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Research article

Distribution of plantar pressures under static conditions, in various areas of the pediatric flatfoot in sensitive period of development – pilot study

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Abstract: (1) Background: Flatfoot can alter the foot's ability to uniformly distribute the body weight on the plantar areas, possibly leading to biomechanical imbalances in the entire body. The purpose of the study was to determine the correlation between flatfoot and plantar pressure distribution in static conditions. (2) Material and methods: The study included a group of 23 children with flat feet (7.43±0.58 years old), which analyzed the correlations between the Foot Posture Index 6 (FPI 6) values and the plantar pressure distribution values. The instruments used were the Foot Posture Index 6 (FPI 6- a quantitative anatomical assessment under static conditions) and the Podata (device for recording images in real time of the body weight distribution on the plantar support). (3) Results: The statistical results have indicated significant correlations of strong intensity between the flat foot and the plantar pressure distribution in the midfoot, but also that the flatfoot significantly influences the values of the plantar pressure distribution in the midfoot. (4) Conclusion: The data showed that flatfeet influence the values of the plantar pressure distribution in the mid-area of the sole.

Keywords: flatfoot, flexible flatfoot, plantar pressure distribution, children development

1. Introduction

Phylogenetically, the human foot has developed in such a way that it would meet the demands of the environment. The foot keeps us connected to the external environment through its rich network of plantar receptors [1]. Any plantar modification can lead to irreversible changes in the foot structure [2], which is why an early diagnosis is vital. In practice, there are cases where the medial margin of the foot can highlight a convex shape, which determines complete contact of the foot with the ground. In this situation, the feet's ability to support the body weight can be perturbed [3]. More than that, the internal and external forces that act upon the foot can be transferred inefficiently, causing overwork in the proximal structures [4].

Flatfoot, or pes planus, is one of the most frequent deformations of children's feet, viewed more as a physiological deviation rather than a pathological disorder. Is classified into flexible and rigid types [5, 6]. The differentiation between these two types is given by the ability of the medial longitudinal arch to return to its concave shape during the specific functional tests that are based on the windlass mechanism of the plantar fascia: tiptoeing, Jack's test, the Silfverskiöld test [7]. The prevalence can be influenced by age, sex, weight, assessment methods, etc. Often, at the age of 7, there is hypokinesia associated with the start of schooling, which results in a tendency to be overweight, revealing disharmony in the development of body posture and neuromuscular control. According to Jane MacKenzie et al., the prevalence recorded values between 0.6% and 77.9% [8]. It is manifested clinically as a collapse of the medial longitudinal arch, valgus of the calcaneus, and abduction of the forefoot [9]. These modifications in the foot structure can alter the foot's ability to distribute the body weight uniformly on the plantar areas (in both static and dynamic conditions), and, consequently, they can increase the pressure values in certain sole regions[10].

The plantar pressure refers to the pressure between the plantar surface of the foot and the support area. In children, the pressure exerted on the sole is different than in adults, because of the different types of walking and the complete process of bone development [11]. Also, it should be considered that the differentiation of the axial load in the habitual posture is the effect of the biomechanical tapes and lateralization.

Biomechanical studies highlight that is crucial to emphasize the significance of measuring plantar pressure accurately [12], especially in the case of preventing foot anomalies and the compensation of proximal structures that could occur [2, 13][14, 15]. This recommendation mirrors the supposition that plantar pressure offers information regarding the function of the foot and ankle [14,15]. According to Cotoros & and Stanciu, plantar pressure could be considered a physiological parameter reflecting the individual's general health state [16]. Rosero-Montalvo et al. think that the data regarding the plantar pressure in the sole cannot only be used to prevent feet anomalies, as the previous authors stated, but it can also be used by experts as an integral part of planning the rehabilitation program, being an instrument that can offer crucial information regarding the current state of the patient's foot[17].

The specialists consider the Foot Posture Index 6 (FPI 6), a useful tool for assessing flatfoot, with good reliability, ranging from fair to substantial [18]. On the other hand, according to Khan et al., the observational methods are relatively subjective in assessing flatfoot accurately. As a result, objective measures and digital systems, have been suggested as alternatives. Recently, pressure platforms have been used to analyze the pressure between the foot and the supporting surface both statically and dynamically. These platforms have been shown to provide highly reliable results and can assist in clinical examinations [19]. The same authors stated that the association between FPI 6 and other plantar pressure techniques could be a gold standard in clinical practice.

