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Segmental Kinematic Analysis of Planovalgus Feet during Walking in Children with Cerebral Palsy

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Abstract: Pes planovalgus (flatfoot) is a common deformity among children with cerebral palsy. The Milwaukee Foot Model (MFM), a multi-segmental kinematic foot model, which uses radiography to align the underlying bony anatomy with reflective surface markers, was used to evaluate 20 pediatric participants (30 feet) with planovalgus secondary to cerebral palsy prior to surgery. Three-dimensional kinematics of the tibia, hindfoot, forefoot, and hallux segments are reported and compared to an age-matched control set of typically-developing children. Most results were consistent with known characteristics of the deformity and showed decreased plantar flexion of the forefoot relative to hindfoot, increased forefoot abduction, and decreased ranges of motion during push-off in the planovalgus group. Interestingly, while forefoot characteristics were uniformly distributed in a common direction in the transverse plane, there was marked variability of forefoot and hindfoot coronal plane and hindfoot transverse plane positioning. The key finding of these data was the radiographic indexing of the MFM was able to show flat feet in cerebral palsy do not always demonstrate more hindfoot eversion than the typically-developing hindfoot. The coronal plane kinematics of the hindfoot show cases planovalgus feet with the hindfoot in inversion, eversion, and neutral. Along with other metrics, the MFM can be a valuable tool for monitoring kinematic deformity, facilitating clinical decision making, and providing a quantitative analysis of surgical effects on the planovalgus foot.

Keywords: Foot**,** Model**,** Pediatric**,** Planovalgus**,** Cerebral palsy**,** Gait

1. Introduction

Foot deformity affects over 90% of children with cerebral palsy (CP), and is often explained by poor muscle control, spasticity, contracture, or lack of antagonist muscle activity [1]. Valgus hindfoot deformities are the most common type of foot deformity among children with CP and pes planovalgus is the most common foot deformity in individuals with diplegia or quadriplegia [2].

Pes planovalgus is characterized by an equinus deformity of the hindfoot, pronation of the mid- and forefoot, and shortening of the lateral column [3]. In typically developing children, the disorder is often flexible and the arch is reconstituted with dorsiflexion of the hallux or with voluntary plantarflexion. Flexible flatfoot is often asymptomatic or causes minor discomfort to the foot and lower extremity, and is treated conservatively with supportive footwear or orthotics [4]. However, the condition can be rigid, evidenced by a persistent flat arch even during non-weightbearing. These cases benefit from bracing or surgical intervention, which may consist of arthrodesis, calcaneal osteotomies with soft-tissue procedures, and subtalar arthroereisis [5].

Clinical management of planovalgus is typically informed by qualitative and quantitative examination techniques. Observation of gait is used to evaluate the foot morphology, progression angle, calcaneal alignment, heel-to-toe contact during gait, knee positioning, and the presence of antalgia [6]. Quantitative assessment includes pedobarography and passive ankle joint range of motion [7]. Standard quantitative gait models have been used to describe tibia-foot kinematics in the planovalgus population [8]. These models however, treat the foot as a single rigid segment and are not adequate for analyzing foot pathologies. Previous work has emphasized the need for measuring multi-segment foot motion to understand pathologic function [9].

Multisegmental foot models can provide a more detailed study of the planovalgus foot and involve measuring inter-segmental foot motion (e.g. hindfoot with respect to forefoot). Previous work with such models has been completed for adults [10] and children [11] with asymptomatic low arches, rheumatoid arthritis [12], children with planovalgus [13], and a mixed population of youth with planovalgus (CP, idiopathic planovalgus foot, peripheral neuropathy, and congenital foot deformity) [14]. These studies have contributed to understanding segmental foot motion, but have not included specific analyses of children with CP and planovalgus foot deformity, despite the common occurrence of planovalgus deformities in the CP population.

The Milwaukee Foot Model (MFM) [15] has been used to investigate multi-segmental foot kinematics during gait in many pathologies and has been evaluated and recommended for use with a pediatric population [16]. The model has recently been improved to remove the assumption of a vertical tibia during the static trial [17]. The MFM uses radiographic images to reference the positions of anatomical markers on the skin to the motion of the underlying bony anatomy. Prior studies have noted the importance of referencing methods when marker placement does not necessarily reflect the true orientation of the underlying bony anatomy [18]. This is particularly true in segments such as the calcaneus, where few mediolateral landmarks are available to facilitate repeatable instrumentation.

The purpose of this study was to characterize the relative motion of four segments of the foot and ankle (tibia, hindfoot, forefoot, and hallux) during gait in 20 children (30 feet) with rigid pes planovalgus secondary to CP using the MFM. The kinematics of the planovalgus population were compared to the kinematics of age-matched typically developing children.

