Comparison of gait with and without ankle-foot orthoses after lower limb surgery in children with unilateral cerebral palsy

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Abstract

Purpose Children with spastic unilateral cerebral palsy (SUCP) frequently undergo lower limb surgery to improve gait. Postoperatively, ankle-foot orthoses (AFOs) are used to maintain the surgical corrections and provide adequate mechanical support. Our aim was to evaluate changes in gait and impacts of AFOs one-year postoperatively.

Methods In all, 33 children with SUCP, 17 girls and 16 boys, mean age 9.2 years (5 to 16.5) were measured by 3D gait analysis walking barefoot preoperatively and walking barefoot and with AFOs one-year postoperatively. Changes in Gait Profile Scores (GPS), kinematic, kinetic and temporal spatial variables were examined using linear mixed models, with gender, gross motor function and AFO type as fixed effects.

Results The results confirm significant gait improvements in the GPS, kinematics and kinetics walking barefoot one year after surgery. Comparing AFOs with barefoot walking postoperatively, there was additionally reduced ankle plantarflexion by an average of 5.1° and knee flexion by 4.7° at initial contact, enhanced ankle moments during loading response, increased velocity, longer steps and inhibited push-off power generation. Stance and swing phase dorsiflexion increased in children walking with hinged AFOs *versus* children walking with ground reaction AFOs. Changes in the non-affected limbs indicated less compensatory gait postoperatively.

Conclusion Major changes were found between pre- and postoperative barefoot conditions. The main impact of AFOs was correction of residual drop foot and improved prepositioning for initial contact, which could be considered as indications for continued use after the one-year follow-up.

Level of Evidence: Level II - Therapeutic

Introduction

Gait deviations are common in children with spastic unilateral cerebral palsy (SUCP). This is mainly due to ankle equinus but involvement at the proximal joints also occurs.[1-3] Early treatment often includes a combination of physiotherapy, serial casting, ankle-foot orthoses (AFOs) and injections of botulinum toxin A to reduce spasticity in the triceps surae muscle and maintain adequate ankle joint range of movement. In cases where fixed deformities impair functional ambulation, orthopaedic surgery may be necessary. In the postoperative rehabilitation period, different types of AFOs are routinely used to provide adequate mechanical support during gait and prevent recurrence of deformities.[2,4-8]

Previous studies using 3D gait analysis (3DGA) have found that surgery at single[7,8] or multiple[5,6] levels improved gait kinematics and kinetics in children with SUCP. Still, residual gait problems, such as drop-foot in the swing-phase are common.[2,8,9] Recurrent equinus has been reported in 38% to 62.5 % of patients with unilateral cerebral palsy (CP) five to ten years after triceps surae lengthening.[10,11] It is, therefore, not surprising that the one-year postoperative evaluation with 3DGA often results in recommendations regarding further treatment, such as prolonged use of orthoses, to prevent recurrent deformities.[8,12]

Several studies have provided valuable documentation regarding effects of orthoses on gait.[13-16] To our knowledge there is no existing study that has evaluated the impact of AFOs after lower limb surgery in children with SUCP. This

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might be important to provide realistic perspectives for the patients, families and caregivers and to establish indications for continued use of AFOs after surgery.

The aim of the present study was to investigate changes in gait function one year after lower limb surgery in children with SUCP. Our objectives were to evaluate if gait function was improved after surgery and whether further changes take place when walking with AFOs compared with barefoot at the one-year postoperative follow-up with 3DGA.

Patients and methods

Participant selection

We included children with SUCP, who underwent preoperative 3DGA and lower limb surgery including triceps surae lengthening to treat ankle equinus, and who used AFOs at the time of postoperative 3DGA. Consecutive sampling during a four-year inclusion period resulted in 43 patients who received written information about the study. Ten patients did not respond or wish to participate which resulted in 33 included patients (17 girls and 16 boys) who gave written informed consent. A total of 22 children were classified as level I and 11 children as level II according to The Gross Motor Function Classification System (GMFCS).[17] The study was approved by the Regional Ethics Committee (REC; 2013/1242).

Data collection

All children were measured with 3DGA in three conditions; preoperatively walking barefoot, postoperatively walking barefoot and postoperatively walking with AFOs and shoes. Data was captured using a Vicon system (Vicon Motion Systems Ltd., Oxford, United Kingdom) with six infrared cameras (Vicon MXF40) and three force plates (AMTI OR[6-7], Advanced Mechanical Technology Inc., Watertown, Massachusetts). Two experienced testers (IS or ABH plus one physiotherapist) reached agreement on marker placement, following the Plug-in-Gait model and marker protocol.[18] Participants were walking at self-selected speed across a 12-metre walkway until a minimum of three trials containing valid kinetic and kinematic data was captured. Data processing with Vicon Nexus software included definition of gait events, i.e. initial contact and foot off, which were determined on the force plates and correlated to all gait cycles in the trial. Prior to the walking trials, a standardized physical examination of joint range of movement, muscle strength, tone and selective motor control was performed. In the postoperative conditions, participants were first measured barefoot. After ten minutes rest, measurement commenced with AFOs and with shoes only on the non-affected side. With AFOs the

pelvis, thigh and knee markers remained on the skin from the barefoot session. Shank and foot markers were repositioned on AFOs and shoes in optimal agreement with movement and segment axes. Differences in shoe heel height were accounted for by measuring the heel-to-toe drop of the shoe sole using an outside calliper, placing the heel marker accordingly higher than the forefoot marker on the shoes and not assuming that the markers were horizontal during static processing.[19]

According to typical procedure, a multidisciplinary team of child neurologist, certified prosthetist orthotist (CPO) (IS, ABH), physiotherapist and orthopaedic surgeon evaluated the pre- and postoperative 3DGA. This involved assessment of patient's gait curves against normative curves from our reference database of 24 typically developing children (11 girls, 13 boys) with a mean age of 9.8 years (5 to 15). Normal ranges were defined as mean (SD). Gait patterns were categorized according to Winters et al[3] into four types: children with Type 1 pattern walk with dynamic ankle equinus or drop-foot in swing; Type 2 walk with true equinus, with the knee in extension or recurvatum during stance; Type 3 with true equinus and flexed knee during stance; and Type 4 present with a stronger proximal involvement, usually with frontal and transverse plane deviations. Each participant's preoperative gait pattern,[3] physical examination and the treatment algorithms suggested by Rodda and Graham[2] guided the decisions regarding surgery and postoperative follow-up, including the type and function of orthoses. Using the Silverskiolds test, children with passive dorsiflexion to 0° with knee flexed usually underwent gastrocnemius recession and children with passive dorsiflexion less than 0° with knee flexed had tendo-achilles lengthening. Treatment recommendations were specified in the children's gait reports. For descriptive analysis, we reviewed the gait reports to register recommendations regarding continued use of AFOs following postoperative 3DGA, and the distribution of gait patterns pre- and postoperatively.

