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Postoperative changes in vertical ground reaction forces, walking barefoot and with ankle-foot orthoses in children with Cerebral Palsy

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ABSTRACT

Background: Children with cerebral palsy often have problems to support the body centre of mass, seen as increased ratio between excessive vertical ground reaction forces during weight acceptance and decreased forces below bodyweight in late stance. We aimed to examine whether increasing ankle range of motion through surgery and restraining motion with ankle-foot orthoses postoperatively would have impact on the vertical ground reaction force in weight acceptance and late stance.

Methods: Ground reaction forces were recorded from 24 children with bilateral and 32 children with unilateral cerebral palsy, each measured walking barefoot before and after triceps surae lengthening. Postoperatively, the children were also measured walking with ankle-foot orthoses. Changes in vertical ground reaction forces between the three conditions were evaluated with functional curve and descriptive peak analyses; accounting for repeated measures and within-subject correlation.

Findings: After surgery, there were decreased vertical ground reaction forces in weight acceptance and increased forces in late stance. Additional significant changes with ankle-foot orthoses involved increased vertical forces in weight acceptance, and in late stance corresponding to bodyweight (bilateral, from 92% to 98% bodyweight; unilateral, from 94% to 103% bodyweight) postoperatively.

Interpretation: Our findings confirmed that surgery affected vertical ground reaction forces to approach more normative patterns. Additional changes with ankle-foot orthoses indicated further improved ability to support bodyweight and decelerate centre of mass in late stance.

1. Introduction

Reduced motor function in children with cerebral palsy (CP) may affect adequate body centre of mass (CoM) support and stability during stance, which are important prerequisites of functional human gait.(Gage, 2004; Perry and Schoneberger, 1992) CoM support can be expressed by the forces exerted on the ground and the resulting vertical component of the ground reaction force (vGRF). In normal gait, the vGRF has a characteristic M-shape with two peaks, each of approximately equal height, about 120% and 110% of bodyweight, respectively (Fig. 1, blue line).(Giakas and Baltzopoulos, 1997; Stansfield et al., 2001; White et al., 1999) The first peak (FZ_1) occurs after loading response with weight acceptance in early stance phase of the gait cycle.(White et al., 1999) The second peak (FZ_2) is associated with push-off in late single stance(White et al., 1999) when the trailing limb decelerates downwards motion of the CoM.(Adamczyk and Kuo, 2009; Gibbs et al., 2014)

Children with CP often have difficulties to support and decelerate the CoM during late stance. This can be observed as a decrease of the FZ_2 below bodyweight,(White et al., 1999; Williams et al., 2011) which often results in rapid weight transfer to the leading limb, enlarged forces (FZ_1) during weight acceptance (Fig. 1, red line) and excessive load on muscles, ligaments and joints. Williams et al. named the occurrence of an increased FZ_1 and reduced FZ_2 as ‘Ben Lomonding’ since the vGRF curve has a similar shape to the Scottish mountain.(Williams et al., 2011) They categorised 74 ambulating children with spastic CP and

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found Ben Lomonding in 87%, whereas 66% had difficulty in generating an FZ_2 above bodyweight implying that the child is about to 'collapse', termed CoM deceleration deficiency. It was therefore claimed that clinical interventions to treat gait problems in children with CP should be aimed at improving their ability to support CoM by generating an adequate FZ_2.

In normal gait, the ankle plantarflexor muscles are the main factor to support CoM and increase vGRF magnitudes in late stance.(Anderson and Pandy, 2003) Eccentric work during 2nd rocker brings the GRF more distal on the foot and anterior to the knee joint centre, producing an external knee extension moment known as the plantarflexion-knee extension couple.(Anderson and Pandy, 2003; Gage, 2004) Third rocker plantarflexion elongates the lower limb, is the most important determinant to reduce CoM displacement(Della Croce et al., 2001) and crucial for efficient step-to step transition during gait.(Adamczyk and Kuo, 2009) These mechanisms rely on a stable foot lever arm, sufficient range of motion, adequate muscular timing and strength, all of which may be compromised in CP.(Gage, 2004) Weak or overlengthened triceps surae reduce the ankle joint stability and torque, whereas equinus contracture may decrease the area of support and range for plantarflexion during push-off. Massaad et al.(Massaad et al., 2004) confirmed that in children with CP there was 1.3 to 1.6 times greater vertical CoM displacement than in typically developing children, indicating a support deficit which was mainly associated with an equinus gait pattern. Surgical intervention which increased ankle dorsiflexion resulted in less abnormal CoM displacement, as calculated from the vGRF.(Massaad et al., 2006) However, in many cases with CP, the plantarflexors may be weakened after surgical release, with reduced ability to stabilise the ankle and generate knee extension moments.(Borton et al., 2001)

Ankle-foot orthoses (AFOs) are routinely used after lower limb surgery to provide adequate mechanical support during the rehabilitation period and prevent recurrence of deformities.(Skaaret et al., 2018; Skaaret et al., 2019; Vuillermin et al., 2011) Reviewing the prerequisites of normal gait, an important purpose of AFOs in ambulating children with CP is to provide stability in stance.(Gage, 2004) Adequately aligned AFOs have been advocated to reduce CoM deceleration deficiency, (Williams et al., 2011) and walking with AFOs has previously been associated with increased FZ_2 in spastic CP.(Lam et al., 2005) Still, there is concern that restriction of ankle motion in AFOs may inhibit ankle push-off and CoM deceleration in late stance.(Desloovere et al., 2006; Huang et al., 2015; Vistamehr et al., 2014)