2. Methods

2.1. Subjects

This study was a retrospective analysis of multisegmental foot motion analysis data. Data from twenty participants (10 female/10 male, age = 11.7 ± 2.7 yrs,) with rigid, symptomatic pes planovalgus (PV Group) as identified by the participant's orthopaedic surgeon were included (10 unilateral and 10 bilateral, for a total of 30 feet, Table 1). Symptoms were described as pain over the medial midfoot with standing and walking activities, skin irritation, callusing, and/or breakdown over the medial midfoot, pain associated with impingement, and/or difficulty with orthosis or shoe wear. All participants were diagnosed with CP (6 hemiplegia, 9 diplegia, 1 triplegia, 3 quadriplegia, 1 dystonia; 5 GMFCS Level I, 9 Level II, 6 Level III). All participants had no prior history of orthopaedic surgery for planovalgus and had not received botulinum toxin (Botox®) injections within one year prior to evaluation. Children were excluded if they presented with cognitive or behavioral impairments that interfered with their ability to understand and follow the commands necessary to participate in gait analysis. Informed consent was provided from the participants' legal guardians and, when appropriate, assent/consent was obtained from the participants as approved by an institutional review board. All data was collected as a part of a diagnostic gait analysis with a plan for possible surgical correction.

Table 1. Patient demographics. Cases were selected on the basis of long term symptomatic presentation with feet requiring boney surgical correction. Symptoms were described as pain over the medial midfoot with standing and walking activities, skin irritation, callusing, and/or breakdown over the medial midfoot, pain associated with impingement, and/or difficulty with orthosis or shoe wear.

Subject #	**Age**	**Gender**	**Height (cm)**	**Weight (kg)**	**Side Affected**	**GMFCS Level**	**Assistive Device**	**Previous Surgery**	**Foot strike pattern**
1	10.6	F	153.6	65.3	right	1			Foot flat at IC, plantigrade foot
2	15.2	M	176.5	66.8	left	2		n/a	Foot flat at IC, does not consistently achieve plantigrade foot
3	15.5	M	176	72.7	bilateral	3		n/a	Foot flat at IC, plantigrade foot
4	10.1	F	137.1	31.4	right	2		Gastrocnemius lengthening	Foot flat at IC, plantigrade foot
5	10.3	M	129.5	42.6	bilateral	3	Posterior Walker	n/a	Foot flat at IC, does not consistentl

Subject #	Age	Gender	Height (cm)	Weight (kg)	Side Affected	GMFCS Level	Assistive Device	Previous Surgery	Foot strike pattern
									y achieve plantigrade foot
6	9.7	M	129.5	24.2	bilateral	1		none	Left heel toe, Right foot flat at IC
7	14.3	M	145	38	right	2		n/a	Foot flat at IC, plantigrade foot
8	8.9	F	132.7	58.5	left	2		n/a	Foot flat at IC, plantigrade foot
9	12.8	M	166.4	43.6	right	2		SPLATT to opposite foot	Foot flat at IC, plantigrade foot
10	11.6	M	129.5	26.2	left	1		n/a	Foot flat at IC, plantigrade foot
11	17.2	F	162.6	59.5	left	2		n/a/	Foot flat at IC, no plantigrade foot
12	13.2	M	161	57.5	bilateral	2		Botox to hamstrings and gastrocnemius	Heel toe
13	8.1	F	128.2	24.3	bilateral	3	Posterior Walker	Botox to adductors and hamstrings	Forefoot IC, no plantigrade foot
14	9.6	F	132	27.3	bilateral	3	Posterior Walker	Botox to adductors and hamstrings	Forefoot IC, no plantigrade foot
15	12.3	F	144.7	28.6	bilateral	2		n/a	Heel toe
16	10	M	142.2	53.1	right	1		n/a	Forefoot IC, plantigrade foot

Subject #	Age	Gender	Height (cm)	Weight (kg)	Side Affected	GMFCS Level	Assistive Device	Previous Surgery	Foot strike pattern
17	10.9	M	137	35.6	bilateral	3	2 canes	n/a	Forefoot IC, plantigrade foot
18	14.5	F	161.2	54.5	left	1		n/a	Heel toe
19	7.2	F	134.6	42.5	bilateral	2		n/a	Foot flat at IC, plantigrade foot
20	12.7	F	140	40.4	bilateral	3	Posterior Walker	Botox to adductors, gastrocnemius, and hamstrings	R: IC with foot flat, plantigrade, L: IC at forefoot, not plantigrade

Previously collected gait data from a control group consisting of 16 typically developing (TD Group, 32 total feet) children (8 female/8 male, age = 11.3 ± 2.0 yrs) without history of foot pathology, injury, or surgery was included for comparison.