The study aimed to investigate the relationship between flatfoot and plantar pressure distribution in static conditions, in order to determine the effect of flatfoot on specific areas of the plantar surface of the foot.

Based on the literature, the misalignment of the foot can increase the risk of developing future pathologies [20], as it may lead to the overuse of certain structures, especially in a such sensitive period of development when body posture and neuromuscular control are getting improving [21]. This framework could provide a guide for interventional therapy and also a prevention strategy for potential risk conditions.

2. Results

The data analysis allowed the extraction of certain descriptive statistical indices in regards to the distribution of the FPI 6 score values and of the plantar pressures on the plantar surface, to the 23 subjects, as follows: FPI 6 right foot score (m=9.78±1.41), FPI 6 left foot score, (m=9.78±1.62), right forefoot plantar pressure (m=66.65±6.15), left forefoot plantar pressure (m=65.52±8.38), right midfoot plantar pressure (m=25.35±2.81), left midfoot plantar pressure (m=25.22±3.88).

2.1. The Pearson correlation coefficient for the FPI 6-rf and FPI 6-lf scores and the dependent variables

The statistical results indicate a positive, strong intensity significant correlation between the FPI 6 left foot score (FPI 6 lf) and the distribution of plantar pressure in the left midfoot area (r= 0.679; p<0.000) - Table 1. There were no significant correlations between the FPI 6- rf, and FPI 6- lf, respectively, and the other dependent variables. Also, there were positive, strong intensity significant correlations between all the dependent variables - Table 2.

Table 1. The Pearson correlation coefficient between the plantar pressure distribution and FPI scores

			Plantar pressure distribution (DVs)			
			RIGHT FOOT		**LEFT FOOT**	
			Forefoot area	**Midfoot area**	**Forefoot area**	**Midfoot area**
(IVs)	FPI 6 – rf score	r	-0.182	0.284	-0.312	-0.281
		p	0.406	0.190	0.147	0.194
		N	23	23	23	23
	FPI 6 – lf score	r	0.247	0.167	0.330	.679**
		p	0.255	0.446	0.125	0.000
		N	23	23	23	23

**. Correlation is significant at the 0.01 level (2-tailed).

Notes: DVs= dependent variables; IVs= independent variables

Table 2. The Pearson correlation coefficient between the dependent variables

		Forefoot area - rf	**Midfoot area - rf**	**Forefoot area- lf**
Forefoot area - rf	r	.840**	.905**	.780**
	p	0.000	0.000	0.000
	N	23	23	23
Midfoot area - rf	r		.724**	.643**
	p		0.000	0.001
	N		23	23
Forefoot area - lf	r			.891**
	p			0.000
	N			23

**. Correlation is significant at the 0.01 level (2-tailed).
Notes: rf= right foot; lf= left foot

2.2. Linear regression model

To determine the ability of the FPI 6 left foot score (FPI 6- lf) to modify the value of the plantar pressure in the left midfoot (midfoot area - lf), a regression model was tested that passed the Fisher test, the regression equation being significant ($F(1.21) = 17.927$, $P < 0.000$), with the value r2 of 0.461- see figure 1 and table 3. Thus, the interpretation of the linear regression model was the following:

- when the FPI-6 left foot score increases by one point, the plantar pressure in the left midfoot area will increase on average by 1.625 pixels;
- the FPI-6 left foot score determines by 46.1% the distribution of plantar pressure in the left midfoot area.

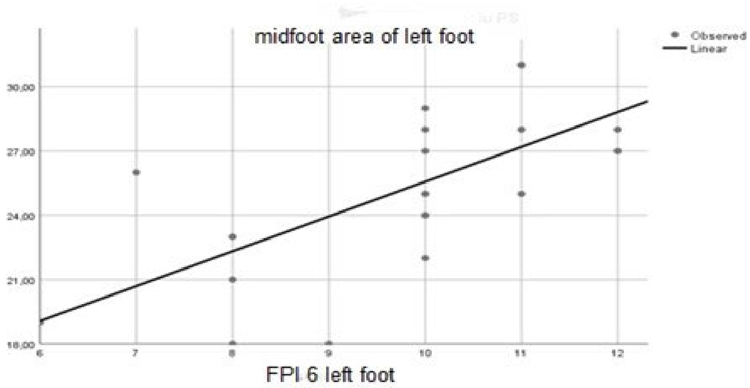

Figure 1. Linear regression model of FPI 6 score and midfoot area of the left foot