A conventional method to study changes in GRF data has been to extract discrete scalars, such as minimum or maximum (peak) values. (Jacobs et al., 1972; White et al., 1999; Williams et al., 2011) The vGRF has been found to be the most consistent and reproducible kinetic outcome variable(Kadaba et al., 1989; White et al., 1999; White et al., 2005) and FZ_2 the least variable peak value,(White et al., 1999) which was not affected by stature or changes in gait speed in typically developing children.(Stansfield et al., 2001) However, for pathological gait vGRF curves may be more complex, causing difficulties in defining peak values.(Jacobs et al., 1972)

An alternative approach is to examine information from entire curves. Frequency domain analysis throughout stance has been shown to reduce the variability of vertical and horizontal GRF components in unimpaired(Giakas and Baltzopoulos, 1997; White et al., 2005) and CP (White et al., 2005) gait. Transforming gait curves to continuous functions of time has previously demonstrated benefits over more traditional methods to assess kinematic gait curves.(Roislien et al., 2009) More recently, Zhang et al. proposed a functional mixed-effects analysis to study kinematic gait curves in children with CP walking with and without AFOs (Zhang et al., 2017). Such approaches would enable comparisons of vGRF curves with greater reliability,(White et al., 1999) before and after intervention, over the entire and parts of the stance phase, and corresponding to the periods where FZ_1 and FZ_2 occur.

Knowledge of changes in the vGRF might be important to improve our understanding of how patient's loading patterns and ability to support bodyweight are affected following interventions to treat gait problems. We found there were limited evidence and thus a need to evaluate how relevant clinical interventions such as surgery and orthoses influence the vGRF magnitude, stance stability and CoM support in children with CP. In the present study we aimed to evaluate the impact of surgical triceps surae lengthening to treat ankle equinus and postoperative AFOs in children with CP, using the vGRF as outcome measure. Our objective was to study changes in curve shape and magnitude through stance while accounting for within-subject correlation in repeated measures, between pre- and postoperative, barefoot and

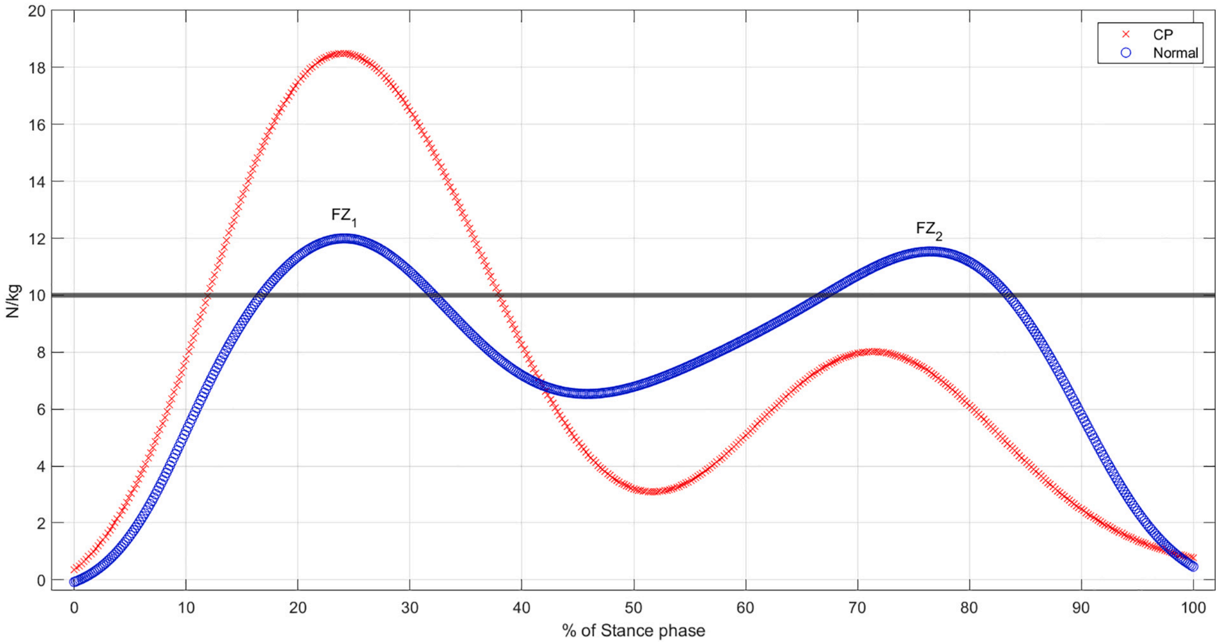


Fig. 1. Example of differences in vertical ground reaction force patterns in a child with unimpaired gait (blue) and a child with bilateral spastic cerebral palsy (red). Forces are normalized to bodyweight (N/kg) and time-normalized from 0 to 100% of stance phase. The horizontal line at 10 N/kg illustrates 100% bodyweight. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

AFO walking. Our hypothesis was that increasing the ankle range of motion through triceps surae lengthening and controlling motion with AFOs would cause significant changes on the vGRF indicating improved CoM support and stability in stance.

