for barefoot (red line & red area) and A. Dyn.O.<sup>®</sup> (black line & dark gray area) conditions of ankle angular displacement (A), moment (D), and power (G). Moment and power are represented during the stance phase only. Second column: SPM {X2} results of normality test of ankle angular displacement (B), moment (E), and power (H); dashed lines represent the critical thresholds. Third column: non-parametric paired sample t test results SnPM {t} of ankle angular displacement (C), moment (F), and power (I); dashed lines represent the critical thresholds and grey areas are the supra-threshold clusters.

plantarflexor moment and peak power generation during stance phase together with higher maximum dorsiflexor moment and peak power absorption. As not all the participants exhibited heel rockers, the analysis was implemented for ankle and forefoot rockers only and showed antipated timing for both in barefoot condition.

SPM applied to mean group waveforms analysis showed, in the FO condition compared to barefoot walking, greater dorsiflexion angle at initial contact (0–2%), from 17% to 65%, and from 77% until the end of GC (Figure 3C). Ankle moment and power were analysed during stance phase only: FO condition presented greater dorsiflexor moment at ground contact until 17% of GC and greater plantarflexion moment from

42% of GC until toe off (Figure 3F). Ankle power with participants wearing the orthosis was characterized by smaller power absorption at ground contact (0–4% of GC) and greater power absorption from 18% to 25% and from 36% to 52% and from 56% of GC until toe off (Figure 3I). Individual analyses for each participant are provided in the Supplementary data.

#### 4. Discussion

This study investigated the effects of a dynamic FO on walking patterns of children with ITW. Findings suggest that the orthosis, when

**Table 3.** Normalized and non-normalized gait spatiotemporal parameters. SD: Standard Deviation; IQR: Interquartile Range; *df*: degrees of freedom; *t*: paired t-test score; *Z*: Wilcoxon signed rank test score; \* statistically significant difference; [a.u.]: arbitrary units.

	BAREFOOT		A.Dyn.O. <sup>®</sup>		<i>df</i>	<i>F</i>	<i>p</i>
	Mean	SD	Mean	SD			
Cadence [steps/min]	126.8	10.3	119.2	9.6	1	7.19	0.015*
Cadence [a.u.]	0.55	0.04	0.52	0.04	1	7.87	0.011*
<i>S</i> <sub>walking</sub> [m/s]	1.07	0.18	1.21	0.2	1	4.31	0.052
<i>S</i> <sub>walking</sub> [a.u.]	0.42	0.06	0.47	0.07	1	4.23	0.054
<i>l</i> <sub>step</sub> [m]	0.51	0.07	0.60	0.09	1	19.98	<0.001*
<i>w</i> <sub>step</sub> [m]	0.1	0.03	0.10	0.03	1	0.88	0.359
<i>w</i> <sub>step</sub> [a.u.]	0.15	0.04	0.15	0.05	1	1.29	0.269
	Median	IQR	Median	IQR	<i>df</i>	<i>F</i>	<i>p</i>
<i>l</i> <sub>step</sub> [a.u.]	0.76	0.12	0.89	0.12	1	35.38	<0.001*
<i>t</i> <sub>stance</sub> [s]	0.54	0.07	0.60	0.07	1	11.59	0.002*
<i>t</i> <sub>swing</sub> [s]	0.41	0.05	0.41	0.04	1	0.31	0.576
<i>t</i> <sub>stride</sub> [s]	0.94	0.1	1	0.1	1	4.21	0.047*

worn, reduced the severity of ITW classification by inducing significant changes in gait kinematics and kinetics thus limiting the typical ITW gait deviations.

The use of the orthosis was effective in improving ITW classification for the most part of participants (Table 1): fourteen (82%) out of seventeen children classified in a moderate or severe class passed to a less severe one. At group level, the presence of the heel rocker in the FO condition (Figure 3A) favored the correct timing of the three rockers, postponing ankle and forefoot rockers. The results discussed henceforth refer to group results, details about within subjects' comparison and individual gait features for the children not improving their ITW class are given in supplementary material.

