Gait & Posture 68 (2019) 430–436

Contents lists available at ScienceDirect

Gait & Posture

journal homepage: www.elsevier.com/locate/gaitpost

Full length article

Kinematic foot types in youth with pes planovalgus secondary to cerebral palsy

Juliet Amene[a,b], Joseph J. Krzak[b,c,d,*], Karen M. Kruger[b,d], Logan Killen[e], Adam Graf[d], Haluk Altiok[d,f], Peter A. Smith[d,f], Gerald F. Harris[b,d]

[a] Department of Physical Medicine and Rehabilitation, Johns Hopkins University, 600 N. Wolfe St., Baltimore, MD, United States
[b] Orthopaedic & Rehabilitation Engineering Center (OREC), Marquette University/Medical College of Wisconsin, 1515 W Wisconsin Ave, Milwaukee, WI 53233, United States
[c] Midwestern University, Physical Therapy Program, College of Health Sciences, 555 31st Street, Downers Grove, IL, United States
[d] Shriners Hospitals for Children®-Chicago, 2211 North Oak Park Ave., Chicago, IL, United States
[e] RUSH University Medical Center, Department of Behavioral Sciences, Biological Rhythms Research Laboratory, 1645 W Jackson Blvd, Chicago, IL, United States
[f] RUSH University Medical Center, Department of Orthopaedic Surgery, College of Medicine, 1611 West Harrison Street, Chicago, IL, United States

ARTICLE INFO

Keywords:
Cerebral palsy
Pes planovalgus
Gait
Multi-segment foot modeling

ABSTRACT

Background: Kinematic variability of the foot and ankle segments exists during ambulation among individuals with pes planovalgus (PPV) secondary to cerebral palsy (CP). Clinicians have previously recognized such variability through classification schemes to identify subgroups of individuals, but have been unable to identify kinematic foot types.

Research question: The purpose of this work was to identify kinematic foot types among children with PPV secondary to CP using 3-dimensional multi-segment foot and ankle kinematics during gait as inputs for principal component analysis (PCA) and *K*-means cluster analysis.

Methods: In a single assessment session, multi-segment foot and ankle kinematics using the Milwaukee Foot Model (MFM) were collected in 31 children/adolescents with pes planovalgus (49 feet) and 16 typically developing (TD) children/adolescents (31 feet). PCA was used as a data reduction technique on 34 kinematic variables. *K*-means cluster analysis was performed on the identified principal components (PCs) and one-way analyses of variance (ANOVA) was done to determine the effect of subgroup membership on PC scores.

Results: The PCA reduced the kinematic variables to seven PCs which accounted for 91% of the total variance. Six distinct kinematic foot types were identified by the cluster analysis. The foot types showed unique kinematic characteristics in both the hindfoot and forefoot.

Significance: This study provides further evidence of kinematic variability in the foot and ankle during ambulation associated with pes planovalgus secondary to CP. The specific contributions of the hindfoot and forefoot would not have been detected using a single segment foot model. The identification of kinematic foot types with unique foot and ankle characteristics has the potential to improve treatment since patients within a foot type are likely to benefit from similar intervention(s).

1. Introduction

Pes planovalgus (PPV) is one of the most common foot deformities affecting individuals with bilateral cerebral palsy (i.e. diplegia and quadriplegia) [1–3]. The deformity includes a combination of ankle plantarflexion, hindfoot valgus, and forefoot abduction and supination [1,3]. This multi-segment, multi-planar deformity negatively impacts gross motion function and causes symptoms including pain over the medial midfoot with standing and walking activities, skin irritation, callusing, breakdown over the medial midfoot, pain associated with impingement, and/or difficulty with orthosis or shoe wear.

Accurate identification of the involved segment(s), plane(s) of motion, and joint excursions during ambulation resulting from PPV is crucial when recommending interventions to control segmental foot alignment. However, PPV is a heterogeneous condition. Kruger et al. used the Milwaukee Foot Model (MFM) to characterize the multi-segment foot and ankle gait kinematics of PPV resulting from CP [4]. They reported that although the presence of transverse forefoot abduction

* Corresponding author at: Midwestern University, Physical Therapy Program, College of Health Sciences, 555 31st Street, Downers Grove, IL, United States.
E-mail address: joekrzak@sbcglobal.net (J.J. Krzak).

https://doi.org/10.1016/j.gaitpost.2018.12.026
Received 11 September 2018; Received in revised form 24 November 2018; Accepted 18 December 2018

was consistent among children with PPV, significant kinematic variability at the forefoot in the coronal plane, as well as the hindfoot and forefoot in the transverse plane were evident. Such complex kinematic variability could explain inconsistencies in the clinical management strategies of PPV among children with CP and the associated range of reported post-interventional outcomes [5–7].