2. Methods

2.1. Participants

The study was based on three repeated measures in a cohort of children with preoperative baseline data, who were initially part of two other studies(Skaaret et al., 2018; Skaaret et al., 2019) to compare walking with AFOs versus barefoot after lower limb surgery. The study was approved by the Regional Committee for Medical Research Ethics –South East Norway (REC; 2013/1242). We included children who underwent triceps surae lengthening to treat ankle equinus, used AFOs postoperatively and were ambulatory in level I-II of the gross motor function classification system (GMFCS).(Palisano et al., 1997) Fifty-six patients; 32 (16 girls and 16 boys) with unilateral, and 24 (8 girls and 16 boys) with bilateral spastic CP, were eligible for inclusion and gave written informed consent. Their main demographic information is presented in Table 1.

Equinus surgery included gastrocnemius recession ($n = 24$) or tendoachilles lengthening ($n = 32$), as recommended in the children's preoperative three-dimensional gait analyses. AFOs and shoes were fitted after removal of postoperative splints, and children instructed to use the orthoses all day until the postoperative gait assessment about one year after surgery. The types of AFOs used in the current study included 33 children with hinged AFOs and 23 with solid AFOs. The hinged AFOs allowed dorsiflexion and restricted plantarflexion to assist foot clearance in swing. Solid AFOs restricted ankle motion entirely and were mainly employed in cases of weak triceps surae and crouch gait patterns.(Rodda and Graham, 2001)

2.2. Data collection

Kinematic, kinetic and temporal-spatial data were collected using a Vicon system (Vicon Motion systems Ltd., Oxford, UK) with six infrared cameras (MXF40), Plug-in-Gait model and marker protocol.(Davis et al., 1991; Kadaba et al., 1990) With AFOs, joint width measures were adjusted and markers were positioned on the devices, aligned with segment and motion axes. Ground reaction forces were collected at 1000 Hz using three strain-gauge force plates (AMTI OR6–7, Advanced Mechanical Technology Inc., Watertown, MA, USA) embedded level with the floor in a 12-m walkway. The children walked with a self-selected speed until at least three trials with clean left and right foot strikes on separate force plates were obtained. Gait events, i.e. initial contact and foot off were determined on the force plates and the vGRF curves inspected for consistency in Vicon Nexus software. Force plate data were noise-reduced using a 4th order zero-lag low-pass Butterworth filter with a cut-off frequency of 5 Hz.

Gait data were collected under three different conditions: 1) Preoperatively walking barefoot (PreBF), 2) Postoperatively walking barefoot (PostBF), and 3) Postoperatively walking with AFOs (PostAFO). Postoperatively, participants were first measured walking barefoot and subsequently with AFOs.

2.3. Data analysis

To retain independence, data from one limb per participant were used in the statistical analyses. This implied the affected side in children with unilateral CP; the most affected, or left side when no side difference was found, in children with bilateral CP.

2.3.1. vGRF curve analysis

For analysis of entire vGRF curves a single representative trial containing valid force plate data was selected from each participant and condition and exported to ASCII format, In MatLab (version R2018a, Mathworks, Natick, MA, USA) vGRF data were normalized to bodyweight (N/kg) and time-normalized from 0 to 100% of stance phase.

To analyze the outcome as a smooth function of time, normalized vGRF data were fitted using generalized additive models,(Wood, 2011; Wood, 2017; Wood et al., 2016) R statistical programming language and *mgcv* library with cubic spline basis set.(Team, 2019) Repeated measures of subjects were accounted for by inclusion of subject-specific random smooth effects whose associated smoothing parameters were assumed to be uniform across subjects. Statistical significance of shape and intercept was assessed with F-tests, to examine how similar two curves were to one another relative to estimates of background variability. The hypotheses tested refer to similarity of the smooth curves in the interval being modeled. For the current study, the fitted vGRF curves were examined across the 0–100% time interval (T) of stance phase, denoted T(Stance); in the interval of the first peak in 15–35% of stance, denoted $T(FZ_1)$; and the interval of the second peak in 65–85% of stance, denoted $T(FZ_2)$.

To evaluate changes on the vGRF following triceps surae surgery we tested PostBF relative to PreBF. To evaluate changes walking with AFOs versus barefoot postoperatively we tested PostAFO relative to PostBF. Comparisons between these condition pairs were tested with the model:

$\mathrm{vGRF} = s(\text{time} \mid \text{population average}) + s(\text{time} \mid \text{individual effect}) + s(\text{time} \mid \text{condition})$, where s() denotes smooth function(s) of time for the indicated strata using a cubic spline basis, and time denotes the interval (T) being examined. This model was chosen based on superiority of model fitness using the Akaike and Bayesian information criteria. To assure identifiability of each term and generalizability of the model, we limited the flexibility of the individual and condition smooth term effects. The smoothing parameter of the model was estimated via generalized cross validation.

Besides testing effects of condition, covariates comprised topographical CP type (unilateral versus bilateral), which was tested in each condition stratum. Within the PreBF, PostBF, and PostAFO conditions, we therefore fit the model:

$\mathrm{vGRF} = s(\text{time} \mid \text{population average}) + s(\text{time} \mid \text{individual effect}) + s(\text{time} \mid \text{CP type})$, where notation is used as previously.