AFOs

In children with Type 1 or 2 gait patterns,[3] who underwent triceps surae lengthening for equinus, AFOs were constructed to allow ankle dorsiflexion, restrict plantar flexion and lift the foot in swing and categorized as hinged AFOs (HAFOs). HAFOs were made with 2.5-mm to 3-mm polypropylene-butylene and integrated joints (Tamarack, Blaine, Washington), with dorsal leg shell to below the fibular head, a circular total-contact foot part and flexible long sole (past the toes) (Fig. 1a). In children with Type 3 or 4 patterns,[3] who underwent hamstrings lengthening and/or rectus femoris transfer, AFOs should restrict dorsal and plantar flexion and apply an external knee extension moment during stance and were categorized as ground
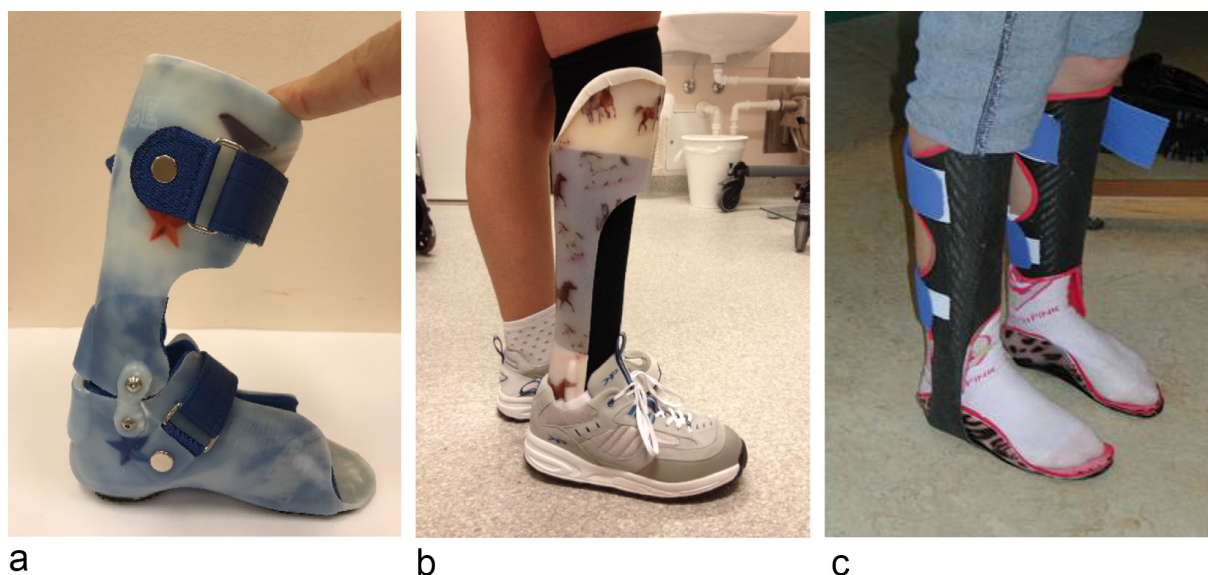
Fig. 1 The different types of ankle-foot orthoses (AFOs) used at the postoperative gait analysis: (**a**) hinged AFO with dorsal shell and foot part connected by integrated Tamarack flexure joints (Tamarack Habilitation Technologies Inc, Blaine, Washington); (**b**) polypropylene ground reaction AFO (GRAFO), with a ventral shell to mid-patella; as shown with shoes and standing alignment; (**c**) carbon composite GRAFOs with ventral shell to below patella.

reaction AFOs (GRAFOs). GRAFOs were fabricated solid, in 5-mm to 6-mm polypropylene, with a ventral shell extending to mid-patella or in carbon composite with a ventral shell to below patella, both with stiff long soles (Figs 1b and 1c).

Casting for postoperative AFOs was made by CPOs after surgical closure. Splints to immobilize ankles in 0° to 5° of dorsiflexion were applied for five weeks. Physiotherapy was started the first day postoperatively and continued throughout the rehabilitation period. Immediately after splint removal, AFOs and shoes were fitted, using a standing alignment with 5° to 10° shank inclination. The children were instructed to use the orthoses all day until the one-year postoperative 3DGA evaluation.

Outcome measures

As a summary measure of gait quality, we calculated the Gait Profile Score (GPS) which is based on nine kinematic Gait Variable Scores (GVS).[20] The GVSs are root mean square differences between patient's sagittal, transverse and frontal plane gait curves and averaged gait curves from our reference database of 24 children with no gait pathology. Smaller GVS and GPS values indicate gait closer to normal. We also analyzed six kinematic and three kinetic variables that were considered relevant to evaluate the outcome after surgery and the impact of AFOs. These included ankle and knee angle at initial ground contact, maximum ankle dorsiflexion during stance and swing phases, stance minimum knee and hip flexion, ankle mean moment during loading response in 0% to 10% of the gait cycle, maximum

external dorsiflexion moment and maximum power generation in terminal stance. Temporal-spatial variables were non-dimensional gait velocity, step length and cadence, normalized by body height to account for growth between the pre- and postoperative evaluations.[21]

