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étude cinématique et morphologique en 3dimensions du pied bot varus équin congénital idiopathique

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Kinematic and biplanar 3D static reconstruction matching: assessment in clubfeet

Abstract

Background

Clubfoot (CF) is a pathology that affects both the morphology and the function and an objective treatment addresses both issues. Yet, to day, few studies combine radiological evaluation and Gait Analysis (GA) in clubfoot children assessment.

The aim of this preliminary study was to assess walking age CF patients combining clinical assessment, 3-Dimensional radiographic evaluation and multi-segment foot model gait analysis so as to link results of these methods, and estimate feasibility in a clinical context.

Methods

We included 10 children with a history of unilateral CF. Feet were classified following the Ghanem and Seringe classification, and a complete physical examination was performed. After placing of the skin markers, a biplanar X-Ray was acquired and the gait analysis recorded. Uncertainty was evaluated through repeatability of placement markers and Monte Carlo error estimation. Finally, 3-Dimensional reconstructions of the feet were performed, and both radiologic and kinematic data were analysed.

Findings

Concerning radiographic evaluation, all parameters were within the range of reference values for Typically Developing children. Calcaneal Pitch and Tibio Calcaneal Angle were different between affected and non-affected feet. Uncertainty was evaluated as low, which allowed report of kinematic and dynamic data of the joints results. A significant difference of maximum mobility of metatarsal to hallux dorsiflexion during stance and of minimum of ankle dorsiflexion moment was reported.

Interpretation

To our knowledge, no previous study used the combination of radiological parameters with this Multi-segment Foot Model gait analysis on CF subjects. It appears that despite the very good functional results of the concerned feet, some radiological and motion differences can be detected thanks to this multi segment foot analysis, making this analysis of high interest compared to GA considering the foot as a one rigid-body segment. Therefore this work opens a wide range of following research combining the 3dimensional radiological study and the Rizzoli multi segment foot analysis of the feet of the children.

Keywords

Clubfeet; children; 3dimensional radiographs; gait analysis; feasibility

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Introduction

Clubfoot (CF) is a congenital pathology characterized by a triple deformation of the ankle-foot complex: equinus, adduction and supination, involving bony and non-bony structures. At birth, consensus is now made for a non-surgical treatment, either based on physiotherapy (French functional therapy[1]) or on casts (Ponseti method[2]). Both treatments are efficient, and surgery is now almost always avoided. However, children born with a CF are reassessed periodically during childhood, as the deformities tend to relapse because of growth. The relapse is often related to muscle imbalance[3], and the early detection of this abnormality is of interest to achieve the more efficient treatment. Related to the complex structure of the foot, and to the combined abnormalities in CF proper assessment of deformities is crucial to plan the treatment options aiming at a functional and painless foot. So far, assessment of clubfoot relies on observations of generic measurements and clinical features[4].

Weight bearing standard radiograph is the only imaging method used by clinicians in daily practice to describe and follow CF patients[5]. These images are essential to quantify bone relationship abnormalities in the sagittal or transverse plane. It has been reported in the literature that several radiographic angles can be used as biomarkers to study CF patients[4,6-9].Radiographic images, however, provide limited information concerning the exact location of the bones with respect to others, as it is a 2-dimensional projection of a 3-dimensional object, and is subject to projection bias. In a recent work[10], 3-dimensional landmarks and associated radiological parameters obtained throughout a low-dose biplanar radiographic system in children normal feet were shown to be reliable[10]. Combined with the already validated use of the 3-dimensional reconstructions of lower limbs in children[11], it opens the way to a new assessment method of lower limb and foot in children.

In addition, Gait analysis (GA) and dynamic investigation of the foot is now frequently used in literature and in clinical practice to describe the feet, or evaluate treatment results[12-16]. Authors globally report on increased internal rotation of the foot, and lowered mobility of the ankle joint in CF patients compared to non-affected ones[17,18]. These studies usually consider the foot as a one rigid-body segment, allowing for example in toeing of the whole foot but with no further understanding of the structure that is inducing this characteristic. To describe more precisely this inter-segmental motion, a high number of markers was proposed to define the parameters of interest and to create the segments between which the motion is located during walk. In the adult foot, the ideal model should consider the foot as a multi-body segment to allow the calculation of motion within the foot[19-21] . In children, the marker placement should also be reliable to be used in small dimensions feet[12,22,23], and these small sizes of the foot raise technical issues, as the lowered distance between markers may increase the error associated to the position detection on the motion capture system. After analyzing several protocols[15-22], we choose the Rizzoli Multi-segment Foot Model proposed by Leardini et al[19] as the most suitable for small and deformed feet, and the most likely to describe internal mobility of the foot. Indeed, this model is reported to have a good reproducibility and considers the foot as a multi segment object, allowing internal motion evaluation. Moreover, the procedure is adequately describe in the report[19] to allow to reproduce the study (Deschamps 24).