2.3.2. Descriptive variables

Descriptive variables were averaged across three trials in each condition. To quantify changes in FZ_1 and FZ_2 magnitudes, we used the highest force values in 15–35% and 65–85% of stance, respectively, and normalized to bodyweight (N/kg). To describe change in dynamic ankle range of motion between conditions we calculated maximum ankle dorsiflexion in late stance. Walking speed was normalized to non-dimensional quantities to account for changes in body height pre-to-

Table 1
Demographics of participants with bilateral and unilateral cerebral palsy.

	n(F)	Age, Pre (years)	Age Post (years)	Mass Pre (kg)	Mass Post (kg)	Height Pre (cm)	Height Post (cm)	HAFO /SAFO
Bilateral	24 (8)	10.3 (2.6)	12.3 (2.7)	34.1 (9.7)	42.5 (10.4)	138.8 (16.4)	149.6 (13.5)	10/14
Unilateral	32 (16)	8.5 (3.1)	10.5 (3.2)	31.5 (15.9)	38.5 (17.6)	132.6 (20.4)	143.1 (17.5)	23/9

Values are presented as mean ± standard deviation (SD).
N, number of participants; F, female; Pre, preoperative gait analysis; Post, postoperative gait analysis; HAFO, hinged ankle-foot orthoses; SAFO, solid ankle-foot orthoses.

postoperatively using the formula Non-dimensional speed(m s^{-1}) = speed/$\sqrt{h\,g}$, where h is the body height (m) and g is the acceleration due to gravity (9.81 m s^{-2}).(Stansfield et al., 2003) Kolmogorov-Smirnov tests confirmed normally distributed residuals whereby changes in descriptive variables between conditions were investigated using linear mixed models(Thoresen and Gjessing, 2012) (SPSS 21 for Windows, IBM corp. Armonk, NY, USA). PostBF was the reference category against which PreBF and PostAFO conditions were compared, respectively. Individual deviations from the population average trend were tested using subject-specific random effects. Since some vGRF peak values have been found sensitive to walking speed,(Stansfield et al., 2001) we also evaluated the correlation of FZ_1 and FZ_2 with non-dimensional speed. (Stansfield et al., 2003)

The level of significance for all hypothesis tests was set at $P < .05$.

3. Results

3.1. vGRF curve analysis

CP type (bilateral versus unilateral) yielded highly significant differences in the vGRF curve across T(Stance); in PreBF ($P < .001$), PostBF ($P < .001$) and PostAFO ($P < .001$) conditions. We therefore performed comparisons between conditions separately in bilateral and unilateral CP groups. Results of the curve analyses are illustrated in Figs. 2 and 3.

3.1.1. Impact of surgery; PostBF versus PreBF

In the bilateral CP group significant changes were found across the entire period of T(stance) ($P < .001$) with reduced forces in T(FZ_1) ($P < .001$) and increased forces in T(FZ_2) ($P < .001$) postoperatively (Fig. 2a). Similar significant changes were also found in the unilateral CP group across T(stance) ($P < .001$), T(FZ_1) ($P < .001$) and T(FZ_2) ($P = .013$) (Fig. 2b).

3.1.2. Impact of walking with AFOs; PostAFO versus PostBF

In both the bilateral and unilateral CP groups differences between conditions were significant across T(stance) ($P < .001$) and with curves indicating higher forces in T(FZ_1) ($P < .001$) walking with AFOs compared to barefoot postoperatively (Fig. 3a–b). In T(FZ_2) differences were also highly significant for both groups ($P < .001$). However, with AFOs increased vGRF magnitudes were more distinct in the unilateral group (Fig. 3b).

All tests of curve shape and intercept (magnitude) between conditions were significant. Significant differences were found even when curves from different conditions seemed highly similar, as seen in Fig. 2b and T(FZ_2) interval. Although the difference in shape was less distinct ($P = .01$), narrow confidence interval indicated high statistical precision of the effect estimate. Generally, all confidence intervals for the T(FZ_2) were narrower than those for the T(FZ_1) suggesting higher precision and less variation in the change occurring in late compared to early stance.

3.2. Descriptive results

Results from descriptive analyses are presented in Table 2. Linear mixed model analyses and graphs illustrating the mean (1SD) vGRF across stance phase of the uni- and bilateral groups in PreBF, PostBF and PostAFO conditions may be found in Supplements.

In the bilateral CP group peak FZ_1 decreased from an average 124 to 104% bodyweight in PostBF versus PreBF ($P < .001$) (Table 2 and Supplements). The mean FZ_2 was below bodyweight with no significant difference ($P = .339$). In children with unilateral CP there was no significant difference in FZ_1 between PostBF and PreBF conditions ($P = .072$), whereas FZ_2 increased from 88 to 94% bodyweight postoperatively ($P = .007$).

Comparing PostAFO with PostBF in the bilateral group, FZ_1 increased from an average 104 to 115% bodyweight ($P = .007$) and FZ_2 increased from 92 to 98% bodyweight ($P = .001$). In the unilateral group FZ_1 increased from 113 to 125% bodyweight ($P = .005$) and FZ_2 from 94 to 103% bodyweight ($P < .001$). (Table 2 and Supplements).

