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Distributed loading and multi-segment kinematics for the functional evaluation of foot pathologies: preliminary experience with varying degrees of flat-foot severity

[1]Claudia Giacomozzi, [2]Paolo Caravaggi, [2]Giada Lullini and [2]Alberto Leardini
[1]Dept. of Technology and Health, Italian National Institute of Health, Rome (Italy), c_giacomozzi@yahoo.com;
[2]Movement Analysis Lab, Istituto Ortopedico Rizzoli, Bologna (Italy)

SUMMARY

Functional flat-foot can cause pain and is associated with other foot deformities if not treated at an early stage. Morphologically the flat-foot exhibits a flattened medial longitudinal arch and a pronated hindfoot. During stance the flat-foot remains pronated longer than a normal foot and no significant rise of the arch is present at push-off. The aim of this study was to investigate whether state-of-the-art technology for gait analysis can better assist clinicians in discriminating different degrees of severity, via classical baropodometry integrated with multi-segment foot kinematics, for a more specific assessment and diagnosis.

An established multi-segment foot kinematics model, and an original baropodometric analysis based on anatomical masking of footprints were employed to compare two different degrees of flat-foot severity (flat-foot, FF; severe flat-foot, SFF) with a normal-foot group (NORM). Statistical analysis was used to assess differences among relevant kinematic and baropodometric parameters across the three foot groups and to investigate correlations within each trial.

All baropodometric parameters were significantly different in the midfoot for the three groups, with greater loading in the lateral midfoot for the FF, and overall greater loading in both lateral and medial midfoot for the SFF. At the midfoot, increased frontal-plane range of motion (NORM 7.4°±1.9°; SFF 10.1°±3.3°; $p<0.05$) and vertical force (NORM 0.1±0.3 %BW; SFF 11.1±8.8 %BW; $p=0.001$), were observed with increased flat-foot deformity, together with higher correlations between corresponding temporal profiles (NORM R=0.2±0.05; SFF R=0.61±0.15; $p<0.05$).

This analysis, with the selected foot-areas, revealed significant correlations between vertical force and joint motion for different degrees of flat-foot. Further investigation of the relationship between these and lower limb gait variables may help to interpret the present results.

INTRODUCTION

The flat-foot is an orthopedic pathology frequently diagnosed particularly in infants. It is characterized by a flattening of the longitudinal arch with the foot remaining pronated longer during the stance phase of walking. In the adult, when not treated, functional and symptomatic flat-foot is often associated to pain following early arthritis of the subtalar joint. It was commonly believed that a flat-foot would exhibit larger eversion and pronation of the hindfoot and larger dorsiflexion of the midfoot and forefoot, but a previous study showed that no such statistical differences exist with a normal group [1]. While plantar pressure measurements have been successfully used to investigate foot deformities and related abnormal pressure peaks, flat-foot assessment may require a thorough baropodometric analysis combined with joint kinematic from multisegment foot models. This instrument integration approach has not been performed to date for the analysis of flat-foot, where objective evaluation of the type and degree of severity is critical to reach a better diagnosis and to choose the best treatment.

METHODS

Three groups with different degrees of foot deformity were analyzed: normal foot (NORM, n=17, age 27±10 years, BMI 21.7±2.3), flat-foot (FF, n=8, age 28±4, BMI=24.3±1.0), severe flat-foot (SFF, n=9, age=20±9, BMI=22.2±2.9) following standard clinical classification by a single experienced physiatrist.

An eight-camera motion system (Vicon, UK) was used to measure foot segments kinematics during the stance phase of level walking, according to an established multisegment foot protocol [2]. This allowed estimation of triplanar motion between the shank, calcaneus, midfoot, and

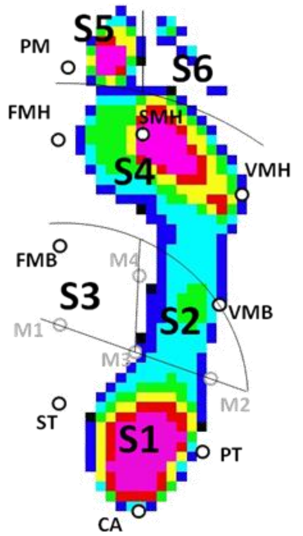

Figure 1: Vertical projections of the foot anatomical landmarks (CA, PT, etc.) tracked by the multi-segment kinematics model and relevant mid-points (M1 to M4), superimposed to the corresponding footprint (typical subject, FF group). These were used for identifying 6 subareas on the footprint (S1-S6), via arcs and line segments (in grey).