CF is a complex congenital malformation, combining structural and functional deformities. Therefore, the evaluation of CF is made jointly on a morphological and on a functional point of view by clinicians. However, few studies combine radiological evaluation and GA in clubfoot children assessment[16, 17,25]despite this is the way to link the functional and the anatomical status of CF treatment. However, it has already been suggested that a comprehensive study of walking age CF children combining GA, pedobarography, kinetic, and patient based outcome would be of interest[18]. GA system and biplanar images and related 3D reconstructions are now easily available for clinicians in health centres. The interest to combine clinical evaluation and these 2 paraclinic ways to evaluate the lower limb and feet has not yet been studied.

Therefore, the aim of this preliminary study was to assess in walking age CF patients the matching of kinematic and radiographic 3dimensional data combining clinical assessment, biplanar radiographic images and a Multi-segment Foot Model gait analysis.

Method

After approval by the ethical committee (Comité de protection des Personnes CPP NX06036), we included 10 children (9 boys and 1 girl) aged from 7 to 11 years old. They were all volunteers, recruited in the outpatient orthopaedic consultation yard. They all had a history of unilateral CF treated in the first week of life by the same Functional method[1]. The only clinical residual flaw accepted to be included in the series was a minor excessive supination of the forefoot, or lowered support of the head of the 1st metatarsal on the floor. The unaffected lateral foot was used as control group.

Feet were classified following the Ghanem and Seringe classification[26] at the time of inclusion. Complete physical examination was also performed, and data as severity at birth, involved side, age, weight, height and past history of surgery were collected.

1. Subject preparation and imaging

After clinical evaluation of the child, and Ghanem and Seringe score completion, the same orthopaedic surgeon, experienced in anatomical palpation, placed 46 skin markers adhering to a written protocole[19] (Figure 5.1).

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Figure 5.1: placement of markers following the Rizzoli Multi segment model[19]

They were placed on the foot and lower limb avoiding tendon and joint motion during gait. To perform the biplanar X-Ray, mini radiologic markers were placed instead of the ones used for the GA, so as to allow correct viewing of the bony structures (Figure 5.2).

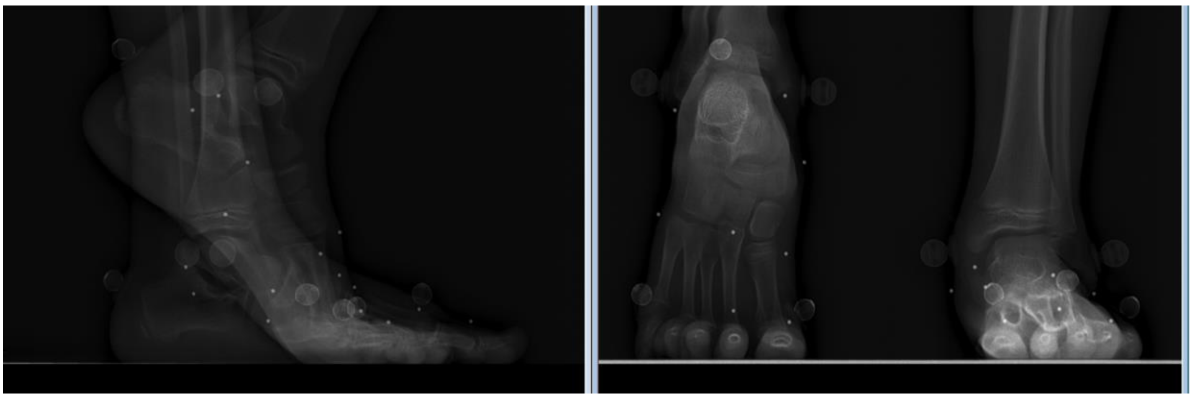

Figure 5.2: lateral and anteroposterior view of the biplanar X-ray acquisition with the markers already positioned.