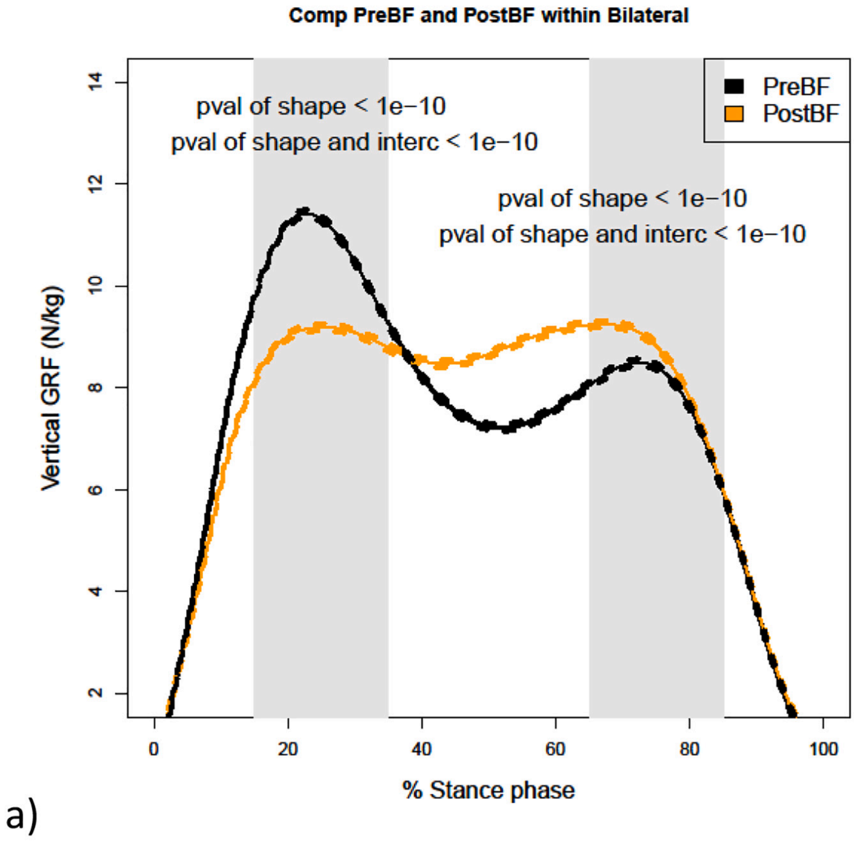
In both bilateral and unilateral groups there was ankle equinus preoperatively, seen as negative maximum ankle dorsiflexion values in PreBF, and enhanced ankle range of motion in PostBF ($P < .001$) (Table 2). Maximum ankle dorsiflexion was reduced in PostAFO versus PostBF for the bilateral ($P = .016$) whereas no difference was found in the unilateral group. Walking speed decreased in PostBF versus PreBF ($P = .009$, bilateral; $P = .088$ unilateral) and increased in PostAFO versus PostBF ($P = .047$, bilateral; $P = .013$ unilateral). Across groups we found a moderate-to-strong positive correlation between non-dimensional speed and FZ_1 (PreBF $r = 0.45$, $P < .001$), PostBF $r = 0.68$ $P < .001$, PostAFO $r = 0.67$ $P < .001$), whereas the correlation between speed and FZ_2 was weak and insignificant.

4. Discussion

After surgery, vGRF decreased in weight acceptance and increased in late stance. Additional changes with AFOs versus barefoot postoperatively involved increased vGRF in weight acceptance and in late stance.

Preoperative graphs (Fig. 2) and descriptive values indicated an enlarged ratio between excessive vGRF during weight acceptance and decreased forces below bodyweight in late stance. The pattern is consistent with deceleration deficiency and Ben Lomonding which has been described as a typical gait pattern in children with CP.(Williams et al., 2011) Although the average FZ_1 did not exceed normative ranges (Giakas and Baltzopoulos, 1997; Stansfield et al., 2001) standard deviations revealed variability and a higher frequency of excessive forces in weight acceptance. However, similar variability has been found in normal gait.(Stansfield et al., 2001) After triceps surae lengthening we found decreased force magnitudes during weight acceptance and increased forces in late stance. Since the vGRF curve reached more normative patterns postoperatively, we may infer that enhanced ankle dorsiflexion and plantarflexion range improved the children's ability to decelerate CoM in late stance. Similar assumptions were made by Massaad et al.(Massaad et al., 2006) where surgical treatment of equinus gait in a limited sample of seven children with spastic CP was related to a decrease in vertical CoM displacement. Nevertheless, we found that the average late stance vGRF was less than bodyweight, suggesting remaining CoM deceleration deficiency walking barefoot postoperatively. Reasons could be overlengthened and/or weak triceps surae postoperatively, especially in the bilateral cases as indicated by their range of maximum ankle dorsiflexion.

