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Cluster analysis to identify foot motion patterns in children with flexible flatfeet using gait analysis—A statistical approach to detect decompensated pathology?

Harald Böhm[a,*], Claudia Oestreich[a,b], Roman Rethwilm[a,c], Peter Federolf[c], Leonhard Döderlein[a], Albert Fujak[d], Chakravarty U. Dussa[a]

[a] Orthopaedic Hospital for Children, Behandlungszentrum Aschau GmbH, Bernauerstr. 18, 83229 Aschau i. Chiemgau, Germany
[b] Chair of Preventive pediatric, Department of Sport and Health Sciences, Technical University of Munich, Georg-Brauchle-Ring 60/62, 80992, München, Germany
[c] Department of Sport Science, University of Innsbruck, Fürstenweg, 6020, Innsbruck, Austria
[d] Friedrich-Alexander-University of Erlangen-Nürnberg, Department of Orthopaedic Surgery, Rathsberger str 57, 91054, Erlangen, Germany

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ABSTRACT

Introduction: The paediatric flexible flatfoot constitutes the major cause of clinic visits for orthopaedic foot problems. It shows variations of deformities in different planes and locations of the foot and its indication for treatment have been extensively discussed. Despite its high prevalence there exists no classification of flatfeet during walking as a prerequisite for treatment decision. Therefore, the aim of this study is to classify flexible flatfeet based on 3D foot kinematics during walking.

Methods: Patients age 7–17 years with flexible flatfeet (N = 129, 255 feet) of non-neurogenic or syndromic origin, were retrospectively included. Patients underwent gait analysis using the Oxford Foot Model after standard clinical examination. A k-means cluster analysis was performed on 3 scores derived from the principal component analysis of the foot kinematic waveforms over the gait cycle. Gait and clinical parameters were then statistically tested between clusters.

Results: Cluster analysis revealed two groups of flexible flatfeet that were discriminated best by the inversion at push-off during walking. Cluster 2, including 110 feet, showed an average eversion instead of an inversion at push-off and a lower number of heel rises in the clinical test. Both was significantly different between clusters ($p < 0.001$).

Discussion: Based on the findings, the resultant clusters can be interpreted as describing compensated and decompensated feet, with the latter presenting a group that may require surgical interventions, even if they are not yet present with pain. The hindfoot inversion capability at push-off is the most important variable in the 3D gait analysis to classify flexible flat feet.

1. Introduction

The flexible flatfoot (FFF) is a common foot problem in the paediatric age group. It is said to be the most common cause of visit to a paediatric foot clinic [1]. It is a complex deformity showing a dominance of severity in different planes [1–3]. The most common form is characterized by a subtalar valgus, a longitudinal sag at the talonavicular joint and a midtarsal abduction [3]. A flat arch is typical for children at birth but resolves spontaneously until 6 years of age [4]. However, in about 24% of school children a flatfoot persists and may require treatment [5]. The flexible flatfeet must be carefully differentiated from those which are rigid. The rigid deformities always need interventions and constitute approximately 5% of the flatfeet. Usual causes for rigid flat feet are tarsal coalition or congenital vertical talus [1,6]. In contrast, the treatment of the flexible flat feet is highly controversial and is extensively debated [1,7].

Surgery is considered in symptomatic feet not responding to conservative measures. The frequent symptoms are pain, fatigue, or an inability to participate in daily activities [8]. A quantitative description of the foot deformity is usually done on a standardized weight- bearing X-ray of the foot in 2 planes. One suggestion of a radiographic criterion that may indicate surgical intervention is the TMT index. It is calculated

* Corresponding author at: Gait Laboratory, Orthopaedic Hospital for Children, Behandlungszentrum Aschau GmbH, Bernauerstr. 18, 83229 Aschau i. Chiemgau, Germany.
E-mail address: h.boehm@bz-aschau.de (H. Böhm).