Then, biplanar X-Ray images of the whole lower limb (including pelvis and feet) were acquired using the EOS device (EOS® Imaging, Paris, France). Three pairs of images were obtained: a whole body acquisition in the free standing position[27] and 2 specific incidences for the feet, one with the right foot in weight bearing position and the left one in ballerina half pointe work, the last incidence inverting the feet[10].
Finally, after placement of markers and EOS image acquisition, each clubfoot subject was asked to walk at self-selected pace a distance of approximately 5 m after a preliminary static reference capture image. A minimum of five valid trials was collected for each subject to ensure enough trials to provide for more reliable estimation of gait patterns. The validity of the walking trial was determined according to the correct passage through the force plates for each foot.

2. Post-process

3-D reconstruction of the pelvis and lower limbs were performed according to the method proposed by Chaibi et al[26] and Quijano and al.[28] using a custom-made software developed in the Institut de Biomécanique Humaine Georges Charpak at Arts et MétiersParisTech. For the feet analysis, the methodology proposed in Rohan et al.[29] was adapted. Then, based on anatomical landmarks, an initial parametric model of the foot was built, and then retroprojected on the AP and profile radiographs. Manual adjustments were then performed to improve the superposition of the projected elements on bone contours[10]. Commonly used radiological parameters were computed[30]: Calcaneal Pitch Angle (CPA), Tibio-Calcaneal Angle (TCA), Talo-Calcaneal Divergence (AP view) (TCD) ,Tibio-Talar Angle (TTA), Talo-Navicular's Coverage Angle (TNCA), Talo-Metatarsal Angle of Meary (TMAM) , Talo-Metatarsal Angle (AP view) (TMA), First Metatarsal bone to Floor Angle (FMFA).

Intra-operator repeatability was assessed by reconstructions of the feet of the patients 1 to 5 three times by the same observer.

Concerning GA, a repeatability study was performed on two healthy subjects (aged 8 and 10 years old) in order to estimate the error associated with marker placement following the protocol used by Schwartz et al[31]. The tester placed the marker on each subject three times and five valid trials were collected for each set of markers placed and for each subject. The results for inter-session and inter-trial variability were then computed and analysed. Then, error estimation was done based on the Monte Carlo simulation, to evaluate the impact of the marker placement variability and error on the final results.

For all subjects, kinematic and dynamic data were collected using a VICON motion capture system, combining 12 cameras and four synchronized AMTI force plates. From the markers, anatomical frames were computed for each considered segment in the foot. The definition of the segments and embedded frames were the one proposed by Leardini et al.[19].

In addition a foot frame was defined using the calcaneum, the 1st (MT1) and the 5th (MT5) metatarsal head. Y-axis was the one perpendicular to the plane formed by these 3 points, z-axis the one perpendicular to the y-axis and going through the MT1 and MT5 points, x-axis the perpendicular one in the gait direction. Plantar/dorsal flexion was represented by the rotation x-axis, abd/adduction was defined by the rotation about the y-axis, and Inv/Eversion represented the rotation around the z-axis (y-axis). The interaction between the following pairs of segments was computed: calf-hindfoot (Ankle), hindfoot-midfoot (Cal-Mid), midfoot-forefoot (Mid-Met), hindfoot-forefoot (Cal-Met), metatarsal-hallux (Met-Hal), hip and knee. Reported inter-segmental motions were the variation of position of the distal segment relative to the proximal segment with respect to the position of reference during the static acquisition and were observed on the sagittal, transverse and coronal plane. The average of all inter-segmental angles of the group of subjects was taken to be the representative trial and used for presentation of results and discussion. The standard deviation was used to create the amplitude corridor of the results.

From ground reaction forces and kinematics, joint moments and powers were also computed through an inverse dynamics procedure.

3. Statistical analysis:

Concerning the 3dimensional radiological assessment, the standard deviation (SD_r) of intra-operator repeatability was computed, and then estimated considering 95% Confidence Interval (95% CI) as 2*SD_r. Anatomical landmarks and geometric elements were selected when 95% CI of their position was under 4 mm. Radiological parameters were considered as repeatable within a 95% CI of 3°.

Then, values of parameters of the affected (A) side were compared to reference values of healthy subjects previously reported[11] and to the contralateral non-affected (NA) one. Concerning the pelvis parameters, they were compared to values of a reference population[11].