metatarsus. At least three walking trials were analyzed.
Simultaneously, a pressure plate (Novel, Gmbh) recorded foot plantar pressure. An anatomical-based selection of areas of interest was employed to divide the pressure footprints in 6 subareas (Figure 1): hindfoot, medial and lateral midfoot, metatarsus, hallux, and 2nd to 5th toes. This was a further development of a methodology presented previously [3, 4]. Normalized contact area, peak pressure, normalized vertical force, pressure- and force-time integrals, and timing of the stance events were determined for each subarea. For each subject, the median across all trials of each of these variables was used for statistical analysis. For a subset of the sample, comprising of at least 10 trials for 3 subjects from each foot group, preliminary kinematic-to-force correlation analysis, using the Pearson coefficient, was performed.
ANOVA test, with Bonferroni correction, was employed to compare the mean of the relevant kinematic and baropodometric variables between groups. In each group, Pearson coefficient was used to explore possible correlations between the temporal profile of midfoot rotation in the calcaneus reference frame, i.e. the Chopart joint, and the vertical force at the two midfoot regions.

RESULTS AND DISCUSSION

The traditional arch index (AI) coefficient, the estimate of the degree of flattening of the medial longitudinal arch, confirmed that the three foot groups had significantly different morphology (NORM 0.18±0.06, FF 0.26±0.02, SFF 0.33±0.04 $p<0.05$). In the medial midfoot (S3), all the baropodometric variables increased with increasing degrees of deformity: the maximum force was 0.1±0.3 (%BW) in NORM and 11.1±8.8 in SFF (P=0.001). In the lateral midfoot (S2), most variables were significantly different in both FF and SFF. Interestingly, peak pressure and pressure-time integrals had the highest values in FF, the increase being statistically significant with respect to NORM but not to SFF.
The kinematic analysis revealed that also the ROM in the frontal-plane increased with the degree of flat-foot: in the midfoot-to-calcaneus rotation this was 7.4°±1.9° in NORM and 10.1°±3.3° in SFF ($p<0.05$). Important correlations were found between kinematics and baropodometric variables for the midfoot (Table 1, Figure 2). In general, moderate correlations ($0.5<R<0.7$) were found between rotations in the frontal-plane and vertical force measurements. On the medial midfoot (S3) the correlation was larger with increasing degree of flat-foot deformity. Sagittal plane rotations had low correlation with vertical force.

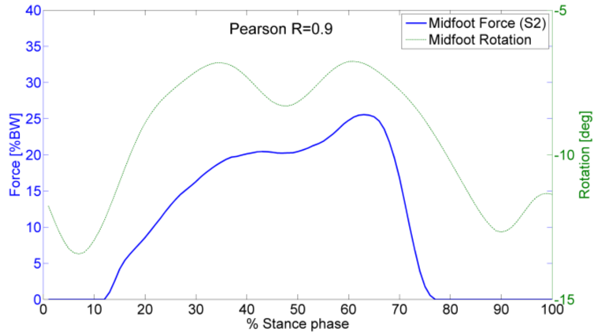

Figure 2: Exemplary high-correlation variable profiles: midfoot-to-calcaneus frontal plane rotation (dashed green) and corresponding vertical force at S2 (solid blue) for one flat-foot (FF group) trial (Pearson coefficient of 0.9).

CONCLUSIONS

Flat-foot deformity has been investigated by a preliminary combination of kinematics and baropodometric analyses based on anatomical regions of interest.
As predictable, the degree of foot deformity was found associated with significant modifications of the main baropodometric variables at the medial side of midfoot. Interestingly, significant changes in loading conditions were found at the lateral side of midfoot already in the low degree of flat-foot deformity (FF). Moreover, the increase of frontal plane motion at the midfoot and metatarsus segments, and the moderate correlation with vertical force, have not been reported before.
The increase of vertical force at the midfoot during midstance, with increasing degree of flat-foot deformity, would require further research into the lower limb dynamics of gait as a function of the altered foot compliance present in the flat-foot.

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Table 1: Mean (±SD) Pearson correlation coefficients between temporal profiles of rotations and vertical force during stance phase at the midfoot segment. Rotations in the sagittal and frontal planes were used for correlation with vertical force at the medial and lateral midfoot.

		Midfoot Lateral (S2) force [%BW]			Midfoot Medial (S3) force [%BW]		
		NORM	FF	SFF	NORM	FF	SFF
Midfoot-to-calcaneus rotation [deg]	Sagittal	0.23 (0.26)	0.17 (0.20)	0.43** (0.18)	0.31 (0.09)	0.31 (0.37)	0.32 (0.20)
	Frontal	0.37** (0.27)	0.69 (0.13)	0.62 (0.18)	0.20 (0.05)	0.39 (0.14)	0.61** (0.15)

* ANOVA statistical different from another group ($p<0.05$)
** ANOVA statistical different from the other groups ($p<0.05$)