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as the sum both of talo-1st metatarsal angles in the anterior posterior and lateral standing radiographs [2]. Others found that lateral navicular displacement (assessment based on the talonavicular coverage angle) was the most striking feature of symptomatic flatfoot requiring corrective surgery [9]. Based on the radiographs of the feet in 2 planes Bourdet et al. classified paediatric flatfeet into 4 groups. These four classes were isolated subtalar valgus, isolated midtarsal abduction, both subtalar valgus und midtarsal abduction and cavovalgus deformity [3]. Labowitz introduced an algorithm based on the theory of planar dominance and the centre of rotation of angulation to assign the best procedure to each type of flatfoot [8]. The authors claim that this allows the optimal correction of the flatfoot based on biomechanical considerations. However, it has been reported that static foot posture showed little relations to dynamic foot kinematics [10–12]. Therefore, classifications based on radiographs acquired during relaxed standing do not reflect the dynamic situation during activities such as walking, running and jumping. An explanation may be that under static loads the shape of the longitudinal arch is determined by the shape and interrelationship of the bones, coupled with the strength and flexibility of the joint capsules and ligaments. Whereas, during locomotion, muscular activity may considerably add to the stability of the arch and may also compensate for structural problems existing in stance [13]. Mann and Inman showed a greater intrinsic muscle activity to stabilize the transverse tarsal and subtalar joints in individuals with flatfoot compared to individuals with an average height arch [13].

Based on these differences between static and dynamic foot posture, Mosca claimed that “Radiographs of the flexible flatfoot are not necessary for diagnosis, but they may be indicated to help with the assessment of uncharacteristic pain, decreased flexibility, and for surgical planning” [7]. Rather than a radiographic examination, the clinical assessment of a child with a flexible flatfoot should consist of a general examination of the musculoskeletal system, and the walking pattern [7]. Besides observation of the walking pattern, instrumented 3D gait analysis has the advantage of a quantitative description of the function of flatfeet in all three planes of motion with respect to typically developed feet [14–17]. The differences in foot kinematics between FFF and typically developed controls in the studies vary depending on the study population and the variables under investigation. Interestingly, differences in foot kinematics between symptomatic and asymptomatic FFF could not be found [17]. However, there exists no standard definition of FFF during walking, making the understanding, examination and treatment of the condition extremely difficult [6]. Hence, there is an urgent need to look at the foot function and characteristics during walking. This may enable us to differentiate and classify the characteristics and patterns of the FFF during walking which may provide us with indications for treatment.

Therefore, the aim of this study was to classify motion patterns among paediatric idiopathic flexible flatfeet using 3D kinematic foot data during walking. In compliance to the classification based on radiographic images, we expect four clusters with subtalar valgus, midtarsal abduction, both together, and cavovalgus deformity [3].

2. Methods

2.1. Participants

In the study patients between 7 and 17 years with idiopathic flexible flatfeet were included. These patients attended our outpatient clinics between January 2011 and July 2018. They were referred by the orthopaedic consultat to the gait laboratory when they perceive pain and did not respond to orthotics within a reasonable time. Besides pain, excessive deformities in the radiographic evaluation may be another reason.

Standardized 3D gait analysis was performed following a written consent and the study was approved by the local ethics committee. Inclusion criteria were available 3D gait analysis, foot kinematics and full standard clinical examination data. Excluded were flatfeet of neurogenic or syndromic origin, rigid feet, coalitions, rheumatoid arthritis and previous orthopedic interventions. Children with obesity were excluded, since structural changes in the arch of the foot may be caused by excessive body weight [18]. Obesity was defined according to the age dependent body mass index threshold [19]. As a reference, the foot kinematics of 52 typically developed (TD) feet of 26 children and adolescents between 7 and 17 years were selected from the gait lab database.

2.2. Clinical examination

The clinical examination was documented on a standard document sheet developed for routine use in the gait laboratory and was repeated the same way in all patients. Four parameter groups specific for FFF diagnosis were evaluated in this study: 1. passive ankle dorsi- and plantarflexion was measured with ruler based goniometry. The patient was positioned supine, the knee extended and the ankle was redressed to the neutral position and the foot was prevented from supinating during dorsiflexion 2. Numbers of single leg heel rises with extended knee, single leg jumps and seconds of single leg balance. 3. Torsional deformities were determined by the hip midpoint of rotation and tibial torsion, both measured with the patient prone and the knees flexed to 90 ° [20]. 4. Passive reposition of the subtalar joint and talonavicular joint was examined in a seated position to confirm the inclusion criteria for flexible flatfeet. Type, location and intensity of pain were recorded from 0 to 10 (10 being severe pain) using the visual analogue scale.