Concerning walking study, Comparison between the A and the NA side was done with the Student t-test (BiostaTGV® software) considering a statistical difference for a p-value<0.05.

Results

Ten children were included. Average age was 9.2 years old (7-11). Complete data concerning these children are reported in table 5.1.

	Affected side	Sex	Age (years old)	Initial severity (equinus)	Achille's tenotomy	Score (Ghanem and Seringe)
1	Left	Male	10	50°	Yes	96
2	Right	Male	11	60°	No	90
3	Right	Male	10	20°	No	100
4	Right	Male	8	70°	Yes	94
5	Right	Male	11	40°	No	96
6	Left	Male	8	50°	Yes	91
7	Left	Female	9	20°	No	91
8	Left	Male	7	30°	No	99
9	Right	Male	8	50°	Yes	88
10	Left	Male	10	45°	Yes	100

Table 5.1: population parameters

1. 3dimensional radiographic assessment

- a. Pelvic parameters: All parameters were within the range of reference values for typically developing (TD) children[11] (table 5.2).

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Parameter	Average Value	Reference population
Sacral slope	40 +/-8	38+/-8
Pelvic tilt	3 +/-9	6+/-7
Pelvic incidence	45 +/- 8	45+/-9

Table 5.2: pelvic parameters obtained from the biplanar reconstruction system. (Average +/-SD)

- b. Lower limbs: longitudinal, rotational and angular parameters were all within the range of already published values in TD children[11] (table 5.3).

Parameter	Affected foot	Non affected foot
HKS	5 ° +/-1	4° +/-1
FTA	178° +/-2	177° +/-1
FHD	35 +/-2	34 mm +/-2
NSA	142 mm +/-7	137° +/8
TMA	88°+/-1	89° +/-2
FMA	93° +/-1	92° +/-2
LN	36 mm+/-4	41mm +/-5
F/T	1+/-0	1+/-0
FT	25° +/-9	25°+/-12
TT	27° +/-23	27° +/-26

Table 5.3: lower limbs longitudinal, angular and rotational parameters: average +/-SD (FTA: femoro tibial angle, FHD: femoral head diameter, NSA: neck shaft angle, TMA: tibial mechanical angle, FMA: femoral mechanical angle, LN: length of femoral neck, F/T: ratio of femoral on tibial length, FT: femoral torsion, TT: tibial torsion)

- c. Foot:
    - Repeatability

Repeatability of the anatomical landmarks and primitives is reported in table 5.4.

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		x	y	z
Calcaneus	**Anterior point of the lower part**	1	3	1
	Postero inferior contact with ground	3	2	4
Hallux	**1st phalanx**	2	2	2
Malleolus	**Lateral**	3	2	3
	Medial	3	1	2
Talus	**Supero lateral part**	3	2	1
	Supero medial part	2	1	1
	Posterior part	2	2	2
Navicular bone		2	2	1
Head of the talus		2	2	1
MT1	**Proximal part**	2	2	1
	Distal part	1	3	1

Table 5.4: Repeatability of all anatomical landmarks on the foot (MT1: first metatarsal bone)

All of them had a SDr under 2 mm. SDr of axis orientation were <2° and <0.5° respectively for tibia axis and talus elliptical cylinder one.
Repeatability of parameters is reported in table 5.5. We considered as repeatable the ones with a CI95%≤3° (table 5.5).

	95% CI 2D value	**95% CI 3D value**
CPA	3	3
TCA	3	3
TTA	2	2
TCD	6	7
TNCA	11	10
TMAM	5	10
TMA	12	10
FMFA	3	3

Table 5.5: Repeatability of all parameters values on the foot (CPA: Calcaneal pitch angle, TCA: Lateral tibio-calcaneal angle, TTA: AP view tibio-talar angle, TCD: talo calcaneal divergence, TNCA: Talo navicular coverage angle, TMAM: talo metatarsal angle of Meary, TMA: AP talo-first metatarsal angle, FMFA: 1st metatarsal to floor angle)

- Parameters values

Lateral tibio-calcaneal angle and calcaneal pitch angle were significantly different between A and NA groups (p<0.05) (table 5.6).