Previous efforts to explain kinematic variability for specific gait deviations aimed to identify clinically relevant subgroups among a sample of participants with CP who presented with a similar deformity [8,9]. Specifically, Krzak et al., used multi-segmental foot and ankle gait kinematics of typically developing children and children with CP as inputs for a combination of principal component analysis (PCA) and cluster analysis to identify four subgroups of equinovarus deformity.

PCA is a statistical method used to reduce a large matrix of data into a smaller number of salient principal components (PCs) while minimizing loss of valuable information. After individual PCs are derived, cluster analysis can be employed to identify subgroups of individuals with similar deformity characteristics. Given the kinematic variability identified among individuals with PPV, the application of these statistical techniques to identify clinically relevant subgroups is a feasible objective to address clinical relevance.

The purpose the current study was to identify subgroups of children with PPV secondary to CP (foot types). Multi-segment foot and ankle kinematics from typically developing children and children with PPV were used as inputs for PCA and cluster analysis. We anticipated that individual foot types would present with unique kinematic characteristics of PPV including the involvement of specific segment(s), plane(s) and joint excursions.

2. Methods

2.1. Participants

This study was a retrospective analysis of multi-segmental foot kinematics collected during ambulation as approved by an institutional review board. Data from 31 participants (CP Group, 14 female/17 male; age = 11.5 ± 2.4 yrs, GMFCS I: 6, GMFCS II: 15, GMFCS III: 10; Hemiplegia: 5, Diplegia: 20, Quadriplegia: 3, Triplegia: 3) with rigid, symptomatic PPV as identified by the participant's orthopaedic surgeon were included (13 unilateral and 18 bilateral, for a total of 49 feet). There were individuals with either one or both feet included in the analysis. For individuals with bilateral involvement, five participants presented with unilateral PPV and had one foot included in the analysis. All data had been collected as part of a diagnostic gait analysis with a plan for possible surgical correction.

Symptoms were described as pain over the medial midfoot with standing and walking activities, skin irritation, callusing, breakdown over the medial midfoot, pain associated with impingement, and/or difficulty with orthosis or shoe wear. The diagnosis of planovalgus was confirmed with radiographic characteristics including forefoot abduction, reduced longitudinal arch height, and/or hindfoot valgus [10]. All participants were diagnosed with CP, had no prior history of orthopaedic surgery for planovalgus and had not received botulinum toxin (Botox®) injections within one year prior to evaluation. Cases were included if the individual had previous orthopaedic surgery as long as procedures to correct planovalgus were not performed.

Previously collected multi-segment kinematics from a sample of 16 typically developing (TD Group, 31 total feet) children (8 female/8 male, age = 11.3 ± 2.0 yrs) without history of foot pathology, injury, or surgery were also included.

2.2. Protocol

Participants underwent quantitative motion analysis using the MFM protocol. Full details of the model have been reported by Kidder and Long [11,12]. Each foot was instrumented with 12 spherical reflective surface markers (9 mm) placed on bony anatomical landmarks of the foot and ankle. A tracing of each participant's feet was made on a piece of cardboard while he/she stood in a comfortable weight-bearing position. This tracing was used to ensure the same standing posture was achieved during the static gait trial and the weight-bearing radiographs. Motion data were collected using a 14-camera Vicon (Oxford Metrics, UK) motion analysis system. A minimum of twelve walking trials at comfortable walking speed were collected for each participant with three representative strides being selected for analysis.

A series of three weight-bearing radiographs of the feet (anterior/posterior, lateral, and modified coronal [13] views) was also obtained for each participant. Specific radiographic offset measurements were taken from the radiographs with respect to global reference lines to allow for calculation of the transformation from marker-based to bone-based motion axis systems [11,12]. Kinematics for the (1) tibia relative to the global coordinate system, (2) hindfoot relative to tibia, and (3) forefoot relative to hindfoot along with temporal-spatial parameters were calculated for each foot. Initial contact with the floor, foot-off, and ipsilateral initial contact on the floor again was used to define the stance and swing phases of each trial.