2.2. Protocol

Each participant underwent a motion analysis assessment using the standard MFM protocol, described in detail previously [15,17]. They were instrumented with 12 spherical reflective surface markers per foot. Markers were placed on bony anatomical landmarks. A static trial was obtained with the subject standing in a comfortable weight-bearing position. During the static trial, a foot position template was made by having the subject stand on a rectangular piece of cardboard and tracing both feet. This tracing was used during radiographs to ensure that the same standing alignment was achieved.

Each participant was instructed to walk "at a comfortable walking speed" over a 15-m walkway. A 14-camera Vicon (Oxford Metrics, UK) motion analysis system was used to record three-dimensional motion data. Sampling rate varied from 60 to 120 frames/s. Pilot analysis showed these sampling frequencies were able to accurately measure kinematic peaks for segmental foot kinematics in this population. At least twelve walking trials were collected for each subject, with three representative strides being selected for analysis.

After the gait analysis the same foot position template was used during a series of three weight-bearing radiographs of the feet (anterior/posterior, lateral, and modified coronal views). Specific radiographic offset measurements were obtained from the radiographs with respect to global reference lines to allow for calculation of the transformation from marker-based to bone-based axis systems [15,17]. Modified coronal view measurements were obtained using the method developed by Johnson et al. [19]. All measurements were made by the same investigator. The angles were measured for each segment relative to the global reference frame.

The motion data and radiographic offset measurements were input into a custom software model (MathWorks, Natick, MA). The model calculates a marker-based axis system using marker locations from the static trial and a bone-based axis system using the radiographic offset angles. A transformation matrix is computed to relate the two axis systems. Full details of the model were reported by Kidder et al. [15]. Temporal-spatial parameters (walking velocity, cadence, stride length, and stance phase duration) and kinematics for the tibia relative to the global coordinate system, hindfoot relative to tibia, forefoot relative to hindfoot, and hallux relative to forefoot were calculated. Foot-off was used to define the stance and swing phases of each trial. Maximum, minimum, and average joint angles were calculated within the stance and swing phase of each subject. Overall joint excursions (ROM) was also calculated.

2.3. Statistical analysis

Statistical comparisons between the PV and TD Groups were made among each of the 96 variables analyzed. A Welch two-sample *t*-test was performed to compare the difference in means of the kinematic data between the two groups ($p = 0.01$).

3. Results

3.1. Temporal-Spatial parameters

Stance duration (PV = 65.1 ± 6.5% gait cycle, TD = 61.5 ± 1.6% gait cycle) was not statistically different between the two groups ($p = 0.005$). Walking speed (PV = 0.67 ± 0.24 m/s, TD = 1.08 ± 0.14 m/s), cadence (PV = 96.94 ± 23.52 steps/min, TD = 115.46 ± 13.80 steps/min), and stride length (PV = 0.81 ± 0.18 m, TD = 1.13 ± 0.14) were significantly lower ($P < 0.001$) in the PV Group.

3.2. Kinematic parameters

The kinematics of each segment were compared to the TD Group in each of the three planes (Figs. 1, 2).