2.3. Gait analysis

A Vicon Nexus system with 8 MX-Cameras was used to capture foot kinematics during barefoot walking at self-selected speed along a 13 m walkway. Markers were placed according to the Oxford Foot Model (OFM) [21] and the modified Vicon Plug-In gait Model [22]. Marker data were sampled at 200 Hz and force plate data were sampled at 1000 Hz via two force plates (AMTI). Gait analysis was repeated until 6 clean steps on the force plates from each foot could be obtained.

2.4. Cluster analysis

The principal component analysis (PCA) was facilitated to identify the most relevant and discriminative foot kinematic waveform patterns. The PCA avoids collinearity and enables to extract a single score for the first 3 independent eigenvectors that describe the kinematic FFF pattern of each foot and can be used for a cluster analysis. In detail, the selected waveforms (400 time points/gaitcycle) were the angles between hindfoot and tibia in the sagittal and frontal plane as well as between forefoot and hindfoot in sagittal, frontal, and transverse plane. The hindfoot to tibia rotation angle was not used, since its reliability was found to be low [21,23]. This results in 3 individual scores for each foot that describe how good its waveforms represent the gait patterns defined by the first 3 eigenvectors.

Based on these 3 scores of the patients’ feet, the suitable number of clusters was determined by the hierarchical ward clustering method [24]. The k-means clustering technique with the defined number of clusters was then applied to identify the feet in the different subgroups [25].

Having identified the patients in the different clusters, selected gait and clinical parameters could be compared between clusters. A one factor ANOVA with post-hoc test between clusters was performed on a significance level of $p < 0.001$. Both feet of patients were treated independently, since no significant correlations $r > 0.4$ were observed between the left and right leg.

2.5. Treatment recommendations

To discuss the clinical relevance of the resultant feet classification, the medical record was screened for surgeries that were recommended. It was distinguished between arthroereisis, osteotomy, and medial malleolar epiphysiodesis. The recommendation was done by experienced medical doctors in the outpatient clinic, based on a synopsis of clinical, radiographic, pedobarographic and 3D gait analysis data. A chi-squared test was used to test the different numbers of surgeries in the different clusters on a significance level of $p < 0.001$.

3. Results

3.1. Patients

The study included 129 children and adolescents with idiopathic flexible flatfeet. Mean age was 11.7 (SD = 2.17) years, mean BMI 18.9 (SD = 2.64) [14–27] kg/m2, 60% were males. In 2 Patients only one foot was included, since only less than 6 valid steps could be evaluated for one side. One patient had only unilateral involvement. As a result, a total of 255 feet were included in the study.

3.2. Cluster analysis

The foot kinematic gait patters of the first 3 eigenvectors are shown in Fig. 1. The first pattern that showed most of the variance in the foot kinematics contains the hindfoot to tibia inversion and forefoot to hindfoot supination. The second pattern consisted of the forefoot to hindfoot abduction, and the third pattern showed a hindfoot to tibia extension together with the forefoot to hindfoot extension.

The suitable number of clusters with the hierarchical ward method was evaluated with the inverse scree test and silhouette coefficients are shown in Fig. 2. Two clusters showed the greatest reduction in the inverse scree test and the maximum mean silhouette coefficient. In consequence, the k-means clustering was done between two clusters, separating the patient collective with FFF into cluster 1 with 145 feet and cluster 2 with 110 feet.

Table 1 shows mean values of anthropometry, clinical and gait data of both clusters. There were no significant differences in age and BMI between clusters. Ankle dorsiflexion was significantly reduced in FFF compared to TD but not between clusters. Cluster 2 showed a significantly lower number of single leg heel rises and single leg jumps in the clinical function test and no inversion at push-off during walking that suggests that their muscles had insufficient function and were not able to maintain normal foot motion. Therefore, the cluster 2 was named decompensated (DC) whereas the feet in cluster 1 showed adequate muscle function and foot motion this cluster was named compensated cluster (CC).