Statistical analysis

From every participant, data from three trials in each condition were averaged and used in the statistical analysis (SPSS 21 for Windows; IBM Corp., Armonk, New York). Data from both limbs were split and the affected and non-affected side analyzed separately. For kinematic and kinetic data analysis one gait cycle per trial was used whereas temporal-spatial data used all available gait cycles (three to four) within each trial. Distributions of the outcome variables and model residuals were tested using the Kolmogorov-Smirnov test. To account for possible correlation between repeated measurements made on the same individual, changes in each outcome variable were analyzed using linear mixed models.[22] The postoperative barefoot condition was defined as the reference category against which the preoperative barefoot and postoperative AFO conditions were compared, respectively. In the model, participants were defined as random effects, whereas fixed effects included gender, GMFCS level and AFO type (HAFOs *versus* GRAFOs) and fixed effects' interaction with each condition. Variance components were used as covariance structure and model selection was based on significance and Akaike's information criterion. The level of significance was set at $p < 0.05$.

Results

Participants

Individual characteristics, including surgical procedures, AFO types and gait patterns are presented in Table 1. GVS components and GPS are displayed in the movement analysis profile (MAP; Fig. 2). The mean age at time of surgery was 9.2 years (5 to 16.5) and mean time from surgery to postoperative 3DGA was 15.5 months (11 to 27). In all, 23 children underwent tendo-achilles lengthening and ten underwent gastrocnemius recession. Concomitant procedures were performed in ten children with tendo-achilles lengthening and two children with gastrocnemius recession. At the one-year postoperative 3DGA 23 children used HAFOs and ten children used GRAFOs, of which three were made of polypropylene and seven in carbon composite. The postoperative gait reports revealed that the multidisciplinary team recommended continued use of AFOs in 32 children (Table 1).

The most frequent gait pattern preoperatively was Type 2 (n = 22) whereas Type 1 was predominant postoperatively (n = 21). Two children deteriorated to a more severe gait pattern after surgery, nine were unchanged and 22 children had improved and showed a less severe gait pattern type. This included three who were within normal ranges after surgery and not classifiable.

Preoperative barefoot versus postoperative barefoot

The mean GPS on the affected side was significantly reduced from 12.6° (SD 3.1°) preoperatively to 10.1° (SD 2.4°) walking barefoot postoperatively (Table 2). Other significant changes were reduced ankle plantarflexion by 7.2° and knee flexion by 3.7° at initial contact, increased ankle maximum dorsiflexion by 14° in stance and 11° in swing, decreased minimum hip flexion and reduced cadence postoperatively. Significant changes in the kinetic variables included reduced external dorsiflexion moments during loading response and increased stance maximum dorsiflexion moment and ankle power generation (Table 2).

Table 1 General table with participant characteristics, type of surgery, type of ankle-foot orthosis (AFO) and recommendations regarding continued use

ID	Gender	Affected side	Age at surgery (yrs)	GMFCS	Preop pattern	Postop pattern	Surgery	Type of AFO	Recommendation AFO
1	M	Left	12.5	I	Type 4	Type 4	TAL, Psoas	HAFO	1
2	F	Left	6.5	I	Type 2	Type 1	GR	HAFO	1
3	F	Right	8	I	Type 2	Type 1	TAL,TibPT	GRAFO	1
4	F	Right	5.5	I	Type 2	Type 1	TAL	HAFO	1
5	M	Left	9.5	II	Type 2	Type 1	TAL	HAFO	1
6	F	Left	6	I	Type 2	Type 2	TAL	GRAFO	1
7	M	Right	7	I	Type 2	Type 1	TAL	HAFO	1
8	M	Right	16.5	I	Type 2	Type 1	GR	GRAFO	1
9	F	Left	13	I	Type 2	Type 1	TAL	HAFO	1
10	M	Right	15	II	Type 3	Crouch	TAL,TibPT, RFT	HAFO	1
11	F	Right	6.5	II	Type 3	Type 1	TAL, Psoas	HAFO	1
12	M	Right	8.5	I	Type 4	Type 1	TAL, Psoas, Hams	GRAFO	1
13	F	Right	13	II	Type 4	Type 1	GR, Psoas, Hams	GRAFO	1
14	M	Right	8.5	I	Type 2	Type 1	GR, TibAS	GRAFO	1
15	M	Left	7	I	Type 2	Type 1	TAL	HAFO	1
16	F	Right	10	I	Type 2	NC	TAL	HAFO	0
17	F	Right	11.5	II	Type 2	Type 1	TAL, Psoas	HAFO	1
18	F	Left	7	II	Type 2	Type 2	TAL	HAFO	1
19	F	Right	5	I	Type 2	Type 2	GR	HAFO	1
20	F	Left	13.5	I	Type 3	Type 1	TAL, Hams	GRAFO	1
21	M	Left	7	I	Type 2	Type 1	TAL	HAFO	1
22	M	Right	10.5	I	Type 2	NC	TAL	HAFO	1
23	M	Right	5.5	I	Type 3	Type 1	TAL	HAFO	1
24	F	Right	15	II	Type 1	Type 1	GR	HAFO	1
25	M	Left	6.5	II	Type 3	NC	TAL, Hams	GRAFO	1
26	M	Left	8	II	Type 2	Type 2	GR	HAFO	1
27	M	Left	12	II	Type 2	Type 1	GR	HAFO	1
28	F	Right	9	I	Type 1	Type 1	GR	GRAFO	1
29	F	Left	9	I	Type 2	Type 1	TAL	HAFO	1
30	M	Right	6	I	Type 2	Type 2	GR	HAFO	1
31	M	Right	12	II	Type 2	Crouch	TAL, FDO	GRAFO	1
32	F	Left	7.5	I	Type 3	Type 1	TAL, Hams	HAFO	1
33	F	Right	6	I	Type 2	Type 2	TAL	HAFO	1