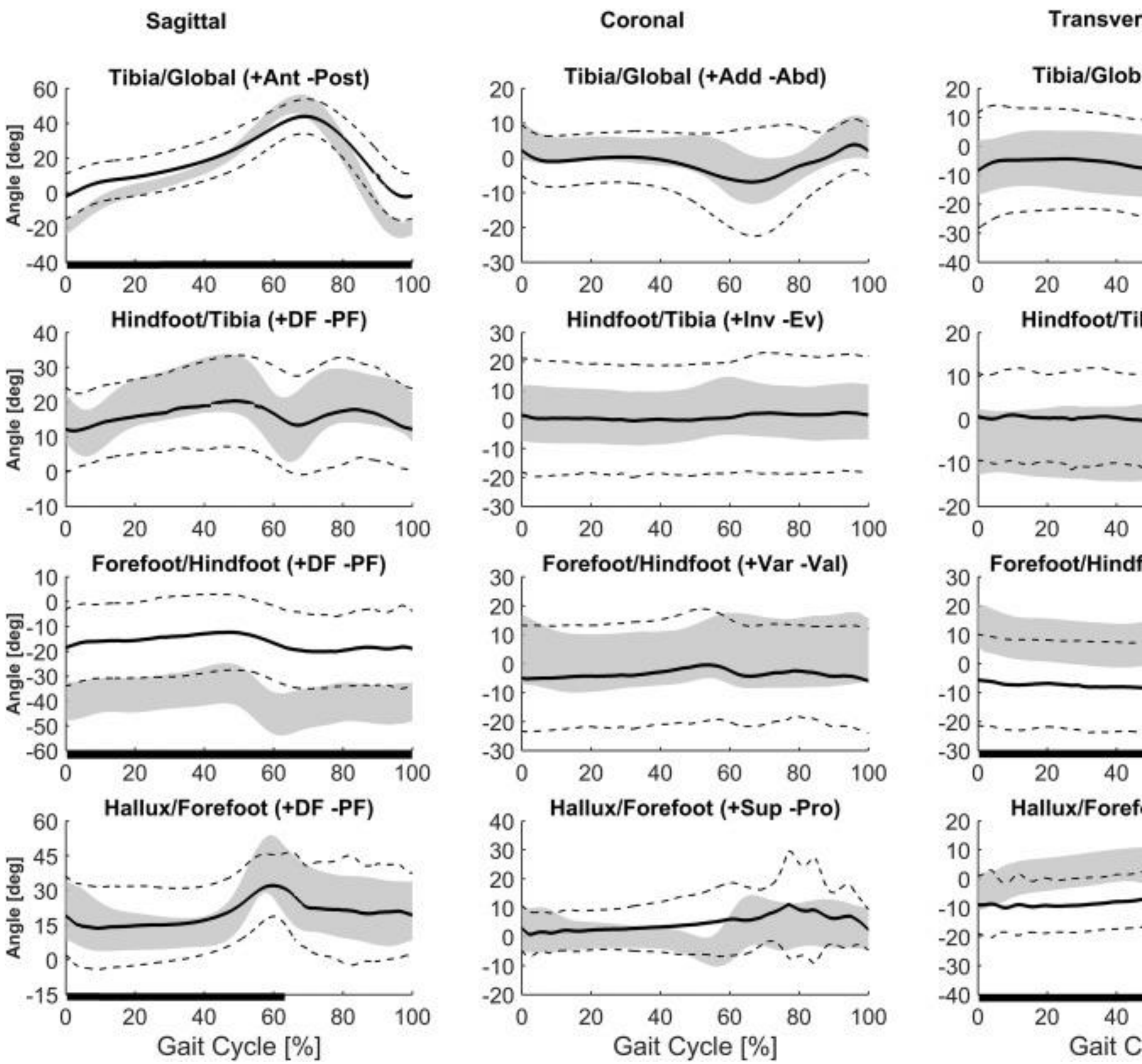

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Fig. 1. Average segmental kinematics throughout the gait cycle. Angles are defined as tibia relative to the global coordinate system, hindfoot relative to tibia, forefoot relative to hindfoot, and hallux relative to forefoot. Gray band indicates TD average ± one standard deviation. Black lines are PV average (solid) ± one standard deviation

(dashed). Black bars on x axis indicate statistically significance difference in either the maximum, minimum, or average joint angle $p < 0.01$.