2.3. Principal component analysis

The input data matrix of the PCA consisted of 34 multi-segment foot and ankle kinematic variables, walking speed, and age at the time of the preoperative evaluation. The kinematic variables were chosen via clinical consensus based on their ability to identify specific segment(s), plane(s), and the relevant joint excursions associated with PPV. These included walking speed, kinematic peaks of the tibia, hindfoot, and forefoot during the stance and swing phase of the gait cycle, as well as joint excursions. Descriptive statistics of the 34 variables were computed, and initial mean comparisons between the CP Group and the TD Group were made using Cohen's *d* effect size calculations [14]. Each variable was then normalized into a z-score by subtracting the mean and dividing by the standard deviation across the entire sample. The PCs were derived from the correlation matrix of the normalized dataset using a Varimax rotation in IBM SPSS Statistics 25 (Chicago, IL). This resulted in 36 initial PCs. Specific criteria to retain variables and PCs have been established and were implemented to ensure that the variables were distinct measures of one specific PC. The criteria used for PC retention included: (1) an eigenvalue of ≥ 1.00 [15], (2) components located to the left of an 'elbow' on the scree plot containing the eigenvalues across all PCs [16], and (3) retaining the minimum number of components such that the cumulative percent of variance accounted for was ≥ 80% [15,17]. Variables were retained in a particular component if: (1) at least 50% of the variance of the normalized variable was accounted for by the retained PCs ($h^2 \geq 0.50$), (2) the variable had a weighting score of ≥ 0.40 or ≤ -0.40 on a PC, and (3) the variable demonstrated a simple structure (i.e. the weighting score of the particular variable was not ≥ 0.40 or ≤ -0.40 on more than one PC [18]. If a variable(s) did not meet the retention criteria, it was removed, and PCA was repeated using the remaining variables until all retention criteria were met. To determine if the final dataset was suitable for PCA, Bartlett's test of sphericity was performed [19]. To determine if the sampling was adequate for analysis, the Kaiser-Meyer-Olkin (KMO) test was also performed [20]. Once the final model was determined, individual PC scores were derived for each participant across all retained PCs for the subsequent cluster analysis using the following equation:

$$PC\ score_{ij} = \sum_{k} \bar{X}_{ik} \propto_{jk}$$

The PC scores of the i^{th} person and j^{th} PC were calculated as the weighted sum of the kinematic variables retained within that particular PC. x_{ik} is original variable value averaged over three walking trials for the k^{th} kinematic measure, and α is a matrix of weighting score coefficients converting the k dimensional vector of kinematic measures into

a six-dimensional vector of PCs.

2.4. Cluster analysis

An initial hierarchical cluster analysis using squared Euclidian distances and Ward's Method was performed on the standardized PC scores for all participants [21,22]. This was done to define the appropriate number of a-priori clusters to be used in the *K*-means cluster analysis. Individual PC scores were standardized into z-scores to allow all PC scores to have equal influence on the initial cluster center locations in the *K*-means analysis. The optimal number of clusters to be used in the *K*-means analysis was determined by calculating the agglomeration distance coefficients across stages as additional cases from 1 to 80 were merged into the clusters. A scree diagram of the distance coefficients across stages was then used to identify the stage where the first significant change occurred in the coefficients as additional cases were added to the clusters. The identified stage was subtracted from the total number of cases (n = 80) to determine the appropriate number of clusters to be used in the *K*-means analysis. Subgroup membership via *K*-means analysis was then determined using a clustering algorithm that categorizes individuals based on the proximity to means, thus maximizing similarities within a subgroup and the differences among the subgroups.

Once subgroup membership was assigned using *K*-means cluster analysis, one-way analyses of variance (ANOVA) were performed to determine the effect of subgroup membership on PC scores. Where a main effect of membership was identified, post-hoc 2-tailed Dunnett's tests were performed to further analyze the pair-wise comparisons to a subgroup identified as a rectus foot type. A rectus foot type was previously defined as a foot with a resting calcaneal stance angle between 0 and 2° of valgus along with a coronal plane forefoot to hindfoot relationship between 0 and 4° of varus [23]. Stance phase kinematics that resembled this description were used to identify a rectus foot type in the current study. The level of statistical significance was set at 0.05.