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	A feet	NA feet	Difference (SD)	Rampal et al. (10)	Bourdet et al. (32)	Davids et al. (30)	Steel et al. (33)	Moraleda et al. (34)
Number of feet	10			10	65	60		135
Age (years old)	7-11			9-13	7 - 18	5 - 17	Adult	Adult
TCA	75° (69° to 81°)	65° (55° to 73°)	-9° (+/-5°)	67° (54° to 77°)		65° to 75°		61° to 83°
CPA	12° (5° to 22°)	21° (16° to 31°)	7° (+/-4°)	20° (14° to 34°)	20° to 30°	5° to 32°	11° 38°	11° to 23°
TTA	-4° (-16° to 4°)	-4° (-11° to -1°)	0°+/-6°)	0° (-10° to 7)		-9° 12°		
FMFA	20° (14° to 31°)	20° (15° to 25°)	-1° (+/-7°)	21° (15° to 30°)	10° 20°	1° 13°	16° 30°	

Table 5.6: Values of reproducible parameters on the affected and non affected feet, and comparison with literature and comparison between Affected (A) and Non-affected (NA) side: average and SD of difference (in degree) (TCA: Lateral tibio-calcaneal angle, CPA: Calcaneal pitch angle, TTA: AP view tibio-talar angle, FMFA: 1st metatarsal to floor angle)

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2. Gait analysis

a.uncertainty

Uncertainty evaluation was based on the repeatability study of the placement markers on healthy subjects and on the Monte Carlo error estimation (figure 5.3)

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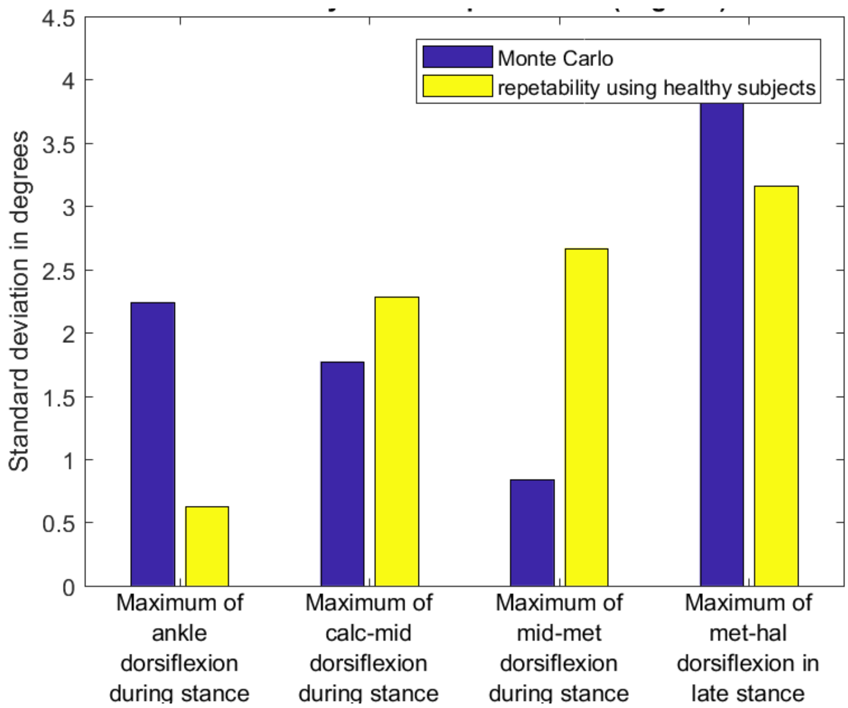

Figure 5.3: uncertainty in clinical parameters (degree) (repeatability and Monte Carlo error estimation)

- b. Gait parameters

Results are reported in table 5.7, figure 5.4 and 5.5. Concerning kinematics, maximum of ankle dorsiflexion during stance and metatarsal to hallux joint mobility were significantly different between A and NA feet. Concerning dynamic ones, a significant difference was found considering the minimal ankle moment.

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	Non-affected		Affected		
	Average	SD	Average	SD	p
Maximum of ankle dorsiflexion during stance (°) (x-axis)	12	4	9	4	0.008
Maximum of calc-mid dorsiflexion during stance (°) (x-axis)	6	2	7	3	0.22
Maximum of mid-met dorsiflexion during stance (°) (x-axis)	2	1	2	1	0.84
Maximum of met-hal dorsiflexion in late stance (°) (x-axis)	43	7	28	9	0.0004
Foot progression angle (°) (y–axis)	-5	5	-10	9	0.15
Minimum of ankle dorsiflexion moment (N.m/kg)	-1.3	0.1	-1.1	0.1	0.0004
Maximum of ankle dorsiflexion moment (N.m/kg)	0.1	0.1	0.2	0.1	0.31
Minimum of ankle plantarflexion power (W/kg)	0.5	0.1	0.4	0.1	0.12
Maximal ankle plantarflexion power (W/kg)	-2.8	0.8	-2.4	0.5	0.27