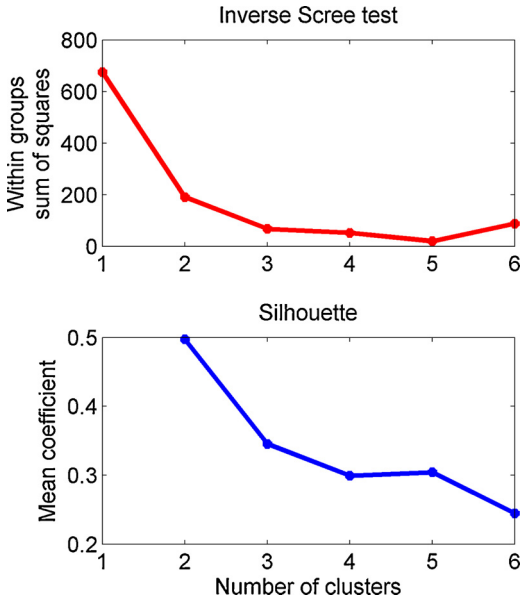

Fig. 2. Inverse scree test and silhouette test to determine the suitable number of clusters. Two clusters showed the greatest reduction in within groups' sums of squares and the highest silhouette coefficient.

Fig. 3 shows the kinematic waveforms of the two clusters calculated with the Oxford foot model compared to TD controls. The cluster DC (110 feet) was characterized in the sagittal plane by a reduced dorsiflexion between hindfoot and tibia and increased forefoot to hindfoot dorsiflexion. In the frontal plane the cluster DC was characterized by excessive eversion in stance and no inversion at push-off and increased supination of the forefoot. In the transverse plane the DC cluster showed excessive forefoot abduction during stance and swing phase. ANOVA supports the significant deviations between the DC and CC clusters and TD controls in all foot kinematic parameters ($p < 0.001$). The compensated feet showed only significant differences in the hindfoot to tibia dorsiflexion and mean forefoot abduction compared to TD controls. Peak ankle moments and powers and the rotational profile did not reveal any differences between clusters or TD controls.

Fig. 4 shows our treatment recommendations. The DC cluster received twice as many arthroereisis and about three times more osteotomies and epiphysiodeses. The difference was significant for arthroereisis and osteotomies both $p < 0.001$, but not for epiphysiodeses

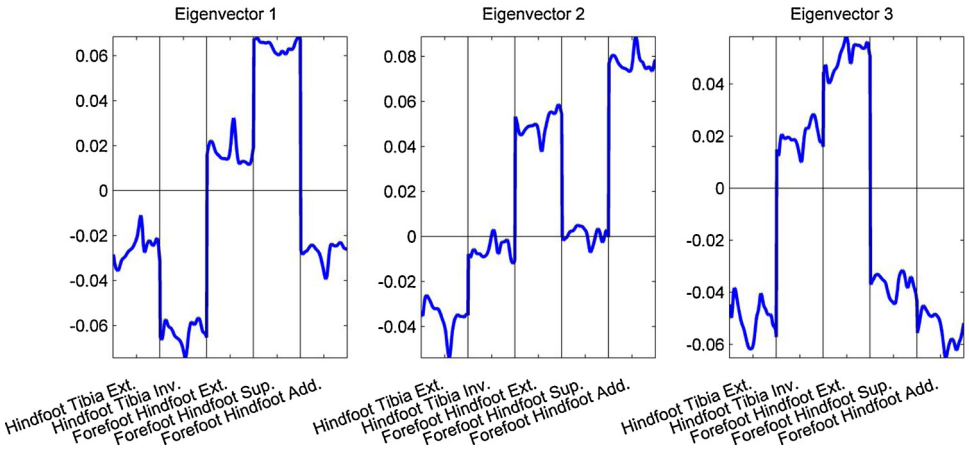

Fig. 1. First 3 Eigenvectors and their weights from the foot kinematic curve waveforms obtained by principal component analysis. The horizontal axis shows the gait cycle of each kinematic curve waveforms, the vertical axis their weights at certain time points of the gait cycle.

Table 1
Mean values and standard deviation of anthropometry, clinical tests, foot kinematics, rotational profile and ankle power of both clusters compared to typically developed (TD) controls. Significance level for ANOVA statistics was $p < 0.001$. Significant post-hoc differences between both clusters of patients with flexible flatfeet are marked in bold.