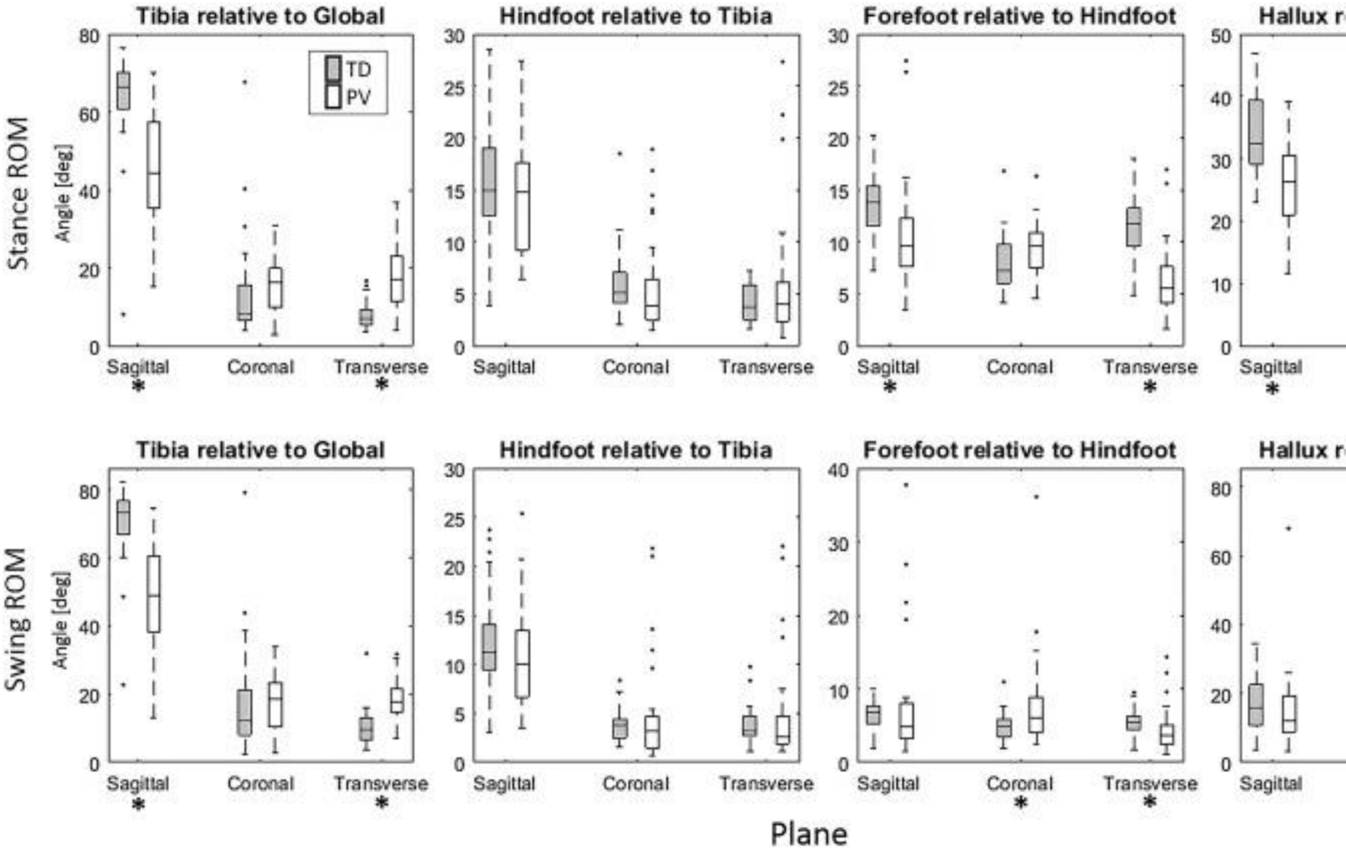

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Fig. 2. Segmental ROM within stance and swing phases for PV and TD groups. For each group, the central mark indicates the median, and the bottom and top edges of the box indicate the 25th and 75th percentiles, respectively. The whiskers extend to the most extreme data points not considered outliers, and the outliers are plotted individually using the '+' symbol. Asterisks indicate statistical significance of $p < 0.01$.

3.2.1. Tibia relative to global

The PV Group had deceased tibia ROM in the sagittal plane and increased ROM in the coronal plane in stance and swing. The PV tibia was also more anteriorly tilted in both stance and swing.

3.2.2. Hindfoot relative to tibia

The sagittal hindfoot kinematics of the PV Group showed a similar curve morphology compared to the TD Group throughout the gait cycle. The only statistically significant difference observed in the hindfoot was increased internal rotation during swing. Standard deviations showed there was greater variability among individuals in the PV Group in the coronal and transverse planes when compared to the TD Group.

3.2.3. Forefoot relative to hindfoot

Decreased forefoot plantarflexion throughout the gait cycle was identified among individuals in the PV Group. Forefoot valgus was observed in the PV Group, though the difference was not statistically significant. Transverse forefoot abduction was observed in the PV forefoot during both stance and swing. Decreased sagittal and transverse plane ROM were observed in stance. Increased coronal plane ROM and decreased transverse plane ROM were observed in swing.

3.2.4. Hallux relative to forefoot

The PV kinematics of the hallux relative to forefoot showed decreased ROM in the sagittal plane during stance and increased transverse plane ROM during swing. Increased dorsiflexion was observed in the sagittal plane during stance. The hallux demonstrated a significant valgus position during both stance and swing.

4. Discussion

While pes planovalgus is a common foot deformity in children with CP, little is known about its effect on the inter-segmental foot kinematics in this population. This study has revealed several significant differences between the pediatric PV Group and the TD

Group. The key finding of these data was that the MFM was able to show that the PV hindfoot does not always show more eversion than the TD hindfoot. The coronal hindfoot alignment angles of the hindfoot measured on the Milwaukee view radiograph (Fig. 3) illustrated cases of PV feet with the hindfoot in inversion, eversion, and neutral. This contradicts the common assumption that individuals with pronated or flat-arched feet will demonstrate increased hindfoot eversion during the stance phase of gait. Previously published reports on segmental kinematics of the PV foot have tended to agree with this assumption [10,13,14,21]. These studies only relied on standard skin markers on the foot which may not accurately represent the underlying bony anatomy of the segments. This is especially evident in the hindfoot because the calcaneus lacks easily identifiable landmarks, making repeatable marker placement difficult. Furthermore, any measurement errors may be exaggerated by the small segment length and angular displacements of the hindfoot [22]. It is critical to understand underlying bony orientation to accurately plan surgical procedures to the foot.