Table 3. Regression model for the FPI-lf score and the midfoot area- lf

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.679	.461	.435	2.920

The independent variable is the score FPI - lf

ANOVA

	Sum of Squares	df	Mean Square	F	Sig.
Regression	152.856	1	152.856	17.927	.000
Residual	179.057	21	8.527		
Total	331.913	22			

The independent variable is the score FPI - lf

Coefficients

	Unstandardized Coefficients		Standardized Coefficients		
	B	Std. Error	Beta	t	Sig.
FPI 6 - lf score	1.625	.384	.679	4.234	.000
(Constant)	9.324	3.803		2.452	.023

The independent variable is the score FPI - lf

3. Discussion

Regarding flatfoot and the distribution of planting pressure, after studying the sources from literature that presented data on this issue, we highlight the ideas that have emerged.

The multitude of diagnosis methods for flatfoot can be the reason why there are a variety of studies regarding the relationship between flatfoot and plantar pressure distribution. Razeghi & Batt have presented the methods of evaluation of the type of foot through a review, aiming to critically describe the ones that are most used: visual non-quantitative inspection, anthropometric values (arch height, longitudinal arch angle, rearfoot angle, navicular drop, navicular drift, valgus index), footprints indices (arch index, modified arch index, arch (footprint) angle, footprint index, arch-length index, truncated arch index, Brucken index), radiographic evaluation (calcaneal inclination angle, height to length ratio, calcaneal-first metatarsal angle). In this sense, numerous researchers have tested the link between flatfoot (diagnosed through one of the methods mentioned above) and the plantar pressure distribution [7].

The results of our study indicated significant, strong intensity correlations between flatfoot and the plantar pressure distribution in the midfoot for the left foot ($r=0.679$; $p<0.001$). More than that, the statistical tests suggest that the FPI 6 score can significantly influence the plantar pressure values in this area ($r2 = 0.461$; $p < 0.000$). The correlation between flatfoot and plantar pressure for the left foot only may be related to lateralization. Studies by other authors [18] have shown a relationship between the dominant foot and the plantar pressure during unipodal standing.

In a similar study, Hsu et al. proved that the pressure exerted in the central area of the foot was significantly higher in the case of subjects with flatfoot [10]. Statistically, there were high-intensity significant correlations between the Arch Index (AI), a method of assessment for the foot posture under static conditions based on ink prints, and the sensors in the medial longitudinal arch area ($r = 0.715$; $p < 0.000$) [10]. Similar results were presented also in a study by Zuil-Escobar et al. These authors have found significant correlations between the FPI-6 score and the footprints ($p < 0.001$; $r2$ |0.663–0.703|)[22].

The results of previous studies coincide with the data from research that studied the testing of flatfoot under static conditions, by applying radiological and podobarographic methods. The authors have concluded that in the case of flatfoot, the pressure exerted by the body weight is higher in the standing position on both feet compared to standing on one foot[23]. Similar data was presented also in a study by Pauk & Najafi. In the case of flatfoot subjects, the contact area under the medial longitudinal arch had higher values by 42% compared to subjects with neutral feet. In regards to the plantar pressure distribution, the results suggest that in the case of flatfoot, the contact area of the midfoot increases, and, as a consequence, the amplitude of the plantar pressure is increased in that area [24].

Multiple studies have proven that subjects with flatfoot have increased values of pressure distribution in the medial area of the midfoot. These results could be argued by the following theoretical aspects: the medial longitudinal arch is formed by the complex constituted by the first three metatarsals, three cuneiforms, navicular, talus, and calcaneus bones of the foot. Passive support is provided by the plantar fascia and the plantar ligaments, while dynamic support is given by the tendon of the tibialis posterior and the peroneus longus; the collapse of the medial longitudinal arch can be caused by one of the previously mentioned structures, their interrelation being perturbed, thus creating anomalies in the distribution of the body weight.

Although the starting premises were similar, multiple authors have invalidated the conclusion of the previous studies. For example, Kanatli et al. did not find correlations between the valgus of the hindfoot and the medial longitudinal arch ($r= 0.044$; $p < 0.489$). These authors have started from the hypothesis that the modification of the hindfoot valgus is preceded by pronation of the subtalar joint and a collapse of the medial longitudinal arch. Statistical results indicate that there are no links between the rearfoot angle (the method used to evaluate the hindfoot valgus) and the arch index (the method used to evaluate the medial longitudinal arch)[25].