Anthropometry	FFF CC	FFF DC	TD	p	CC-DC	CC-TD	DC-TD
number of feet	145	110	52	N/A			
age [years]	12.0 (2.17)	11.4 (2.1)	11.9 (3.8)	0.139			
sex [males/females]	79/66	75/35	25/27	N/A			
bodyweight [kg]	46.9 (11.4)	45.6 (10.9)	42.8 (16.1)	0.301			
bodyheight [cm]	157 (12)	154 (14)	150 (19)	0.297			
BMI [kg/m*m]	18.8 (2.6)	18.9 (2.7)	18.2 (3.0)	0.376			
Clinical assessment							
passive ankle dorsiflexion [°]	10.6 (6.7)	10.8 (7.3)	20.0 (5.8)	< 0.001	0.846	< 0.001	< 0.001
passive ankle plantarflexion [°]	36.6 (9.0)	35.3 (9.4)	40.5 (8.1)	0.008			
single leg heel rises [No]	16.0 (5.5)	13.5 (6.4)	17.3 (2.5)	< 0.001	< **0.001**	0.149	< 0.001
single leg jumps [No]	19.8 (3.2)	17.4 (5.7)	20.0 (0.3)	< 0.001	< **0.001**	0.741	0.005
single leg balance [sec]	18.2 (4.4)	15.0 (6.4)	19.0 (2.0)	< 0.001	< **0.001**	0.235	< 0.001
hip rotation midpoint [°]	5.4 (11.43)	3.7 (11.0)	4.5 (6.7)	0.482			
tibia torsion [°]	−22.1 (8.6)	−18.6 (8.5)	−23.5 (5.9)	0.001	0.002	0.325	0.001
pain score [1–10]	4.8 (1.8)	4.8 (1.8)	N/A	N/A	1.0	N/A	N/A
Spatio-temporal parameters							
velocity [non-dimensional]	0.45 (0.04)	0.45 (0.03)	0.48 (0.03)	0.003			
step length [non-dimensional]	77.7 (7.4)	77.6 (6.4)	82.1 (8.5)	0.002			
cadence [non-dimensional]	0.58 (0.04)	0.58 (0.02)	0.59 (0.03)	0.354			
Foot kinematics during stance [°]							
hindfoot to tibia peak dorsiflexion	9.4 (4.5)	6.2 (4.4)	14.1 (4.8)	< 0.001	< **0.001**	< 0.001	< 0.001
hindfoot to tibia peak eversion	−6.9 (3.8)	−16.2 (4.3)	−7.7 (5.0)	< 0.001	< **0.001**	0.266	< 0.001
hindfoot to tibia inversion at push off	5.4 (4.7)	−4.4 (5.0)	7.4 (5.2)	< 0.001	< **0.001**	0.021	< 0.001
forefoot to hindfoot peak dorsiflexion	8.6 (4.3)	11.2 (4.6)	6.2 (4.8)	< 0.001	< **0.001**	0.002	< 0.001
forefoot to hindfoot mean supination	6.0 (3.9)	15.0 (4.8)	3.7 (5.6)	< 0.001	< **0.001**	0.002	< 0.001
forefoot to hindfoot mean adduction	−0.8 (5.4)	−4.9 (5.4)	6.5 (7.4)	< 0.001	< **0.001**	< 0.001	< 0.001
Rotational profile during walking [°]							
mean hip rotation stance	3.4 (2.6)	3.9 (3.4)	3.6 (2.6)	0.342			
mean knee rotation stance	−9.5 (11.3)	−6.6 (11.4)	−9.4 (10.2)	0.114			
mean foot progression stance	−5.3 (7.1)	−6.0 (7.8)	−5.4 (5.6)	0.724			
Ankle kinetics							
peak ankle moment stance [Nm/kg]	1.4 (0.1)	1.3 (0.2)	1.4 (0.2)	0.056			
peak ankle power gait cycle [W/kg]	4.0 (0.9)	3.9 (0.9)	4.2 (0.9)	0.140			