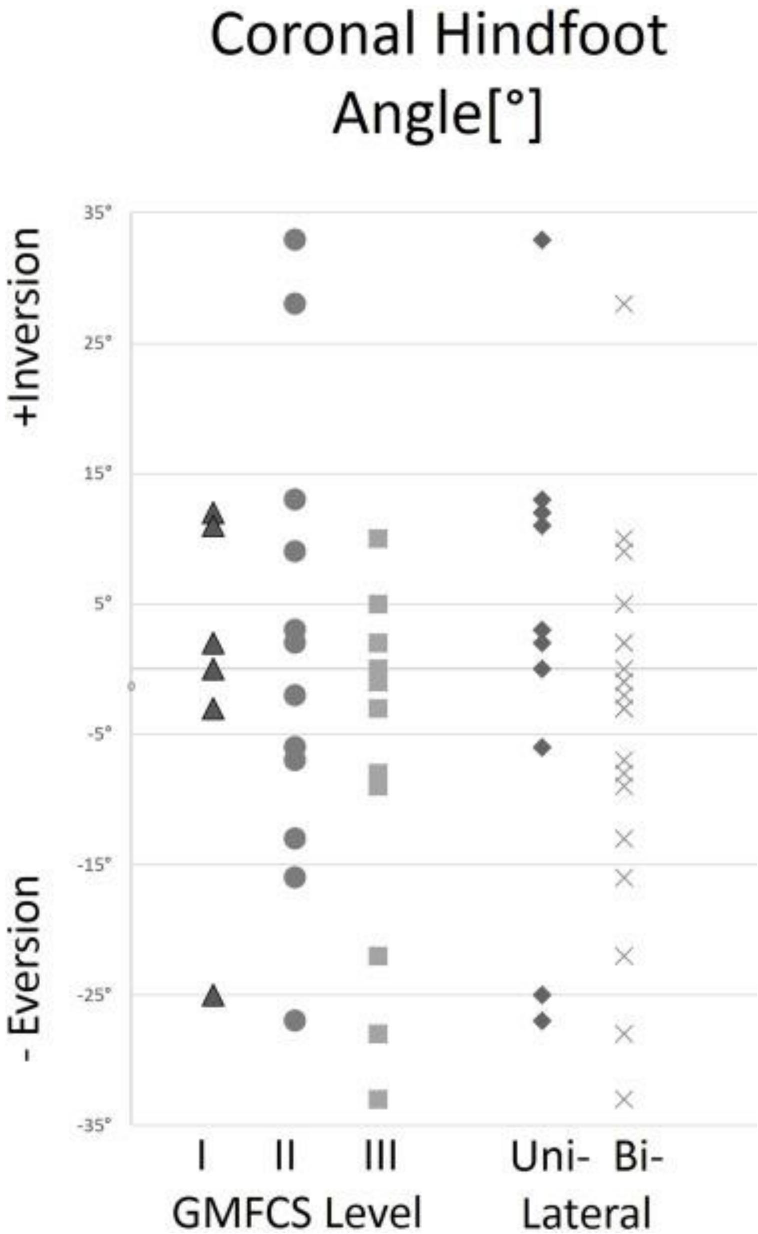

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Fig. 3. Individual patient values of the coronal hindfoot alignment angles as measured on the Milwaukee view radiograph. Measured angles are displayed by GMFCS Level (left) and laterality (right).

The radiographic indexing of the MFM provides a unique quantitative approach to a better understanding of intersegmental relationships during gait in planovalgus foot deformity. A previous parametric study by our group showed that when the hindfoot orientation angles were perturbed as little as 2° from their true orientation, significant changes to the kinematic output resulted [23]. The effect is most significant in the plane of the perturbation, but significant non-zero effects have also been reported in the transverse plane when perturbations are done in the coronal plane. This emphasizes the need for repeatable and reliable x-ray measurements in the current model. It also highlights the importance of using bony measurements.

The results of this study highlight the ability of the MFM radiographic indexing method to detect subtle changes in hindfoot orientation which may not be accessible by visual inspection. Fig. 4 depicts photos and modified coronal plane radiographs of two study participants. The individual on the left side has a 22° eversion of the hindfoot with respect to the tibia, which is typical of this population. The subject on the right side shows an 8° inversion of the hindfoot with respect to the tibia, although the photo shows an apparent eversion. The model output of the individual data, plotted below the photos, shows that the radiographic indexing accounts for skeletal abnormalities including the orientations shown in the radiographs.