Recommendation AFO: 0, discontinue; 1, continue

GMFCS, Gross Motor Function Classification System; Preop, preoperative; Postop, postoperative; NC, no classifiable gait deficit; TAL, tendo-achilles lengthening; P, psoas lengthening; GR, gastrocnemius recession; TibPT, tibialis posterior transfer; RFT, rectus femoris transfer; Hams, hamstrings lengthening; TibAS, tibialis anterior shortening; FDO, femoral derotation osteotomy; HAFO, hinged AFO; GRAFO, ground reaction AFO
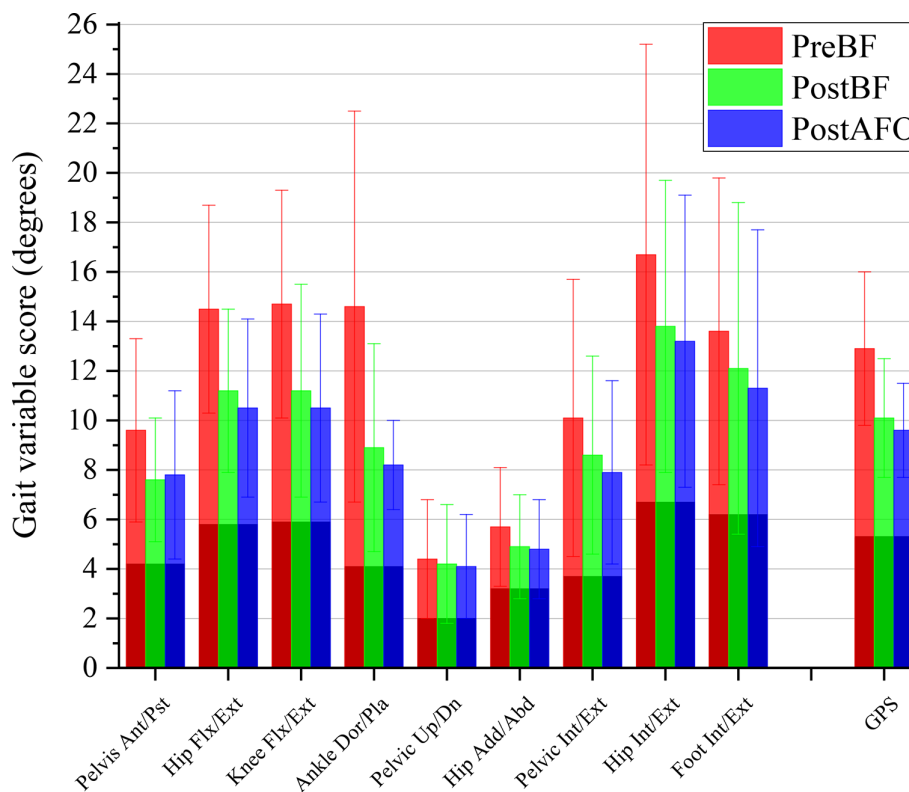
Fig. 2 Movement analysis profile (MAP) with Gait Variable Scores (GVS) and Gait Profile Scores (GPS)[20] in the three measurement conditions: preoperatively walking barefoot (PreBF), postoperatively walking barefoot (PostBF) and postoperatively walking with ankle-foot orthoses (PostAFO). Each column represents the root mean square difference across the gait cycle, averaged and with 1 SD for all participants (n = 33), with mean scores from our normal reference data (n = 24) in the darker base of each column (Ant, anterior; Pst, posterior; Flx, flexion; Ext, extension; Dor, dorsiflexion; Pla, plantarflexion; Dn, down; Add, adduction; Abd, abduction; Int, internal; Ext, external.

Postoperative AFO versus postoperative barefoot

Further reduction of the mean GPS to 9.6° (SD 1.9°) walking with AFOs *versus* barefoot was not significant (Table 2). With AFOs, the main improvements took place at initial contact with a significant reduction of ankle plantarflexion by 5.1° and knee flexion by 4.7°. The moments generated about the ankle joint in 0% to 10% of the gait cycle changed significantly from external dorsiflexion moment walking barefoot, to plantarflexion moments walking with AFOs. Ankle power generation was reduced when children were walking with AFOs. Both gait velocity and step length increased significantly, while cadence was reduced (Table 2).

Non-affected sides

Changes on the non-affected side walking barefoot postoperatively *versus* preoperatively included increased stance maximum dorsiflexion, knee and hip flexion, increased late stance ankle dorsiflexion moment and power generation (Table 3). In the AFO condition and with shoes on the non-affected side, significant changes included reduced knee flexion at initial contact, increased

plantarflexion moment in 0% to 10% of the gait cycle, reduced stance ankle maximum dorsiflexion and power generation compared with barefoot postoperatively.

Fixed factors

We found no significant group effect of gender or GMFCS level. The increase in swing phase maximum dorsiflexion in the postoperative AFO *versus* barefoot condition was significant, but only when AFO type was included in the model as a fixed effect (p = 0.015). Interaction effect between AFO type and the postoperative AFO condition indicated that stance ankle maximum dorsiflexion increased by 10.5° (p = 0.010) in children walking with HAFOs *versus* children walking with GRAFOs (see Supplemental Material). Children who used GRAFOs had an estimated 7.6° more knee flexion at initial contact preoperatively (p = 0.027) (Fig. 3).

Discussion

After surgery, improvements were seen for the GPS, key kinematic and kinetic variables on the affected sides. An