3. Results

The means, standard deviations, ranges, and effect size of the variables included in the initial PCA are shown in Table 1. As expected, the mean walking speed of the TD Group was greater than that of the CP Group. There was more variation of all variables in the CP Group as shown by the larger standard deviations of the CP variables. As expected, the CP Group generally demonstrated increased peak plantar flexion, internal rotation, and valgus of the hindfoot, as well as increased peak dorsiflexion, varus, and abduction of the forefoot when compared to the TD Group.

3.1. Principal component analysis

Of the 34 variables that were used for initial PCA, 32 variables met the inclusion criteria for retention (Table 2). The retained variables were reduced to 7 PCs accounting for 91% of the total variance. PCA was deemed appropriate by Bartlett's test of sphericity ($p < 0.001$). The KMO test revealed that there was adequate sampling (KMO > 0.5). The 7 PCs described the hindfoot and forefoot position in each plane and the segment range of motion in each plane across the gait cycle.

3.2. Cluster analysis

K-means clustering identified six unique foot types (Table 3). The rectus foot group was used as the control to which the other foot types were compared. The ANOVA test demonstrated the effect of each foot type on PC scores as seen in Table 3. A main effect of foot type was not identified for PCs 6 and 7; therefore, post-hoc analysis was not performed on those PC scores. The kinematic patterns of each foot and the number of feet in each group included:

- **Rectus foot type**: (15 TD, 2 CP) Control group
- **Planus foot type**: (13 TD, 3 CP) Hindfoot valgus with forefoot varus
- **Foot type 1 (classic PPV)** (12 CP): Hindfoot valgus with forefoot varus (planus), reduced forefoot plantar flexion, and forefoot abduction
- **Foot type 2**: (2 TD, 14 CP) Reduced forefoot plantar flexion, forefoot abduction, and hindfoot internal rotation
- **Foot type 3:** (1 TD, 7 CP) Hindfoot varus with forefoot valgus, reduced hindfoot dorsiflexion with reduced forefoot plantar flexion, forefoot abduction, and hindfoot internal rotation
- **Foot type 4**: (8 CP) Severe hindfoot valgus with forefoot varus (planus), reduced hindfoot dorsiflexion with reduced forefoot plantar flexion, and severe forefoot abduction

The mean kinematics across the gait cycle for each of the subgroups are shown in Fig. 1. Each subgroup identified has unique gait types and distinct kinematic features (Table 4).

4. Discussion

The current study successfully identified six clinically relevant kinematic foot types from a sample of TD children and children with PPV secondary to CP. Foot types were created using multi-segmental foot and ankle kinematics obtained using the MFM as inputs for PCA and *K*-means cluster analysis. PCA was used to reduce 32 clinically relevant kinematic variables describing the segment(s) and plane(s) of involvement to seven PCs. *K*-means cluster analysis was used to identify subgroups of participants with planovalgus who presented with variable involvement ranging from primary hindfoot valgus to forefoot dorsiflexion. Foot type classifications included deviations in multiple foot segments and range of motion. Together, this information can be used to explain the kinematic variability previously identified among individuals with PPV and facilitate clinical decision making, as individuals with a specific foot type would benefit from similar interventional strategies.

Variability of foot and ankle function is not only found among individuals with foot deformity. In the current study, the majority of the typically developing children clustered within the first two subgroups which were identified as rectus and planus foot types. This finding supports the variability in function of normal, healthy feet and is expected as previous work has identified three biomechanical foot types in healthy adults [23,24]. The planus foot type consisted of hindfoot valgus and forefoot varus. Interestingly, not all of the participants from the TD Group clustered as rectus and planus foot types. Two feet from the same individual in the TD Group were categorized as Foot type 2 (reduced plantar flexion and abduction of the forefoot along with hindfoot internal rotation). One foot from another participant in the TD Group was classified as Foot type 3 (hindfoot varus with forefoot valgus, reduced hindfoot dorsiflexion/forefoot plantar flexion, forefoot abduction and hindfoot internal rotation). Such findings raise the question whether these deviations are representative of the variability among typical foot biomechanics or if these individuals presented with an underlying, undiagnosed, foot and ankle pathology that will become more apparent as they continue to develop. Individuals were included in the TD Group if they had no history of foot pathology or pain.