While wearing the orthosis, gait features were modified towards more physiological values, as supported by comparison of current results with barefoot walking data obtained from typically developed children. Several analyzed parameters fell within physiological ranges described in the referenced literature: step length [28], dorsiflexion angular excursion and range of motion [18], and maximal plantarflexor moment [19]. Although shoes are known to alter gait features, barefoot data were considered as reasonable reference for physiological values, since no studies are available on shod walking in children using the

same kinematics and kinetics models or data normalization adopted in this study.

Irrespective to their similarity or dissimilarity from the behavior of typically developing children, gait parameters modifications induced by the orthosis should be interpreted in the light of investigating their causal relationships. Toe walking is usually characterized by reduced step length, resulting in reduced whole body progression and walking speed [29]. The use of the FO induced an increase in step length without causing a significant increase in walking speed due to a reduction of step cadence; the reduced step cadence resulted from an increase of the sole stance phase duration. This may be linked to a significant delay of ankle and forefoot rockers timings, i.e., the reappearance of the heel strike and the related delayed heel rise. Simultaneously, the longer stance phase duration may be due to the need of improving dynamic stability, in response to the downward force exerted by the orthosis on the hindfoot. A previous study [14] on ITW and FO similarly observed a longer stance phase, interpreting it as an adaptation to improve dynamic stability due to the sensory feedback given by the orthosis.

Regarding ankle kinematics, the worn device caused a more dorsiflexed pattern during the majority of the GC, both at peak level, during the last three arcs, and over the entire GC. The SPM analysis highlighted a statistical significance for this increase in six of the eight GC phases: initial contact, mid stance, terminal stance, pre-swing, mid swing, and terminal swing (Figure 3A). Interestingly, only these phases are mainly impaired in case of excessive ankle plantarflexion, while, during loading response and early swing, the ankle is normally characterized by a plantarflexion movement [22]. The pattern differences in each phase support the claim of a more physiological pattern while wearing the orthosis. A greater dorsiflexion angle was found when wearing the orthosis by SPM analysis (Figure 3A–C) but not by peak analysis during the initial stage of GC (first arc), corresponding to the typical ankle position at heel strike. Physiological dorsiflexion was also restored during mid and terminal stance, allowing the forward movement of the shank. In barefoot conditions, conversely, a reduced dorsiflexion caused a premature heel rise and shorter step length. Lastly, the worn orthosis reduced ankle equinus during mid and terminal swing, granting for floor clearance and resulting in an adequate position of the foot before ground contact. Summarily, while wearing A. Dyn.O.<sup>®</sup> children switched towards the usual heel-to-toe gait.

When wearing the orthosis, ankle kinetics showed higher peak maximum dorsiflexor and plantarflexor moments. Consistently, the SPM analysis (Figure 3D–F) showed an increased dorsiflexor moment during

**Table 4.** Ankle planta-dorsiflexion maximal and minimal angular positions, overall range of motion and maximal moment (plantarflexor and dorsiflexor) and power (generation and absorption) during the stance phase, timing of ankle and forefoot rockers. RoM: Range of Motion; ≈ indicates concomitant events; zero subscript (<sup>0</sup>*x*<sub>0</sub>) corresponds to starting point; one subscript (<sup>1</sup>*x*<sub>1</sub>) corresponds to ending point; SD: Standard Deviation; IQR: interquartile range; *df*: degrees of freedom; *t*: paired t-test score; *Z*: Wilcoxon signed rank test score; \* statistically significant difference.

	BAREFOOT		A.Dyn.O. <sup>®</sup>		<i>df</i>	<i>F</i>	<i>p</i>
	Mean	SD	Mean	SD			
First arc: Max plantarflexion [deg]	-4.28	5.20	-3.98	3.30	1	0.17	0.683
Second arc: Max dorsiflexion [deg]	4.17	5.02	14.79	4.42	1	69.17	<0.001*
Third arc: Max plantarflexion [deg]	-12.6	5.89	-9.2	4.94	1	4.54	0.046*
Fourth arc: Max dorsiflexion [deg]	1.3	4.14	5.93	3.98	1	18.10	<0.001*
RoM [deg]	17.13	4.45	24.76	3.31	1	20.42	<0.001*
	Median	IQR	Median	IQR	<i>df</i>	<i>F</i>	<i>p</i>
Peak dorsiflexor moment [Nm/kg]	-0.02	0.06	-0.17	0.21	1	12.07	0.001*
Peak plantarflexor moment [Nm/kg]	1.05	0.33	1.4	0.6	1	7.85	0.008*
Peak power absorption [W/kg]	-0.63	0.78	-0.9	0.60	1	3.86	0.056
Peak power generation [W/kg]	1.4	0.90	1.25	0.54	1	0.46	0.504
<sup>ankle</sup> Rocker <sub>0</sub> [% GC]	1	6	8	3	1	22.33	<0.001*
<sup>ankle</sup> Rocker <sub>1</sub> ≈ <sup>forefoot</sup> Rocker <sub>0</sub> [% GC]	21	24	50	3	1	18.84	<0.001*
<sup>forefoot</sup> Rocker <sub>1</sub> [% GC]	57	2	60	1	1	38.77	<0.001*