Table 2 Changes in gait variables on the affected side

	Affected side				Comparisons (p-value)	
	Reference data	PreBF	PostBF	PostAFO	PreBF *vs* PostBF	PostAFO *vs* PostBF
GPS (°)	5.3 (1.8)	12.6 (3.1)	10.1 (2.4)	9.6 (1.9)	**< 0.001**	0.247
Ankle						
Angle at initial contact (°)	-2.2 (3.1)	-18.4 (10)	-11.2 (8)	-6.1 (4.7)	**< 0.001**	**0.002**
Maximum dorsiflexion 30% to 60% GC (°)	13.2 (3.9)	-4.8 (12)	9.2 (8.3)	9.9 (7.1)	**< 0.001**	0.694
Maximum dorsiflexion in swing (°)	2.9 (3.1)	-16 (10.2)	-5.1 (8.6)	-2.3 (4.5)	**< 0.001**	0.098
Mean moment 0% to 10% GC (Nm/kg)	-0.1 (0.08)	0.47 (0.2)	0.3 2 (0.2)	-0.04 (0.2)	**0.001**	**< 0.001**
Maximum moment 30% to 60% GC (Nm/kg)	1.2 (0.18)	0.81 (0.2)	1.06 (0.2)	1.13 (0.2)	**< 0.001**	0.116
Maximum power 30% to 60% GC (W)	3 (0.9)	1.52 (0.6)	2.16 (0.6)	1.64 (0.7)	**< 0.001**	**< 0.001**
Knee						
Angle at initial contact (°)	4.9 (4.5)	15.1 (9)	11.4 (7.4)	6.7 (8.7)	**0.022**	**0.004**
Minimum flexion 30% to 60% GC (°)	1.6 (4.4)	4.4 (10.3)	3.5 (8.4)	0.5 (11)	0.613	0.074
Hip						
Minimum flexion 30% to 60% GC (°)	-11.7 (6.4)	-2.9 (7.7)	-5.2 (6.1)	-5.7 (6.6)	**0.038**	0.668
Temporal-spatial						
Non-dimensional velocity (vel/√Hxg)		0.40 (0.04)	0.39 (0.04)	0.45 (0.05)	0.089	
Non-dimensional step length (step/H)		0.33 (0.05)	0.31 (0.05)	0.34 (0.05)	0.075	
Velocity (m/sec)*	1.35 (0.09)	1.19 (0.17)	1.18 (0.17)	1.27 (0.16)		**0.011**
Step length (m)*	0.62 (0.06)	0.53 (0.08)	0.56 (0.07)	0.64 (0.07)		**< 0.001**
Cadence (step/min)	133 (8.7)	138 (21)	126 (18)	121 (14)	**< 0.001**	0.054

Values are presented as mean (SD)

Reference data, values from our laboratory database of 24 typically developing children

*pre- and postoperative comparisons were performed with non-dimensional values

p-values are from linear mixed model analyses. Bold letters indicate significant difference with p < 0.05

PreBF, preoperatively walking barefoot; PostBF, postoperatively walking barefoot; PostAFO, postoperatively walking with ankle-foot orthoses (AFOs); GPS, Gait Profile Score; GC, gait cycle; H, height; g, gravity

Table 3 Changes in gait variables on the non-affected side

	Non-affected side				Comparison (p-value)	
	Reference data	PreBF	PostBF	PostAFO	PreBF *vs* PostBF	PostAFO *vs* PostBF
GPS (°)	5.3 (1.8)	10.1 (1.9)	9.5 (1.9)	9.6 (1.7)	0.064	0.858
Ankle						
Angle at initial contact (°)	-2.2 (3.1)	-2.1 (4.7)	-2.3 (4.7)	-1.9 (5.6)	0.836	0.711
Maximum dorsiflexion 30% to 60% GC (°)	13.2 (3.9)	10.4 (6.4)	13.8 (5.9)	8.7 (6.1)	**0.002**	**< 0.001**
Maximum dorsiflexion in swing (°)	2.9 (3.1)	4.1 (4.8)	4.9 (4.7)	3.2 (5.1)	0.400	0.085
Mean moment 0% to 10% GC (Nm/kg)	-0.1 (0.08)	0.053 (0.15)	0.05 (0.15)	-0.06 (0.1)	0.809	**< 0.001**
Maximum moment 30% to 60% GC (Nm/kg)	1.2 (0.18)	1.21 (0.3)	1.34 (0.2)	1.4 (0.18)	**0.001**	0.185
Maximum power 30% to 60% GC (W)	3 (0.9)	3.62 (1.14)	4.05 (1)	3.54 (0.8)	**0.011**	**0.003**
Knee						
Angle at initial contact (°)	4.9 (4.5)	7.6 (6.2)	9.8 (6)	6.2 (6.3)	0.068	**0.004**
Minimum flexion 30% to 60% GC (°)	1.6 (4.4)	0.2 (7.1)	4.5 (8.6)	1.9 (7.2)	**0.001**	0.059
Hip						
Minimum flexion 30% to 60% GC (°)	-11.7 (6.4)	-11.8 (5.4)	-9.7 (6.4)	-10.3 (5)	**0.030**	0.543
Temporal-spatial						
Non-dimensional velocity (vel/√Hxg)		0.33 (0.05)	0.31 (0.06)	0.34 (0.06)	0.190	
Non-dimensional step length (stepl/H)		0.39 (0.04)	0.40 (0.04)	0.44 (0.05)	0.860	
Velocity (m/sec)*	1.35 (0.09)	1.19 (0.17)	1.18 (0.17)	1.27 (0.16)		**0.020**
Step length (m)*	0.62 (0.06)	0.52 (0.07)	0.57 (0.07)	0.62 (0.06)		**<0.001**
Cadence (step/min)	133 (8.7)	138 (21)	126 (18)	121 (14)	**<0.001**	0.053

Values are presented as mean (SD)

Reference data, values from our laboratory database of 24 typically developing children

*pre- and postoperative comparisons were performed with non-dimensional values

p-values are from linear mixed model analyses. Bold letters indicate significant difference with p < 0.05