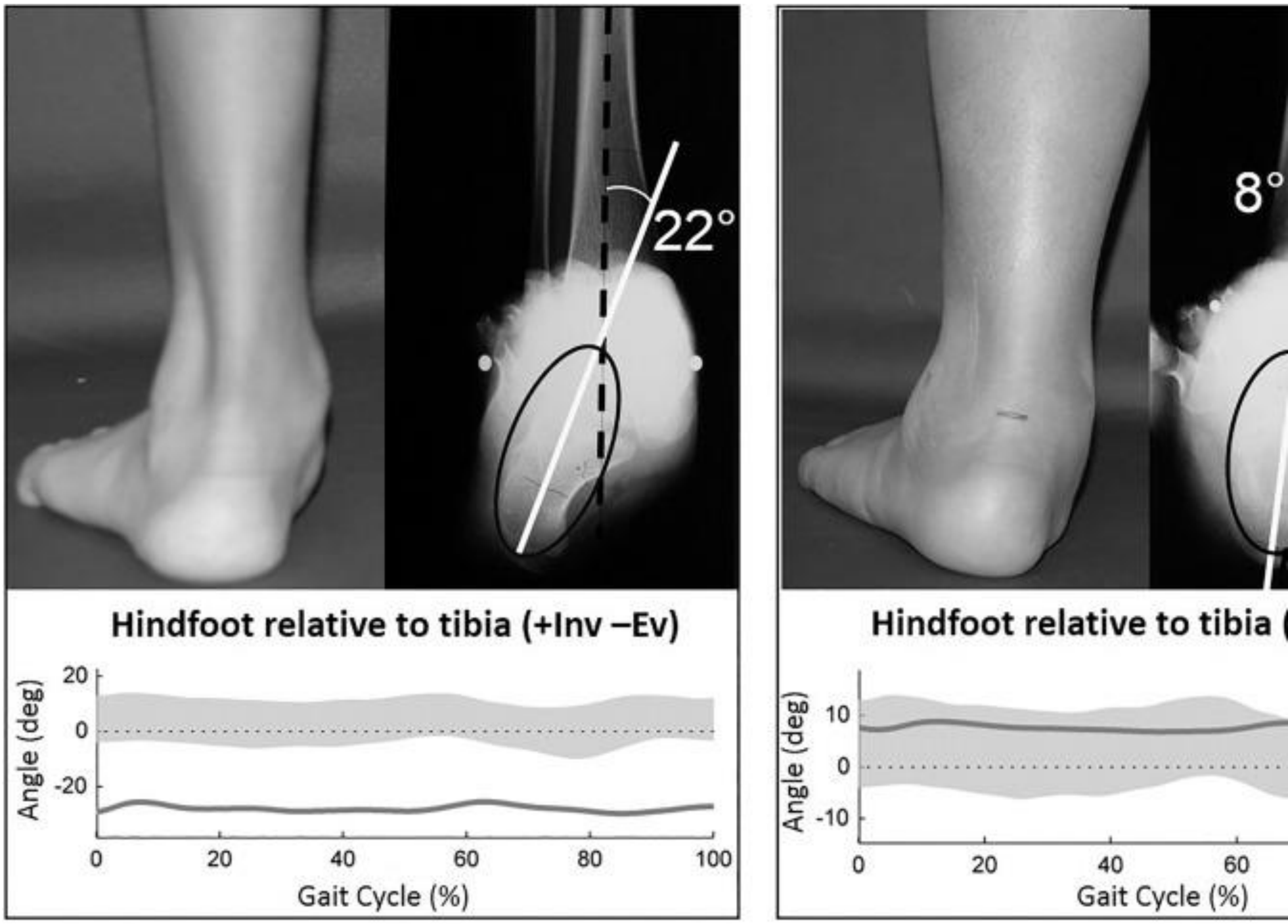

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Fig. 4. Two sets of individual subject data illustrating the advantage of skeletal indexing in the PV population. One the radiographs, the calcaneus is defined as an ellipse, the tibia axis is defined by a dashed line, and the calcaneus axis is defined by a solid line. On the plots, black lines depict an average of the subjects' three trials; gray band indicates control average ± one standard deviation.

This study also revealed several significant differences between this population of children with pes planovalgus secondary to CP and the control population of TD feet consistent with other studies of the general PV population. The PV population showed decreased plantarflexion of the forefoot relative to hindfoot which is characteristic of the flattened medial-longitudinal arch and mid-foot break commonly found in individuals with planovalgus. Hunt and Smith [24] and Church et al. [14] similarly described decreased forefoot plantar flexion (increased dorsiflexion of the forefoot relative to the hindfoot) in individuals with PV. In contrast, a study of patients with asymptomatic flexible flatfeet with no history of neuromuscular disease did show an increase in plantar flexion in the forefoot during late stance [10]. The authors suggested increased activity in the muscles responsible for plantarflexion could account for this in their study population however this is vastly different from the sample of individuals with CP used in the current study.