Previous reports characterizing PPV secondary to cerebral palsy using kinematic analysis identified significant variability, particularly coronal plane motion of the hindfoot and forefoot [4]. *K*-means cluster analysis used in the current study identified two foot types (1 and 4) with the characteristic coronal plane hindfoot valgus and compensatory forefoot varus. Foot type 2 showed coronal plane alignment similar to that of the rectus foot type. Interestingly, there were even seven feet (Foot type 3) with hindfoot *varus* in the presence of a reduced hindfoot dorsiflexion/forefoot plantar flexion and forefoot abduction. Similar

Table 1
Means, standard deviations, and ranges of the variables included in the initial PCA.

Variables	Typically Developing Children				Cerebral Palsy				Effect Size
	Average	SD	Range		Average	SD	Range		Cohen's *d*
			Min	Max			Min	Max	
Walk Speed	1.08	0.14	0.84	1.4	0.72	0.24	0.1	1.15	0.83
Sagittal plane kinematics									
Peak Anterior Tibia Tilt	50.42	6.24	26.67	62.61	44.22	15.2	10.3	89.8	1.89
Sagittal hindfoot ROM	17.33	5.75	7.2	30	17.24	8.43	5.7	48.8	0.04
Peak hindfoot dorsiflexion during stance	25.67	7.94	5.6	44.7	21.36	18.42	5.6	87.3	1.19
Peak hindfoot dorsiflexion during swing	22.76	7.07	3.3	40.1	18.92	17.91	−8.5	79.1	1.09
Peak hindfoot plantar flexion during stance	8.88	7.04	−12.5	21	5.7	17.62	−33	61.3	0.9
Peak hindfoot plantar flexion during swing	10.37	8.23	−17.1	26	6.11	18.12	−33.4	57.1	1.18
Sagittal forefoot ROM	13.72	2.68	8.9	20.3	15.28	8.64	6.6	39.9	0.65
Peak forefoot dorsiflexion during stance	−32.25	7.39	−43.9	−19.7	−8.57	14.55	−34.1	40.8	7.15
Peak forefoot dorsiflexion during swing	−39.36	7.4	−55.1	−27.4	−13.49	13.94	−35.9	31	7.92
Peak forefoot plantar flexion during stance	−45.72	7.95	−63.9	−31.4	−21.89	13.68	−46.5	23.3	7.24
Peak forefoot plantar flexion during swing	−45.68	7.77	−62.8	−31.9	−22.9	13.08	−49.3	7.3	7.06
Coronal plane kinematics									
Peak tibia adduction	7.72	4.9	−0.8	18.5	8.54	9.43	−6.3	35.6	0.31
Coronal hindfoot ROM	5.77	2.03	2.2	11.2	7.04	5.6	2	29	0.65
Peak hindfoot inversion during stance	5.29	9.52	−14.8	27.2	−1.15	11.96	−25	23.9	1.97
Peak hindfoot inversion during swing	5	9.42	−14.1	27.2	−0.57	12.28	−26.2	20.9	1.69
Peak hindfoot eversion during stance	−0.23	9.07	−19.9	18.3	−6.75	11.94	−31.1	18.4	2.01
Peak hindfoot eversion during swing	1.33	9.01	−18.6	20	−5.83	12.26	−33.9	19.3	2.19
Coronal forefoot ROM	8.87	2.9	4.7	17.8	13.85	4.92	6.6	26.7	2.51
Peak forefoot varus during stance	7.17	10.83	−11	39.5	11.94	13.77	−13.5	48.2	1.36
Peak forefoot varus during swing	6.83	11.83	−14.1	41.5	9.92	14.45	−14.5	48.6	0.85
Peak forefoot valgus during stance	−0.73	9.67	−17.7	27.6	0.7	13.12	−28.2	32.9	0.42
Peak forefoot valgus during swing	2.06	11.71	−18.7	36	0.75	12.97	−24.6	34	0.37
Transverse plane kinematics									
Peak tibia external rotation	16.05	10.87	40.47	1.61	25.57	19.42	84.5	−6.8	2.45
Transverse hindfoot ROM	4.85	1.86	2.3	9.7	7.28	5.78	1.6	32	1.24
Peak hindfoot internal rotation during stance	−3.3	7.8	−17	18.9	3.67	9.56	−14.9	32.3	2.37
Peak hindfoot internal rotation during swing	−4.19	7.62	−16.5	19.2	4.25	10.01	−16.2	32.1	2.84
Peak hindfoot external rotation during stance	−7.35	7.7	−22.4	11.9	−2.02	8.69	−22.1	19.3	1.86
Peak hindfoot external roatation during swing	−7.81	7.68	−22.1	10.9	−1.09	8.85	−21.5	18.4	2.33
Transverse forefoot ROM	12.38	3.6	4.8	19.1	9.78	5.04	2.8	27.6	1.25
Peak forefoot adduction during stance	17.46	6.84	2.8	32.9	−2.76	12.28	−26.9	26.2	6.54
Peak forefoot adduction during swing	17.95	6.76	3.5	33.2	−2.44	12.59	−25.1	25.9	6.55
Peak forefoot abduction during stance	5.74	7.33	−6.6	24.9	−10.67	12.24	−38.1	19.8	5.25
Peak forefoot abduction during swing	12.6	7.01	−0.9	28.9	−8.81	12.26	−33.7	23.5	6.9