PreBF, preoperatively walking barefoot; PostBF, postoperatively walking barefoot; PostAFO, postoperatively walking with ankle-foot orthoses (AFOs); GPS, Gait Profile Score; GC, gait cycle; H, height; g, gravity
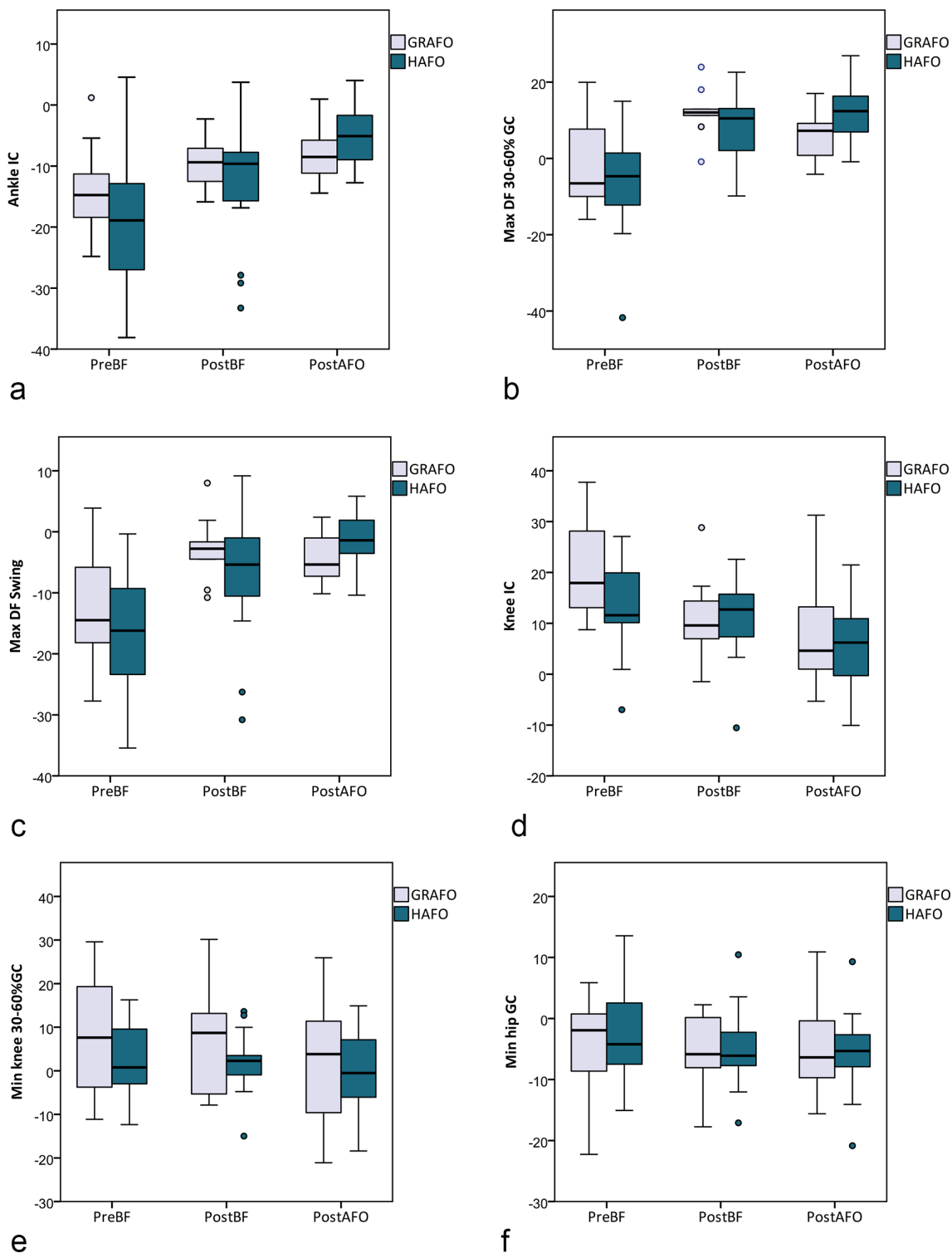
Fig. 3 Box-plots illustrating medians and interquartile ranges for all kinematic variables in the three conditions: preoperatively walking barefoot (PreBF), postoperatively walking barefoot (PostBF), postoperatively walking with ankle-foot orthoses (AFOs) (PostAFO) and clustered by AFO type: (**a**) ankle angle (°) at initial contact (IC), dorsiflexion (DF) positive and plantarflexion negative; (**b**) maximum (max) ankle DF (°) in 30% to 60% of the gait cycle (GC); (**c**) max ankle DF (°) in swing; (**d**) knee angle (°) at IC, knee flexion positive and knee extension negative; (**e**) minimum (min) knee flexion (°) in 30% to 60% GC; (**f**) min hip flexion (°) during GC (HAFO, hinged AFO; GRAFO, ground reaction AFO).

average GPS reduction of 2.5° walking barefoot was more than the previously defined minimal clinically important difference of 1.6°.[23] Still, the average postoperative GPS exceeded the normal range, indicating that the gait problems were not completely corrected. In swing and at initial contact the average ankle plantarflexion implied residual dynamic equinus or drop-foot, which contributed to ground contact with the forefoot and external dorsiflexion moment during loading response. Our results support previous research,[8,9] which stated that while triceps surae lengthening improves dynamic ankle range of movement; swing-phase drop-foot frequently persists, possibly due to inadequate activation of the dorsiflexors. The findings are less consistent with those of Tylkowski et al[7] who reported normalized ankle kinematics in both stance and swing phases after tendo-achilles lengthening in SUCP.

When the children walked with AFOs, the GPS was reduced and closer to normal, but not sufficiently to reach significance. Danino et al[24] questioned whether gait indices such as the GPS are sufficiently sensitive to measure AFO efficiency. In our belief it is an appropriate measure of gait quality, but because it is a summary score calculated across several kinematic components and entire gait cycles, single key variables should also be reported. Similar to previous studies comparing AFOs and barefoot gait in children with unilateral CP, we found improved pre-positioning for initial contact at the ankle[13-15] and knee,[14] and enhanced ankle moments during loading response.[14,15] Our study also confirmed decreased power generation resulting from restricted ankle movement in AFOs.[13-16] However, this decrease in push-off propulsion did not, as previously proposed,[16] have an adverse effect on gait velocity. Velocity increased and gait could be termed more energy-efficient since the children were taking longer steps at a lower cadence walking with AFOs compared with barefoot postoperatively (Table 2). After surgery, there was less knee flexor tightness which resulted in improved terminal swing reach and knee extension at initial contact. Additional knee extension with AFOs versus barefoot postoperatively could be explained by less activation of knee flexors secondary to improved ankle prepositioning in the orthoses. Supporting this theory, decreased electromyographic activity in biceps femoris has been found from mid- to terminal swing in children with SUCP walking with AFOs compared with barefoot.[25] Another explanation for additional knee extension is that the distally added weight of shoes and orthoses may increase knee angular momentum.