Decreases in hindfoot relative to tibia and forefoot relative to tibia ROM were observed in the PV Group. Reduced hindfoot and forefoot ROM is consistent with a rigid deformity. Decreased hindfoot ROM during pre-swing can additionally be associated with plantarflexor weakness which is common in this population. This impacts the individual's ability to push off, and worsens with increasing functional severity. The sagittal plane kinematics of the PV group showed a decrease in plantarflexion of the forefoot relative to the hindfoot which agreed with previous reports [11,13,24]. This was expected as the average calcaneal pitch in the PV group in the current study was 6.4°, while that of the TD Group was 20.4°. Other kinematic differences observed were consistent with known characteristics of the deformity and were increased forefoot abduction throughout the gait cycle [1,14,24,25] and increased hallux valgus when compared to the TD Group [14]. It has been established that walking speed can impact lower extremity kinematics [26]. Unfortunately, reliable methods for how to account for this have not yet been described [27].

While the radiographically-based MFM is well-suited to analyze segmental foot kinematics tailored to an individual's bony anatomy, there are limitations in the current study. It is assumed bony orientation with respect to the markers is consistent during the static trail and gait. Skin motion or soft tissue artifact would affect this assumption. Studies have addressed the issue of soft tissue artifact in multisegmental foot models. Shultz et al., used single-plane fluoroscopy to report a maximum of 16 mm translational soft tissue artifact at the navicular, up to 13.2 mm at the calcaneus, and less than 1° rotational artifact in hindfoot and forefoot marker clusters

[28]. Fluoroscopy has been used to avoid soft tissue artifact and track talocrural and subtalar motion during gait [29] but such systems are not widely available and much more costly than foot models which can be implemented in standard gait laboratories. Other limitations to these systems include a small field of view and concerns with radiation dosage. A further limitation for this work is that the output of the current MFM does not include the opposite limb strike and stride events. Therefore, analysis of gait by phases of single and double support, as has been recently suggested [27], was not possible with this retrospective data. Further data collection with the MFM should include collection of these events to allow for analysis using these phases.

Although planovalgus is a common foot and ankle deformity among individuals with bilateral CP, our institution also identified cases with both unilateral and bilateral involvement. Coronal hindfoot angles revealed significant variability of static hindfoot alignment within both the unilateral and bilateral groups (Fig. 4). Individual contributions of the hindfoot and forefoot kinematics were variable among the group as a whole. Such variability explains the non-significant differences between the PV and TD Groups, particularly in the coronal and transverse planes of the hindfoot and forefoot.

The averaging of heterogeneous data can contribute to the flattening of kinematic curves. Clinicians have previously addressed such variability by developing classification schemes to identify subgroups of individuals based on their kinematics. For example, Rodda et al. developed a commonly used classification scheme of gait patterns for children with spastic diplegia using sagittal plane kinematics of the lower extremities [30]. One such way to designate kinematic subgroups in the PV population is by foot strike patterns (i.e. forefoot, flatfoot, heel toe). Recent approaches of developing gait classification schemes at the foot and ankle used more systematic approaches including principal component analysis and cluster analysis [25]. Future studies could use such approaches to identify kinematic subgroups of planovalgus using multisegmental foot and ankle kinematics.

The accurate and reliable collection and analysis of multisegmental foot data is becoming important for procedure planning and follow-up in the clinical setting. Similar methods of quantitative assessment have been used extensively in the analysis of lower extremity kinematics in children with cerebral palsy for several decades [20]. Quantitative kinematic information gathered before a procedure, when used in conjunction with additional measures such as physical examination findings and kinetics, can help clinicians more accurately and definitively plan their treatment. Quantitative follow-up allows a causative analysis of surgical (treatment) effects. These quantitative methods can be used to analyze severity and track foot deformity progression over time.

5. Conclusions

This study demonstrated that it is feasible to apply the MFM to individuals with pes planovalgus resulting from CP. The radiographic indexing of the MFM allowed for improved representation of the underlying bony anatomy of the planovalgus foot. This indexing allowed for proper measurement of coronal plane excursion of the hindfoot. These results showed the PV hindfoot can be either inverted or everted relative to the tibia and radiographic measurement is necessary for accurate assessment. Results showed several significant differences between the PV group and age-matched population of typically developing children. Along with other metrics, the MFM can be a valuable tool for monitoring kinematic deformity, facilitating clinical decision making, and providing a quantitative analysis of surgical effects on the planovalgus foot.

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Appendix A. Supplementary data

The following is Supplementary data to this article:

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