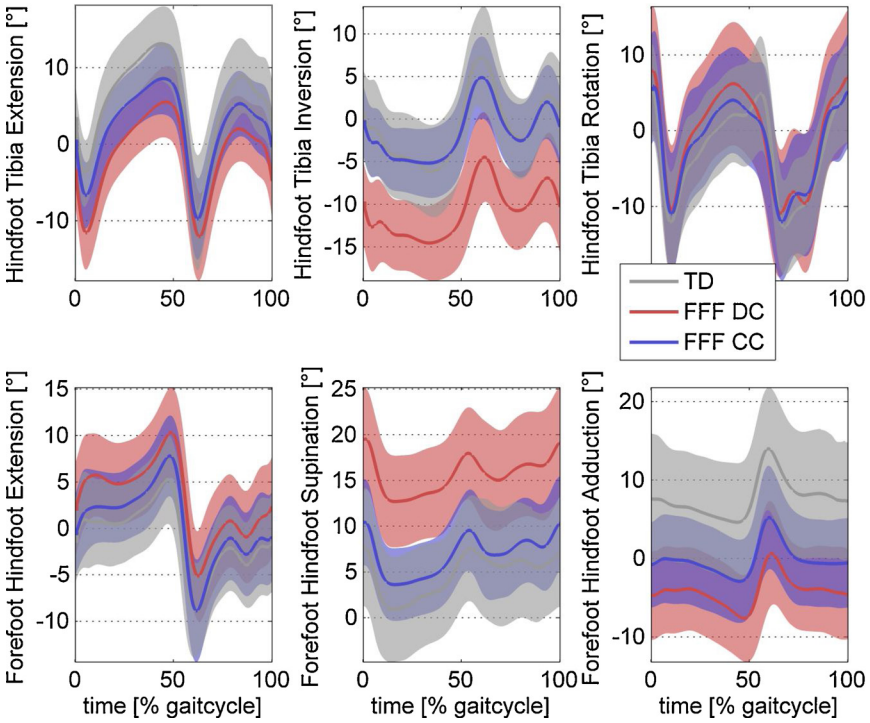

Fig. 3. Average foot model curves of the compensated (FF CC) and decompensated (FF DC) clusters of flexible flatfeet, with respect to the laboratory reference group (TD) in gray.

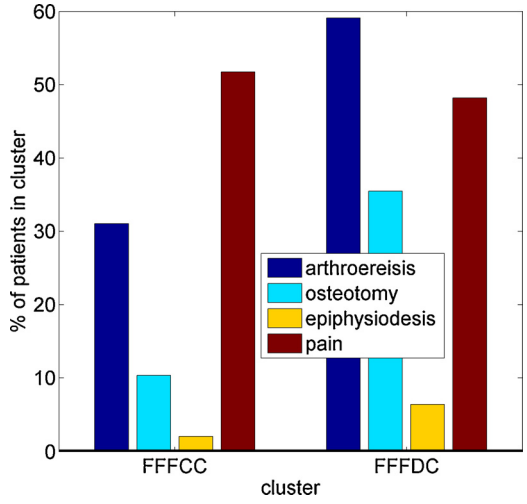

Fig. 4. Interventions in both clusters.

(p = 0.08). The percentage of patients with perceived pain was similar with 52% of patients in the CC and 48% in the DC cluster with exactly the same mean score of 4.8 (SD = 1.8).

4. Discussion

The cluster analysis divided this patient collective with FFF in 2 distinct groups that can be interpreted as muscular compensated and decompensated feet, respectively. No further functional types or subtypes could be clearly identified. This was contrary to the expectations from standing radiographic classification that revealed 4 deformation types [3]. The reason may be that the forces during standing bear little resemblance to those during gait in terms of magnitude or direction and internal forces from muscles are largely absent [26]. Therefore, kinematics resulting from the forces applied to the foot in gait will differ from those in a static standing pose. Therefore, the classification on muscular compensation may be unique to the walking situation. The muscular contribution may cover the classifications obtained from radiographs during relaxed standing.

4.1. Clinical relevant interpretation of clusters

It must be kept in mind that the cluster analysis used in the current study is a pure mathematical analysis of foot kinematics, when applying the results to a clinical setting and all the more during surgical decision making. Nevertheless, the cluster classification into DC and CC gives not only logical but also a meaningful clinical implication. This is reflected in the frequency for indication of a surgery in the DC cluster. However, it is interesting to note that this classification does not throw any light on the cause of pain in FFF. The incidence of pain was similar in both clusters but the incidence of surgery was different.