Walking with AFOs, results from curve and peak analyses confirmed higher forces in both weight acceptance and late stance periods compared to barefoot postoperatively. An explanation for enlarged vGRF in weight acceptance may be increased walking speed with AFOs. The FZ_1 increased with increasing speed, while there was no positive correlation between speed and FZ_2. In agreement, a longitudinal study of typically developing children found that FZ_1 amplified with increased speed, whereas FZ_2 showed consistency and little variability.(Stansfield et al., 2001) Similarly, the magnitude of vertical weight acceptance forces, termed 'collision', during step-to step transition has been found to increase with speed in dynamic walking models.(Adamczyk and Kuo, 2009) Using the definition of deceleration deficiency, a clinically important improvement would imply an increase of late stance vGRF ≥ bodyweight. Descriptive analysis confirmed increased vGRF equivalent to bodyweight, supporting our hypothesis that control of ankle motion with AFOs improves CoM deceleration and support in late stance. However, late stance forces improved most in the children with unilateral CP where maximum ankle dorsiflexion with AFOs resembled the barefoot condition. In this group hinged AFOs were predominant ($n = 23$) which allowed a greater range of motion. Hence, this AFO type may be beneficial to increase late stance vGRF, provided triceps surae strength and plantarflexion-knee extension coupling is adequate.



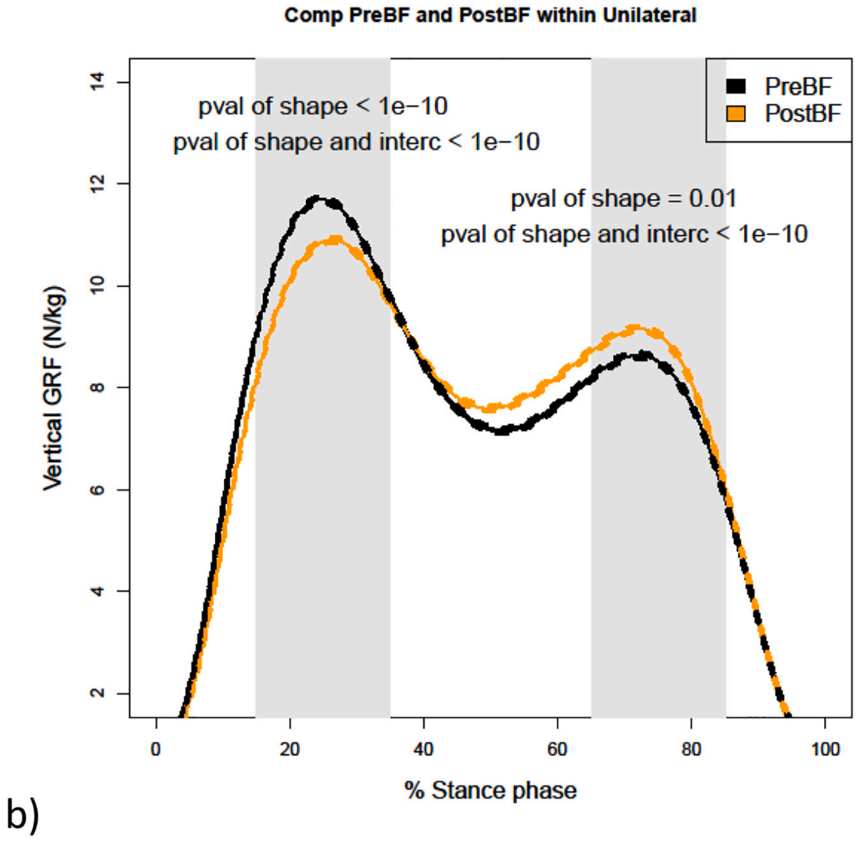


Fig. 2. Functional curve analysis comparing Preoperative barefoot (PreBF; black) and Postoperative barefoot (PostBF; orange) conditions in 0–100% stance for a) bilateral group, and b) unilateral group. The difference in the curves shown is an average (solid) condition effect with confidence interval (dashed) over the population being modeled and controlling for individual variation. Grey bars indicate *P* values for tests of curve shape and intercept (magnitude) in subintervals 15–35% stance; T(FZ_1), and 65–85% stance; T(FZ_2).