loading response and the presence of a physiological plantarflexor moment during the terminal stance phase. Physiological loading response is usually characterized by such dorsiflexor moment [22, 29], as a ground reaction force applied at the heel is posterior to the ground projection of the joint center. Conversely, a plantarflexor moment at loading response observed in the barefoot condition, indicates a forefoot (or mid foot) contact with ground. During terminal stance, the increase in plantarflexion moment caused by the worn orthosis could be related to the kinematic changes towards a more dorsiflexed pattern of the ankle mentioned above as a result of the forward movement of the tibia over the foot flat on the ground. Consequently, a greater forward fall of the entire body may occur, determining the higher peak plantarflexor moment during terminal stance phase.

The worn orthosis similarly produced changes in ankle power. Precisely, enhanced power absorption, during initial and mid stance phase, and power production, during terminal stance phase, were observed by the SPM analysis (Figure 3G–I). In initial and mid stance, plantarflexor muscles eccentrically control the dorsiflexion movement of the ankle, thus determining a power absorption at the joint level. A wider dorsiflexion at mid-stance favours plantarflexor muscles elongation, enhancing the subsequent plantarflexor muscles concentric contraction which rapidly moves the ankle toward plantarflexion before toe off, favoring body propulsion and determining a higher peak power production.

Current results must be interpreted in the light of the following limitations. Differences found between conditions may be influenced by differences between barefoot and shod walking. However, the standard clinical assessment procedure comprised barefoot and foot orthosis walking recordings. Given a low compliance of this population to experimental procedures, recoding unbiased data for a reference shod condition would have not been possible. Although the shoes alone may alter ankle kinematics, the magnitude of the changes observed in this study is bigger than the one usually reported for non-orthotic shoes [30]. Moreover, the design of the shoes used with the orthosis (i.e., boots with a flat sole) allows for firm fixation of the rearfoot within the shoe. Lastly, only plantar-dorsiflexion movement was characterized, as commonly analyzed in clinical settings, despite the use of the orthosis may impact other joints of the lower limb as well as other planes of motion of the ankle.

## 5. Conclusions

In conclusion, with the orthosis being worn children improved ankle function correcting the typical gait deviations characteristic of ITW. As necessary adjustments to counteract the rigidity of the orthosis, heel strike was present, thus promoting the correct timing of ankle and forefoot rockers and allowing a proper kinetic exploitation of the ankle muscles. A Dyn.O.<sup>®</sup> could be adopted in concomitance with other correction strategies to prevent children from walking on toes, and thus limiting the risk factors related to this condition. Further research is needed to assess the long-term effects of the use of this device (alone or with other conservative treatments).

## Declarations

### Author contribution statement

Paolo Brasiliano: Wrote the paper; Analyzed and interpreted the data.  
Martina Alvini: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data.

Giuseppe Vannozzi: Conceived and designed the experiments; Performed the experiments.

Giuseppe Di Rosa: Analyzed and interpreted the data.

Eugenio Di Stanislao and Valentina Camomilla: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed materials, analysis tools or data.

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## Data availability statement

Data will be made available on request.

## Declaration of interest's statement

The authors declare the following conflict of interests: The authors declare that Giuseppe Di Rosa and Eugenio Di Stanislao are inventors of the orthosis and that ITOP SpA Officine Ortopediche is the patent holder. Martina Alvini and Eugenio Di Stanislao are employed in ITOP SpA Officine Ortopediche. All other authors have no conflict of interest associated with this publication.

## Additional information

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