The most frequent orthoses used in our study were HAFOs, which allow free ankle dorsiflexion and unrestricted tibial progression over the stationary foot during stance. There is concern that this AFO type could over-lengthen the soleus muscle instead of treating gastroc-

nemius tightness.[26,27] Nevertheless, HAFOs are often preferred since they allow more freedom of movement. Also, children with unilateral CP are less at risk compared with bilaterally affected children of developing calcaneal gait secondary to over-lengthening of the triceps surae.[10,28] Our results confirmed increased ankle dorsiflexion in stance and swing phases with HAFOs, supporting their use to maintain functional triceps surae length and to allow range for tibialis anterior activation. Alternatively, preservation of ankle movement during stance and push-off power generation could be optimized using energy-storing carbon fibre springs[14] or joints with dynamic response to plantar- and dorsiflexion.[16]

After surgery, significant changes consistent with improvement were also seen in the non-affected limbs, indicating that changes on the affected side may influence gait bilaterally. Increased ankle dorsiflexion, knee and hip flexion in stance postoperatively suggest that compensatory vaulting, or limb extension, was no longer necessary to ensure opposite foot clearance during swing. However, in the AFO condition, stance ankle dorsiflexion decreased in the non-affected limb. This was surprising, since less compensatory vaulting should have been necessary when AFOs enhanced swing phase clearance on the affected side. One explanation is that the added shoe heel height may leave the ankle on the non-affected side more plantarflexed relative to the floor.

Recommendations to continue with AFOs were in most cases in accordance with the treatment algorithms defined by Rodda and Graham for the various gait types.[2] The main change in pattern after surgery was to Type 1 which requires an AFO to correct drop-foot.[2] However, one child with crouched gait pattern was recommended to continue with HAFO, which is not mechanically appropriate to apply an extension moment at the knee. Also, two children with normalized postoperative gait patterns and no apparent need for orthoses were recommended continued use of AFOs. Individual factors, such as foot deformities, pain or patient preferences which might have indicated use of orthoses, were not described or documented as part of the present study.

Borton et al[10] found that children with SUCP had a prevailing 38% risk of recurrent equinus deformity five to ten years after isolated calf muscle lengthening. Over ten years, Joo et al[11] found that 62.5% of the children with SUCP underwent repeated surgery to treat recurrent equinus. Risk factors for recurrent equinus were young age at surgery (≤ 8 years)[11] and male gender,[10] with higher incidence in unilateral versus bilateral CP.[10,11] While neither study assessed use of AFOs after surgery as a factor, both raised doubts concerning the preventive effect of AFOs. Instead, reoperation was recommended in cases where deformity recurred. It appears, however, more viable to prescribe conservative treatment, such as AFOs, in

cases where deformity is expected. Our study confirmed the functional efficacy of AFOs one-year postoperatively, particularly in improving swing phase clearance and prepositioning of the foot for initial contact. However, longer-term results are warranted to investigate the role of AFOs in reducing the risk of recurrence after surgery. Previously, maintenance of passive and active ankle range of movement with AFOs has been demonstrated over a one-year study period.[13] Hosl et al[27] found that after on average 16 weeks (SD 4) of AFO use, passive ankle dorsiflexion improved, but gastrocnemius fascicles shortened, and muscle volume decreased. Nevertheless, the adverse changes in muscle morphology were considered as outweighed by functional gains related to increased gait velocity and improved ankle kinematics with AFOs.

There were some limitations to this study. We focused on changes in the sagittal plane and evaluation of transverse and frontal planes was limited to the GVS elements of the GPS. The small number of participants may have influenced the power of the statistical analyses, particularly in analyses of fixed effects and grouped data. In some cases, the time from surgery to postoperative gait analysis was considerably delayed (up to 27 months) and 12 children received concomitant lower limb surgeries, which added heterogeneity to the sample and could have had an impact on the results. Best-practice guidelines recommended a shoes-only instead of barefoot control condition in studies evaluating the effect of AFOs.[29] However, many children experience fatigue during testing and barefoot data was therefore prioritized for comparison with preoperative data. Previously, no clear difference was found in barefoot *versus* shoes-only conditions.[14] Similar results were found by Böhm et al[30] who concluded that barefoot walking is sufficient as control condition when evaluating impacts of AFOs in children with CP. Since preoperative data of participants walking with AFOs was not available, it is difficult to precisely deduce in what way contractures and subsequent surgery influenced AFO efficacy. This is a limitation which should be addressed in future investigations. Further research should also include patient-reported outcomes to evaluate function and satisfaction with the orthoses.

Conclusion

The most clinically significant changes in gait were found between pre- and postoperative barefoot conditions. One year postoperatively, correction of residual drop-foot and improved prepositioning for initial contact at the ankle and knee were the main impacts of AFOs and could be considered indications for continued use.

COMPLIANCE WITH ETHICAL STANDARDS

ETHICAL STATEMENT

Ethical approval: The study was approved by the Regional Ethics Committee (REC; 2013/1242). All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional research committee and with the 1964 Helsinki Declaration and its later amendments or comparable ethical standards.

Informed consent: Informed consent was obtained from all individual participants included in the study.

ICMJE CONFLICT OF INTEREST STATEMENT

All authors declare that they have no conflict of interest.

AUTHOR CONTRIBUTIONS

IS: Study concept and design, data collection, analysis and interpretation, drafting article and final approval of submitted version.
HS: Interpretation of data, revising article and final approval of submitted version.
ABH: Data collection and interpretation, revising article and final approval of submitted version.
IH: Study concept and design, interpretation of data, revising article and final approval of submitted version.

SUPPLEMENTAL MATERIAL

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REFERENCES

1. **Dobson F, Morris ME, Baker R, Graham HK.** Unilateral cerebral palsy: a population-based study of gait and motor function. *Dev Med Child Neurol* 2011;53:429-435.