Table 5.7: maximal value of mobility of joints, minimum and maximum moments and power of the affected and non-affected feet (average and SD)

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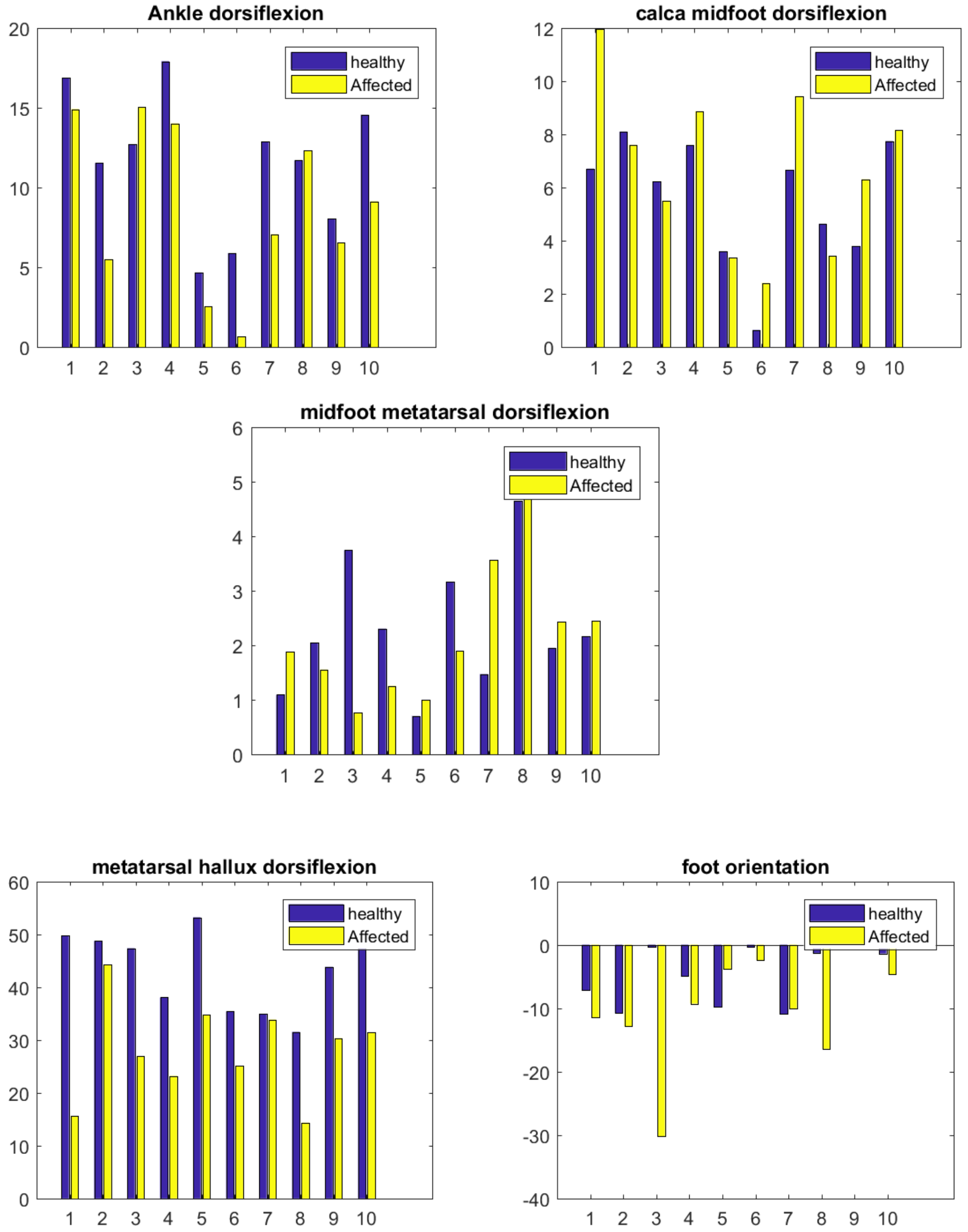

Figure 5.4: comparison of studied joint maximal mobility and global foot orientation of Affected and Non-affected foot for each subject.