variability was identified by Kruger et al. [4] highlighting the ability of the MFM radiographic indexing method to detect subtle changes in hindfoot orientation which may not be accessible by visual inspection [4]. Typical marker-based gait analysis techniques of the hindfoot are limited because the calcaneus lacks easily identifiable landmarks to ensure (1) repeatability of marker placement, and (2) that the surface markers represent the orientation of the underlying skeletal anatomy. Alignment issues at more proximal segments (e.g. the shank or thigh) or other planes of the foot may present as hindfoot valgus when radiographic indexing shows the calcaneus is actually in inversion relative to the tibia [4]. For example, the presence of knee valgus can make it appear that the hindfoot is in eversion but radiographic indexing has shown that in some cases, the calcaneus may actually be in neutral or inversion relative to the tibia.

All planovalgus foot types (1–4) presented with reduced plantar flexion of the forefoot relative to the hindfoot (PC2) likely suggesting stress of the longitudinal arch, possibly to the point that it is no longer functioning in a meaningful way. In severe cases, such stress on the arch can additionally result in a midfoot break. All foot types also showed various levels of abduction of the forefoot (PC3) while hindfoot internal rotation (PC4) was observed in types 2 and 3. Kinematic variability was identified both between and within the participants in the current study. There were individuals with bilateral involvement who had feet categorized into two different subgroups. This discrepancy can be explained by the presence of varying degrees of involvement/severity between right and left side among participants with asymmetric diplegia and triplegic CP.

Identification of multiple foot types can facilitate clinical decision making as individuals with similar deformity characteristics may benefit from the same intervention strategy. For example, the purpose of the medial calcaneal sliding osteotomy is to correct hindfoot valgus deformity and shift the pulling force of the achilles tendon medially [25]. Such an osteotomy would not be indicated for individuals without hindfoot valgus such as those who were identified with a type 2 or type 3 foot. Additionally, surgical procedures such as a lateral column lengthening have direct effects on hindfoot correction with anticipated indirect effects on the mid- and forefoot position [26]. Lengthening of the lateral column at the calcaneus pushes the navicular bone medially, reduces the talus over the calcaneus and straightens the midfoot/forefoot. While this procedure may correct the mid- and forefoot in individuals with more mild deformity, it may not be robust enough to have an effect on more severe deformity observed in individuals assigned to foot type 4. Such individuals may require either additional osteotomies at the midfoot as described by Mosca [27] and Kim et al. [25], or joint fusion/arthrodesis [6,28]. Unfortunately, results from the current study did not include midfoot kinematics. One of the limitations of the MFM, and many other multi-segment foot models, is that the midfoot is considered a transitioning segment between the hindfoot and forefoot. Modeling midfoot kinematics is technically difficult as skin-based markers are unable to represent much of the motion that occurs

Table 2
Individual weighting scores with the amount of variance accounted for among variables within the retained principal components. The eigenvalues and cumulative variance are also reported for each PC.