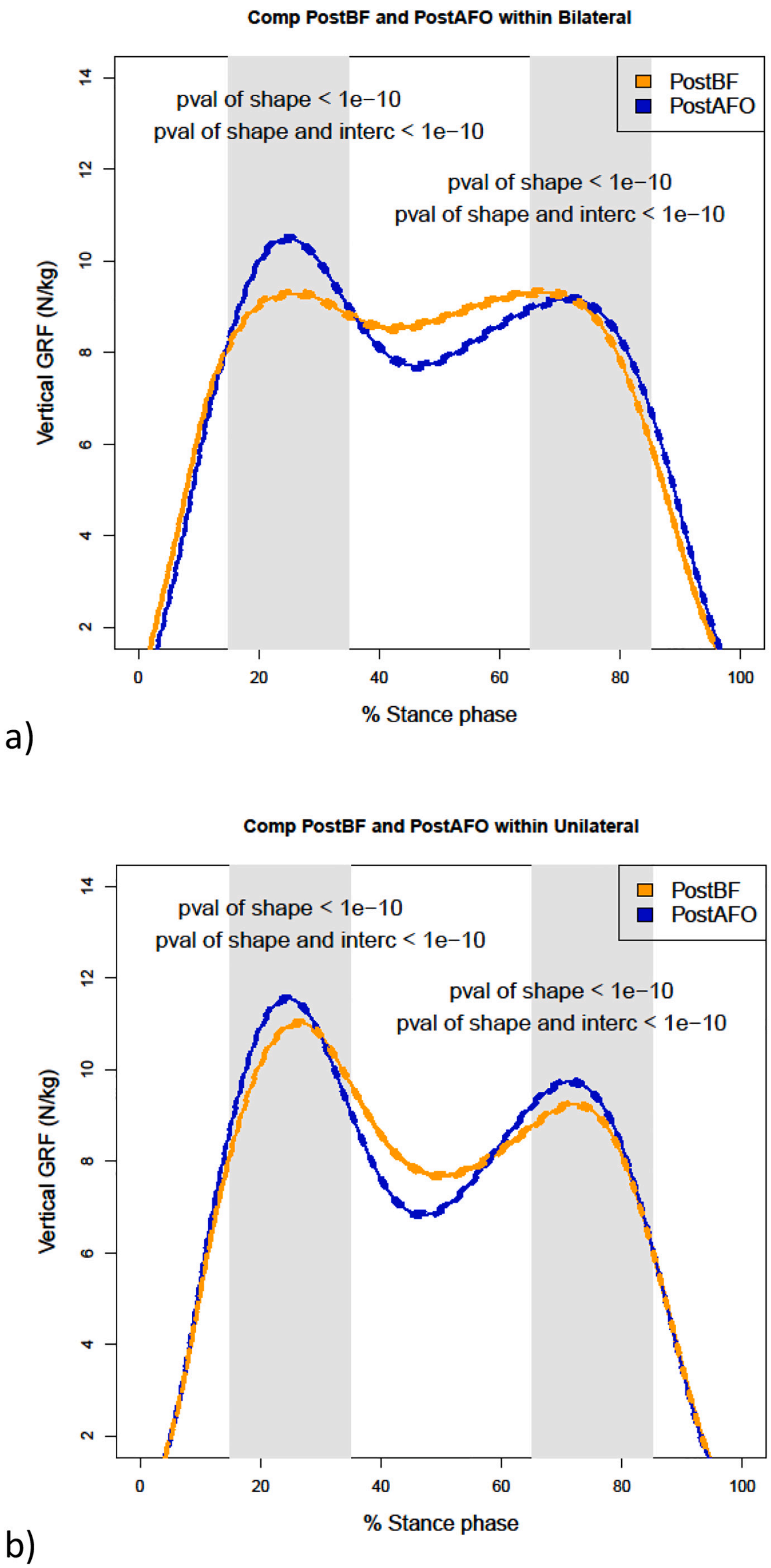


Fig. 3. Functional curve analysis comparing Postoperative AFO (PostAFO; blue) and Postoperative barefoot (PostBF; orange) conditions in 0–100% stance for a) bilateral group, and b) unilateral group. The difference in the curves shown is an average (solid) condition effect with confidence interval (dashed) over the population being modeled and controlling for individual variation. Grey bars indicate P values for tests of curve shape and intercept (magnitude) in subintervals 15–35% stance; T(FZ_1), and 65–85% stance; T(FZ_2). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 2

Results from analyses of descriptive variables.

	Bilateral $n = 24$			Comparisons *p* value	
	PreBF	PostBF	PostAFO	PostBF vs PreBF	PostAFO vs PostBF
FZ_1 (N/kg)	12.38 (2.5)	10.42 (1.3)	11.49 (1.7)	<0.001	0.007
FZ_2 (N/kg)	8.99 (0.8)	9.16 (0.7)	9.79 (0.6)	0.339	0.001
Max ankle DF stance phase (°)	−5.54 (11.6)	13.5 (6.3)	7.8 (4.6)	<0.001	0.016
ND speed (speed/ $\sqrt{Hxg}$)	0.28 (0.07)	0.25 (0.05)	0.28 (0.6)	0.009	0.047

	Unilateral n = 32			PostBF vs PreBF	PostAFO vs PostBF
	PreBF	PostBF	PostAFO		
FZ_1 (N/kg)	11.82 (1.6)	11.29 (1.6)	12.46 (1.9)	0.072	0.001
FZ_2 (N/kg)	8.87 (1.1)	9.45 (0.8)	10.31 (0.8)	0.007	<0.001
Max ankle DF stance phase (°)	−4.2 (10.5)	9.8 (8.5)	9.9 (6.9)	<0.001	0.956
ND speed (speed/ $\sqrt{Hxg}$)	0.33 (0.05)	0.31 (0.05)	0.34 (0.05)	0.088	0.013

Values are presented as mean ± standard deviation (SD). P values are from linear mixed model analyses. Bold letters indicate significant differences with $P < .05$. PreBF, preoperatively walking barefoot; PostBF, postoperatively walking barefoot; PostAFO, postoperatively walking with ankle-foot orthoses; DF, dorsiflexion; FZ_1 denotes 1st peak within 15–35% of stance; FZ_2 denotes 2nd peak within 65–85% of stance; DF, dorsiflexion; ND, non-dimensional, N, Newton; H, body height; g, gravity (9.81 m/s^2).