The interpretation of clusters as compensated and decompensated feet originates from the principal component analysis that determines the hindfoot to tibia inversion at push-off as the parameter with the most discriminative value in FFF. The decompensated cluster showed on average 4.4° eversion at push-off whereas the compensated cluster showed 5.4° inversion at push-off, which is more similar to 7.4° inversion in TD controls. Inability to invert the heel at push-off may be interpreted mainly as muscular deficit during propulsion. A foot is defined as decompensated when the heel fails to invert to become a more rigid and stable lever for thrust [27]. It has been shown that the locking of the midfoot is influenced by hindfoot position [28]. With the calcaneus in eversion, the calcaneocuboid and the talonavicular joint have parallel axes of rotation, resulting in a flexible transverse tarsal articulation. During inversion the axes of rotation diverge, resulting in a rigid midfoot [28]. The instable lever arm of the midfoot in the decompensated group is demonstrated by a significantly increased peak dorsiflexion in the midfoot. This may result in less peak dorsiflexion of the rear foot at the second ankle rocker rather than a reduced passive ankle dorsiflexion in the clinical test that not different between both clusters.

Regarding the surgical intervention between 2 clusters groups; osteotomies were often performed in the DC cluster. However 32% of feet in the compensated cluster still received a surgical intervention and mostly an arthroereisis. All feet treated in the compensated group were painful. This shows that irrespective of the classification of the feet may it be radiological or functional, pain is an important factor when indicating surgery. This is supported by another study that did not find any significant differences in the foot kinematics between symptomatic and asymptomatic feet during walking [17] and a heel raise test [29]. Anatomically restoring the footshape and kinematics in flatfeet requires increased muscular activity, making the muscles more susceptible to injury.

Patients in the decompensated group were also treated when they did not perceive pain. However, they may experience typical symptoms as fatigue of the foot, reduced performance, and swelling of the inner side or excessive shoe wear that was unfortunately not documented in our questionnaire that focussed only on pain.

4.2. Consequence for therapy and decision making

It is easier to get an agreement for treatment in a child with a symptomatic flatfoot. The difficulty lies in convincingly indicating a surgery in a pain free flatfoot. A pain free decompensated foot, if left untreated, may result in fixed deformities of the rear- and forefoot in adulthood as a result of chronic instability aggravated by body weight and age over time [30]. This may end in arch pain and tendonitis of the tibialis posterior [27].

The results of the current study help to identify decompensated feet during walking. Inversion at push-off was the most important discriminator between decompensated and compensated flatfeet, followed by forefoot abduction at push-off and lastly by a reduced peak dorsiflexion of the hindfoot to the tibia, combined with an increased dorsiflexion of the forefoot. Hindfoot inversion, the most important characteristic for distinguishing decompensated from compensated feet during walking, was measured in this study by 3D gait analysis. However, in clinical practice it may be more easily assessed by the standing on tip-toes although not quantitatively [7]. An eversion of the heel during toe-standing despite a flexible rearfoot, indicates most likely a decompensated foot.

5. Limitations

The accuracy of 3D foot kinematics is influenced by how closely the trajectories of surface markers represent the motion of underlying bones [31]. The inter-observer repeatability of the OFM in children with foot deformities was best in the sagittal plane (flexion/extension) with the poorest repeatability in the transverse plane hindfoot to tibia rotation [21,23]. The latter was excluded in the cluster analysis so that arbitrary variations due to the examiner were expected to be rather small in the current study.

The decision for surgical intervention was a synopsis of all available information including gait analysis. Therefore, excessive deviations in foot kinematics may have increased the likelihood for recommendation towards an intervention. This limits the explanatory power of the number of surgeries to evaluate the clusters.

For the decompensated cluster a reduced function during walking would be expected, that may result in a reduced walking speed, peak moments and powers at the ankle joint. However, a significant difference between clusters was not found for speed and power and only a trend for a reduced peak ankle moment (p = 0.056). This is probably

due to the low demands on the foot during walking in the gait lab. Measuring the gait parameters during running would have revealed more differences between clusters. More intense were a single leg heel rise and jumping test that showed lower performance in decompensated feet in this study. It may also be recommended to use a more intense agility test, simulating the situation during sportive game play, to reveal differences in performance between FFF types [32].

6. Conclusion

In the current study we were able to discriminate compensated from decompensated flexible flatfeet based on gait analysis. This is important, since decompensated feet are more prone to require surgical interventions, even if they are not yet associated with pain. Hindfoot to tibia inversion at push- off was the most important discriminator that describes a compensated foot. Inversion of the heel can also be evaluated in the toe-standing test that has been recommended in the clinical examination of flatfeet [7,33].

Conflicts of interest

None.

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