Variable	Principal Component (Eigenvalue, Percent Cumulative Variance)						
	1 (7.3, 22.9%)	2 (4.6, 37.2%)	3 (4.3, 50.5%)	4 (4.0, 63.0%)	5 (3.9, 75.2%)	6 (3.8, 87.0%)	7 (1.3, 91.0%)
Walk Speed		−0.54					
Peak tibia adduction							−0.91
Sagittal hindfoot ROM						0.89	
Peak hindfoot dorsiflexion during stance					0.96		
Peak hindfoot dorsiflexion during swing					0.97		
Peak hindfoot plantar flexion during stance					0.97		
Peak hindfoot plantar flexion during swing					0.94		
Coronal hindfoot ROM						0.66	
Peak hindfoot inversion during stance	0.89						
Peak hindfoot inversion during swing	0.89						
Peak hindfoot eversion during stance	0.88						
Peak hindfoot eversion during swing	0.89						
Transverse hindfoot ROM						0.8	
Peak hindfoot internal rotation during stance				0.88			
Peak hindfoot internal rotation during swing				0.86			
Peak hindfoot external rotation during stance				0.92			
Peak hindfoot external roatation during swing				0.93			
Sagittal forefoot ROM						0.69	
Peak forefoot dorsiflexion during stance		0.93					
Peak forefoot dorsiflexion during swing		0.93					
Peak forefoot plantar flexion during stance		0.95					
Peak forefoot plantar flexion during swing		0.94					
Coronal forefoot ROM						0.51	
Peak forefoot varus during stance	−0.96						
Peak forefoot varus during swing	−0.94						
Peak forefoot valgus during stance	−0.95						
Peak forefoot valgus during swing	−0.94						
Transverse forefoot ROM						0.81	
Peak forefoot adduction during stance			0.92				
Peak forefoot adduction during swing			0.91				
Peak forefoot abduction during stance			0.92				
Peak forefoot abduction during swing			0.89				

beneath the skin. Novel applications of technology, including biplane fluoroscopy, would provide more insight into *in-vivo* pathologic midfoot motion, the effect of interventions on improving midfoot alignment/motion, and the accuracy of existing multi-segment foot models.

Future studies could use a combination of pre-operative foot type, combination of surgical procedures chosen and post-operative results to explain the variability in short and long-term outcomes following intervention. These studies could evaluate the utility of these novel PC Scores as kinematic outcome measures following surgical correction. The relationships between improvements in kinematic measures and functional outcome measures could also be evaluated to determine the effect of surgical correction on improving foot mechanics and functional mobility. Another important next step in evaluating the variability in foot deformity among individuals with PPV secondary to CP is to identify potential patient-specific characteristics which may contribute to the complexity or severity in the deformity. We did perform a preliminary comparison of age, height, and weight among the foot types. No significant group effect was identified.

This work is limited in that hindfoot motion was modeled as a combination of talus and calcaneus motion. This is a limitation of all marker-based multi-segment foot models due to the lack of available landmarks for marker placement on the talus. Single and biplane fluoroscopy have been using to track talocrual and subtalar motion in the ankle [29,30]. These systems are costly and time consuming to run, have limited field of view, and have concerns with radiation exposure. Therefore, they are currently limited to small research applications.

In conclusion, this study presented an objective means to classify the multi-segment foot and ankle kinematics in children with pes planovalgus secondary to CP and TD children. The analysis identified six distinct kinematic subgroups with involvement of the hindfoot and forefoot in all three planes of motion when compared to a control group. These quantitative methods can ultimately be used to analyze severity and track progression of deformity. When used in conjunction with information such as kinetics, EMG, and physical examination measures, identification of segmental involvement utilizing kinematic subgroups would also facilitate treatment planning and follow-up care.

No author of this paper has a conflict of interest, including specific financial interests, relationships, and/or affiliations relevant to the subject matter or materials included in this paper.

Declarations of interest

None.

Table 3
Constructs of the seven principal components.