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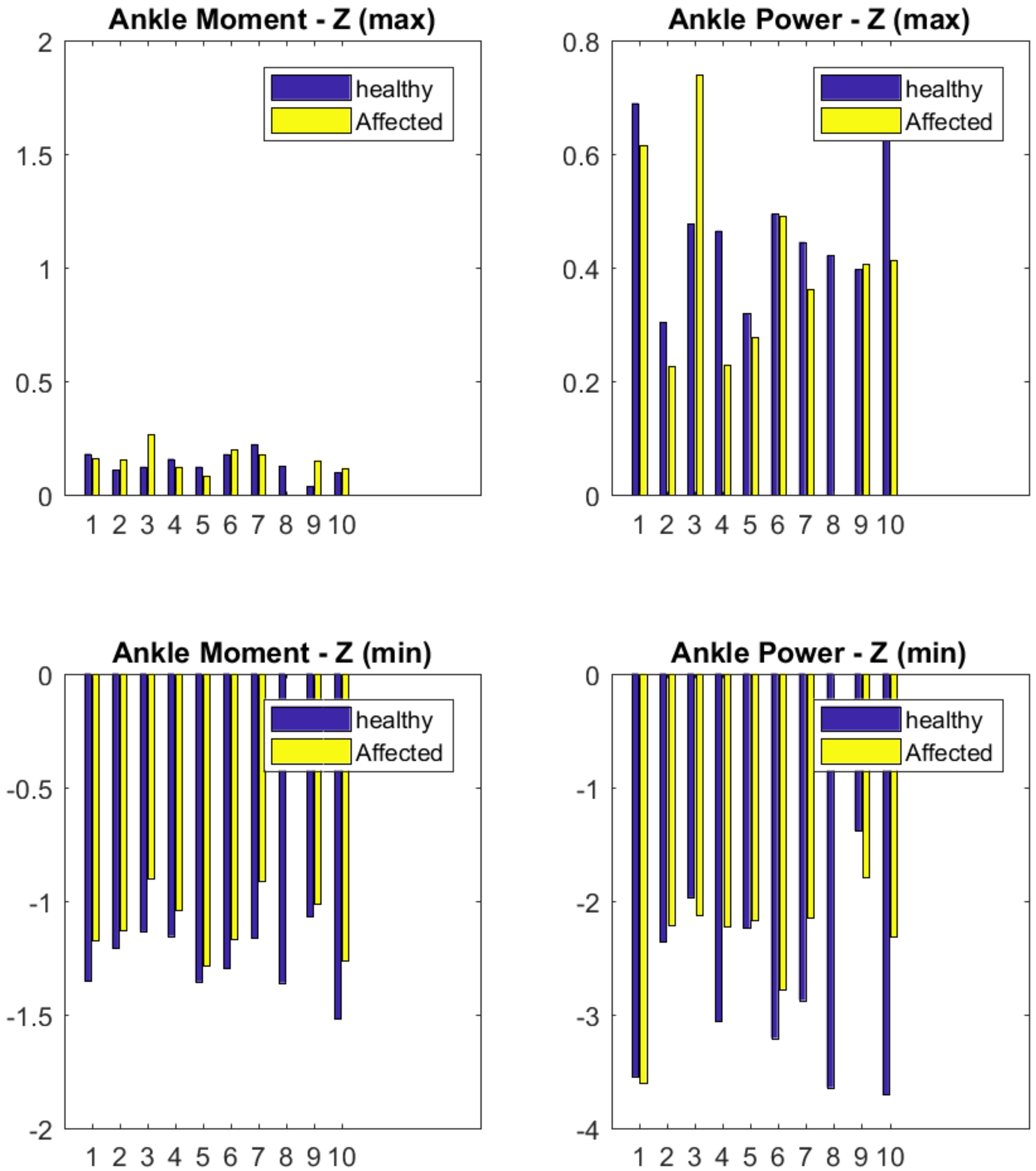

Figure 5.5: comparison of ankle moment and power of Affected and Non-affected foot for each subject.

Discussion

To our knowledge, no previous study used the combination of radiological morphological parameters with the gait functional evaluation on subjects with CF recurrence. Moreover, the method reported by Leardini et al.[19] was never previously used in literature to study CF cases, and usual evaluation of feet in gait analysis is based on a one-segment foot model. This is why we assessed walking age CF patients combining clinical assessment, 3-Dimensional radiographic evaluation and a complete multisegment foot evaluation during gait. The aim was to point out difference between affected and non-affected side as far as the internal joints of the foot were concerned, and to evaluate the feasibility of these combined procedures in a clinical context.