(Vuillermin et al., 2011) Kitaoka et al. found that ankle immobilisation with solid AFOs was associated with reduced late stance vGRF, whereas hinged AFOs provided enhanced midfoot stabilisation, but without affecting the vGRF.(Kitaoka et al., 2006a) However, their results refer to normal adult gait and are not entirely pertinent to CP. Stabilisation of flexible feet with AFOs may have enhanced efficient force transfer in our participants, however we did not evaluate subtalar foot motion to confirm this theory. Previously, lever arm dysfunction that caused impairment of the midtarsal locking mechanism has been associated with a decreased second peak of the vGRF.(Kothari et al., 2016) Further studies are warranted to clarify how differences in AFO mechanical design, ankle and foot stabilisation affect vGRF magnitudes during gait in persons with neuromuscular diagnoses.

Testing the CP type as a covariate, the curve analyses revealed highly significant differences between bilateral and unilateral groups in each of the tested conditions. Besides dysfunction in both lower limbs and diminished gait speed, all participants with bilateral CP used AFOs on both sides which may have contributed to the differences. It is difficult to explain why Ben Lomonding occurs in children with unilateral CP; if excessive weight acceptance forces in the leading limb results from late stance deceleration deficiency in the opposite, trailing limb(Williams et al., 2011) insufficient late stance stability was suggested in the non-affected limbs. However, ankle equinus in the affected limb with inadequate prepositioning for initial contact and reduced contact area with the ground most likely contributed to the pattern. In addition, compensatory strategies such as vaulting may have caused sub-optimal CoM support in non-affected limbs. Previously, White et al. found asymmetric vGRF patterns between more and less affected limbs in children with CP, although their study did not differentiate between topographical CP types.(White et al., 2005) In future studies consecutive force plate recordings from affected and non-affected limbs may help explain vGRF patterns in children with unilateral CP.

Examining the entire vGRF using curve analyses revealed significant differences between all compared conditions, and the graphs demonstrated where differences were most pronounced. Differences in intercept, i.e. magnitude, and shape of the vGRF were determined within the specified intervals. The differences found by curve analysis were at large identified by analysis of peak values and both methods handled within-subject dependencies in the data caused by repeated measurements. Still, peak value analysis did not pick up significant differences in the FZ_2 area for the bilateral and FZ_1 for the unilateral group in PostBF versus PreBF comparisons. In early works by Jacobs et al. functional representations of vGRF curves were found to be particularly useful to study pathological gait where patterns are less consistent than in unimpaired gait (Jacobs et al., 1972). Several investigators promoted analyses that examine oscillations of ground reaction forces throughout stance(Giakas and Baltzopoulos, 1997; White et al., 2005) since larger areas of the curves provide a more representative variable, and coefficients of variations are reduced. Furthermore, functional curve analyses have advantages over alternatives such as multiple pointwise tests along the curves, which require corrections of *P* values (Bonferroni etc) to more conservative levels.(Pataky et al., 2013; Roislien et al., 2009; Thoresen and Gjessing, 2012; Zhang et al., 2017) Limitations exist in testing effects of relevant continuous covariates such as speed when the dependent variable is a function.(Roislien et al., 2009) In comparison, the linear mixed model analysis with peak FZ_1 and FZ_2 dependent variables enables evaluation of both categorical and continuous covariates. (Thoresen and Gjessing, 2012)

In our analyses we claimed differences in one single component of the vGRF, and in pre-specified time periods that were thought to be of clinical importance. Choices regarding timing and lengths of subintervals were based on previous work(Kitaoka et al., 2006b) and visual inspection of the vGRF graphs, to achieve an adequate curve representation in areas where the highest magnitudes occurred. An advantage of our method is that there is no periodicity assumption in the underlying functions used to model gait, ensuring that local characteristics of the curves are adequately modeled. Røislien et al.(Roislien et al., 2009) suggested the influence of covariates be expressed as estimated mean effects with 95% confidence interval. The area in the gait cycle where the confidence interval did not include zero corresponded to a *P* value below 0.05 and statistically significant effect.(Roislien et al., 2009) Statistical parametric mapping is an alternative method where GRF components may be analysed as one multi-component vector changing through time and space, and covariates may be tested across a defined time domain, using *P* values to explain significant differences. (Pataky et al., 2013) Both approaches could be adequate in future studies.

Limitations included heterogeneity in the cohort, especially with regards to surgery where 22 children underwent isolated triceps surae lengthening and 34 received concurrent surgical procedures as part of single-event multilevel surgery. Increasing the sample size and controlling for type of surgery, including triceps surae surgery (e.g. gastrocnemius recession versus tendo-achilles lengthening), would be relevant. The unbalanced number of hinged versus solid AFOs made it difficult to test and quantify the impact of AFO type in the subgroups. Use of a shoes-only control condition could differentiate possible effects of shoes from AFOs. The use of a single force plate is another limitation that implied the bipedal phases of gait could not be evaluated. Finally, further research should involve several lower limb variables, such as ankle and knee moments and power, to help explain changes in GRF components, CoM support and stability.

5. Conclusions

Our results indicate that the vGRF is responsive to evaluate treatment of gait problems with surgery and AFOs in children with CP. Decreased forces in weight acceptance and increased forces in late stance imply that fewer children walked with Ben Lomonding postoperatively. Walking with AFOs versus barefoot postoperatively, vGRF magnitude in late stance increased equivalent to bodyweight, which could be considered a clinically important improvement indicating reduced deceleration deficiency and more adequate CoM support.

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Declaration of conflict of interest and competing interest

The authors declare that they have no conflict of interest.

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Appendix A. Supplementary data

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