Principle Component (PC)	Construct	Principle Component (PC)	Construct
PC1	Hindfoot Inversion/Forefoot Varus	PC5	Sagittal Hindfoot Plantarflexion
PC2	Sagittal Forefoot Dorsiflexion	PC6	Hindfoot and Forefoot Range of Motion
PC3	Transverse Forefoot Abduction	PC7	Tibia Obliquity
PC4	Transverse Hindfoot Internal Rotation		

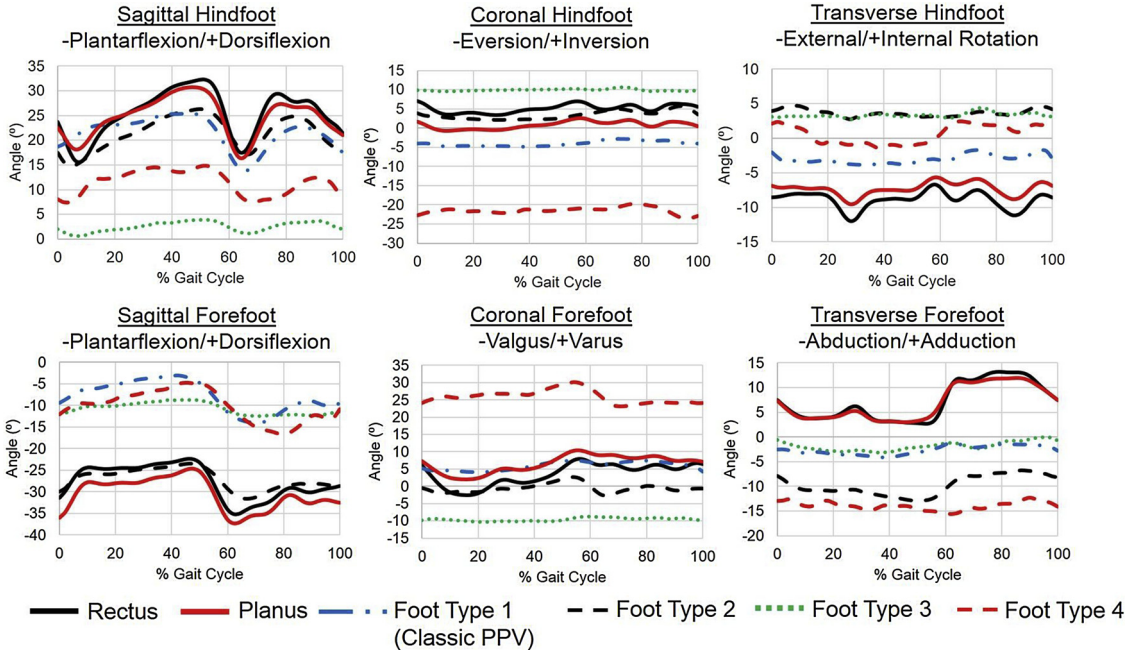

Fig. 1. Mean multi-segment kinematics for each foot type among the Rectus Foot Type, Planus Foot Type, and Foot Types 1–4.

Table 4
The number of participants assigned to each subgroup, interpretation of the subgroups, the means of the individual principal component scores, and comparisons of prinicpal component scores to the Rectus Foot Type.

Subgroup	Population (n = 80)	PC1	PC2	PC3	PC4	PC5	PC6	PC7
Rectus Foot Type	n = 17; 15 TD, 2 CP	37.8	−156	47.4	−19.7	72.3	48.7	−7
Planus Foot Type	n = 19; 13 TD, 3 CP	−74.4*	−138	44.1	−25.7	67.7	48.8	−7.8
Foot Type 1	n = 12; 12 CP	−47.8*	−24.2*	−20.4*	−5.8*	46.1	51.7	−8.4
Foot Type 2	n = 16; 2 TD, 14 CP	19.5	−107.0*	−36.7*	17.4*	71	47.8	−4.9
Foot Type 3	n = 8; 1 TD, 7 CP	89.3*	−43.1*	−6.8*	22.8*	0.7*	38.7	−10.3
Foot Type 4	n = 8; 8 CP	−176.0*	−46.8*	−51.0*	4.2	36.3*	63.5	−4.7

* Represents a significant difference from the Rectus (Control) Foot Type at $p < 0.05$.

Acknowledgements

The authors would like to thank Ms. Kathryn Reiners for her assistance with data collection, as well as, the children and families who gave their time to participate in this project. This work was supported in part by the US Department of Health and Human Services - National Institute on Disability, Independent Living, and Rehabilitation Research (NIDILRR): Advanced Rehabilitation Research Training in Pediatric Mobility for Physicians and Engineers. 90AR5022-01-00 (Formerly H133P140023-14).

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