2. **Rodda J, Graham HK.** Classification of gait patterns in spastic hemiplegia and spastic diplegia: a basis for a management algorithm. *Eur J Neurol* 2001;8:98-108.

3. **Winters TF Jr, Gage JR, Hicks R.** Gait patterns in spastic hemiplegia in children and young adults. *J Bone Joint Surg [Am]* 1987;69-A:437-441.

4. **Gage JR.** In: Hart HM, ed. *The treatment of gait problems in cerebral palsy.* London, UK: Mac Keith Press, 2004.

5. **Graham HK, Baker R, Dobson F, Morris ME.** Multilevel orthopaedic surgery in group IV spastic hemiplegia. *J Bone Joint Surg [Br]* 2005;87-B:548-555.

6. **Rutz E, Passmore E, Baker R, Graham HK.** Multilevel surgery improves gait in spastic hemiplegia but does not resolve hip dysplasia. *Clin Orthop Relat Res* 2012;470:1294–1302.

7. **Tylkowski CM, Horan M, Oeffinger DJ.** Outcomes of gastrocnemius-soleus complex lengthening for isolated equinus contracture in children with cerebral palsy. *J Pediatr Orthop* 2009;29:771–778.

8. **Lofterod B, Terjesen T.** Local and distant effects of isolated calf muscle lengthening in children with cerebral palsy and equinus gait. *J Child Orthop* 2008;2:55–61.

9. **Lofterod B, Fosdahl MA, Terjesen T.** Can persistent drop foot after calf muscle lengthening be predicted preoperatively? *J Foot Ankle Surg* 2009;48:631–636.

10. **Borton DC, Walker K, Pirpiris M, Nattrass GR, Graham HK.** Isolated calf lengthening in cerebral palsy. Outcome analysis of risk factors. *J Bone Joint Surg [Br]* 2001;83-B:364–370.

11. **Joo SY, Knowtharapu DN, Rogers KJ, Holmes L Jr, Miller F.** Recurrence after surgery for equinus foot deformity in children with cerebral palsy: assessment of predisposing factors for recurrence in a long-term follow-up study. *J Child Orthop* 2011;5:289–296.

12. **Kay RM, Dennis S, Rethlefsen S, Skaggs DL, Tolo VT.** Impact of postoperative gait analysis on orthopaedic care. *Clin Orthop Relat Res* 2000;374:259–264.

13. **Buckon CE, Thomas SS, Jakobson-Huston S, Sussman M, Aiona M.** Comparison of three ankle-foot orthosis configurations for children with spastic hemiplegia. *Dev Med Child Neurol* 2001;43:371–378.

14. **Desloovere K, Molenaers G, Van Gestel L, et al.** How can push-off be preserved during use of an ankle foot orthosis in children with hemiplegia? A prospective controlled study. *Gait Posture* 2006;24:142–151.

15. **Romkes J, Brunner R.** Comparison of a dynamic and a hinged ankle-foot orthosis by gait analysis in patients with hemiplegic cerebral palsy. *Gait Posture* 2002;15:18–24.

16. **Wren TA, Dryden JW, Mueske NM, et al.** Comparison of 2 orthotic approaches in children with cerebral palsy. *Pediatr Phys Ther* 2015;27:218–226.

17. **Palisano R, Rosenbaum P, Walter S, et al.** Development and reliability of a system to classify gross motor function in children with cerebral palsy. *Dev Med Child Neurol* 1997;39:214–223.

18. **Davis RB, Ounpuu S, Tyburski D, Gage JR.** A gait analysis data-collection and reduction technique. *Hum Mov Sci* 1991;10:575–587.

19. **Baker R.** The conventional gait model. In: Hart HM, ed. *Measuring walking: A Handbook of Clinical gait Analysis.* London, UK: Mac Keith Press, 2013:43–44.

20. **Baker R, McGinley JL, Schwartz MH, et al.** The gait profile score and movement analysis profile. *Gait Posture* 2009;30:265–269.

21. **Stansfield BW, Hillman SJ, Hazlewood ME, et al.** Normalisation of gait data in children. *Gait Posture* 2003;17:81–87.

22. **Thoresen M and Gjessing HK.** Mixed models. In: Veierød MB, Lydersen S and Laake P, (eds.). *Medical statistics in clinical and epidemiological research.* 1st ed. Oslo, Norway: Gyldendal Norsk Forlag, 2012:231–273.

23. **Baker R, McGinley JL, Schwartz M, et al.** The minimal clinically important difference for the Gait Profile Score. *Gait Posture* 2012;35:612–615.

24. **Danino B, Erel S, Kfir M, et al.** Are gait indices sensitive enough to reflect the effect of ankle foot orthosis on gait impairment in cerebral palsy diplegic patients? *J Pediatr Orthop* 2016;36:294-298.

25. **Romkes J, Hell AK, Brunner R.** Changes in muscle activity in children with hemiplegic cerebral palsy while walking with and without ankle-foot orthoses. *Gait Posture* 2006;24:467–474.

26. **Owen E.** The importance of being earnest about shank and thigh kinematics especially when using ankle-foot orthoses. *Prosthet Orthot Int* 2010;34:254–269.

27. **Hosl M, Bohm H, Arampatzis A, Doderlein L.** Effects of ankle-foot braces on medial gastrocnemius morphometrics and gait in children with cerebral palsy. *J Child Orthop* 2015;9:209–219.

28. **Wren TA, Rethlefsen S, Kay RM.** Prevalence of specific gait abnormalities in children with cerebral palsy: influence of cerebral palsy subtype, age, and previous surgery. *J Pediatr Orthop* 2005;25:79–83.

29. **Ridgewell E, Dobson F, Bach T, Baker R.** A systematic review to determine best practice reporting guidelines for AFO interventions in studies involving children with cerebral palsy. *Prosthet Orthot Int* 2010;34:129–145.

30. **Böhm H, Matthias H, Braatz F, Döderlein L.** Effect of floor reaction ankle-foot orthosis on crouch gait in patients with cerebral palsy: what can be expected? *Prosthet Orthot Int* 2018;42:245–253.