Concerning radiological parameters, we compared the CF radiological parameters values to the contralateral foot, and to a population of TD children. In the considered population, pelvic and lower limbs parameters values do not differ significantly neither from one side to the other nor from the one of TD children of previously published series[11,35]. Concerning the foot, it has to be noted that this work is the first one reporting on 3D radiological parameters values in non-TD children. Repeatability of the reconstruction is adequate to allow us consider the parameters values, and these are concordant with previous study[10] in TD children. However, calcaneal pitch angle and tibio-calcaneal angle were respectively significantly lower and higher in A feet than in NA ones. The overall small difference of the radiological parameters values between the CF patients of this series and TD children is related to the excellent result of the CF treatment for these patients, revealed by high score of Ghanem and Seringe[26].

Considering GA, we aimed to point out internal mobility of the foot, to describe more precisely the eventual flaws or tendency to relapse of the CF. Therefore, and to our knowledge for the first time in literature in CF children, we choose the Rizzoli Multi-segment Foot Model proposed by Leardini et al.[19], as it considers the foot as a multi-body segment, on the opposite of usual used model considering it as one rigid element[12,19-23]. Indeed, while considering the foot as 3 segments element (the calcaneus, the midfoot and the metatarsal bones) the Leardini model[19] gives access to the motion between the calcaneus and the mid-foot, the calcaneus and the metatarsus and the mid-foot and the metatarsus. The only report of this model in a children population[22] neither evaluates the reproducibility of the markers' placement, nor focuses on the internal foot mobility given by the markers.

As expected, the maximum of ankle dorsiflexion during stance is significantly lower in the A group than in the NA one, which is a usual finding in CF patients[13,15,16]. A complication to conservative treatment of CF describe in various form of treatment[36-39] is the rocker bottom deformity of the foot. This comprises dorsiflexion of the forefoot without correction of hindfoot equinus, resulting in a plantar convexity with false sagittal correction. Clinical examination can be misleading as the increased forefoot dosiflexion can be interpreted as improvement of the ankle dorsal flexion. In 95% of cases, the apex of the deformity is the midtarsal joint[39] represented in our series as the calcaneum and midfoot mobility. This is a feared complication as surgery is therefore required in more than 90% of cases[39]. To diagnose this complication, lateral radiograph is reported to be essential [39], and in this work, we found a difference between affected and NA feet in the radiological 3D position of the calcaneum (overly horizontalized). However, in the considered feet, with a very good result of treatment, we failed to highlight a significant difference between the A and the NA feet internal motilities concerning the kinematic data of the mobility of the internal joints of the feet.

Finally, our study shows that the Multi-segment foot model is usable in children, as the uncertainty evaluation gives good results. The repeatability of the placement markers is high enough not to impair the Monte Carlo estimation error, and to allow relying on the obtained results. Therefore, when a GA lab and an EOS biplanar X-Ray system are associated in the same medical centre, they can be easily associated to obtain a complete evaluation of the feet. The GA requires around 1h30 to be completed, and the EOS acquisition only 10 to 15 minutes. The markers used for the GA do not impair the radiological images as despite them, bones can be easily evaluated.

One of the limits of the work is that we only collected data from 10 patients, all with a very good function of the foot thanks to a good result of the treatment. It would be of interest to have more children, and to enrol bad results' feet.

Conclusion

To conclude, despite the limited results obtained in this work by each of the methods, it confirms the interest to couple them to evaluate completely the feet. The association of clinical evaluation, morphological description by 3D imaging, and functional assessment by gait analysis is of interest in CF children, as some flaws can be seen only in one or the other of the method, making their association worthy. In particular, the Rizzoli multi segment foot analysis used in this series is of high interest, as it could points out in more pathological feet not clinically or radiologically perceptible defects.

To improve the joint analysis, a key element has to be solved: we need to get a better view of the hind-foot on the stereoradiographic analysis, so as to make its description more accurate, in particular as far as the talus and the calcaneus are concerned. That might be done through a modified positioning of the foot in the EOS cabin.

Therefore this work opens a wide range of following research combining the 3dimensional radiological study and the Rizzoli multi segment foot analysis of the feet of the children.

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