Feet deformations observed in children can become a permanent condition and may cause other deficiencies. Jankowicz-Szymańska et al. state that over 50% of the subjects included in their study had deviations in foot alignments, and 57.5% of them had hindfoot valgus [26]. Even if the statistical data suggests a similar conclusion as in the analysis conducted by Kanatli et al., the authors recommended that the therapeutic decision regarding the correction of the valgus should be varied and be taken following the quality of the medial longitudinal arch.

Ledoux and Hillstrom have proven that the values of the vertical force distribution on the plantar surface of the flatfoot have been higher in the subhallucal area and not in the medial region of the foot [27].

Our study has some limitations that need to be considered. Firstly, the sample size is small and prevents extracting a general conclusion about the prevalence of flatfoot in this range of population. Secondly, the plantar pressure distribution could be influenced by other natural and uncontrolled factors of the growth and development of the children.

Strengthens are given by the correlation between the FPI evaluation tool and the distribution of plantar pressure in this age category. Both could be provided a fast screening flatfoot tools. We can see the possibility of extending the sample size in future research, with other factors determining the relationship between flat feet and plantar pressure, for example, determining the dominant leg.

In a practical view, our study could be a framework for pediatric specialists. First of all, the literature mentions that the FPI-6 total score and its six items were found to be reliable, ranging from fair to substantial. These provide clinicians and researchers with a dependable way to assess foot posture [18]. Secondly, our results demonstrate that flatfoot affects the midfoot area, which suggests that interventions should take a global perspective rather than just focusing on flatfoot. This approach could prevent the overuse of the vulnerable structures of the foot and ankle only but could stop the possible compensation in superior segments that appear like a biomechanical adaptation of the flatfoot and the increasing plantar pressure in the mid-foot area.

4. Materials and Methods

4.1. Participants

In the initial stage of the subject selection, an interdisciplinary team consisting of a physician, a physical therapist, and a physical education teacher proposed a sample of 64 subjects. Out of these, 51 children were selected for furthermore investigation (mean (m) of age 7.54 years ±0.61).

After applying inclusion and exclusion criteria, twenty-three right-handed subjects (11 girls, 12 boys) aged between 7 and 9, (m=7.43±0.58; median (me)=7) were selected to participate in this study. The subjects had a body weight between 19 and 44.3 kg (m=28.65±8.74; me=23;). On average, the height of the subjects was 127.39±6.51 cm (me=127).

The inclusion criteria were based on the demands regarding age (7-9 years old), type of foot (children with a higher FPI 6 score than 5), children with flexible flatfoot, and parental permission to participate in the research. The subjects with normal feet, musculoskeletal disorders, biomechanical problems, or recent foot traumas were excluded from the study.

To facilitate the understanding of the subjects' involvement, the researchers explained, using clear and straightforward language for children, the whole procedure of data collecting. Considering the age of the subjects, consent was obtained from the holders of parental responsibility (all details and additional information were provided to enable them to make an informed decision). Parents were allowed to withdraw from the study at any time.

We obtained ethical approval from the board of the "Vasile Alecsandri" University of Bacau, Romania (no. 5051/2/07.04.2024).

4.2. Methods

The subjects' feet were evaluated using Foot Posture Index-6 (FPI 6), and the plantar pressure distribution was assessed using Podata, a component of the Global Postural System (GPS 400).

Before the assessments, both the children and the parents/legal guardians were informed regarding the study. The signing of the informed consent forms represented the agreement of the subjects to participate voluntarily in the investigation.

Instrument of assessment

a) Foot posture index 6 (FPI 6) is an instrument for rating foot posture under static conditions, using standard criteria and a simple psychometric scale. It is a clinical tool used to establish the type of foot: pronated, neutral, or supinated. It allows the gathering of information regarding the clinical manifestation of the hindfoot, midfoot, and forefoot in the three anatomical planes. More than that, FPI 6 is a real help to the specialists since the assessment is not conditioned by space or material resources (sophisticated, expensive, massive equipment) [28].

From the viewpoint of the systematic assessment steps [29], the following successions need to be followed: 1) talar head palpation; 2) supra and infra lateral malleoli curvature (viewed from behind); 3) calcaneal frontal plane position (viewed from behind); 4) prominence in region of talonavicular joint; 5) congruence of medial longitudinal arch; 6) abduction/adduction of forefoot on hindfoot. The rating system is based on a psychometric scale, where the score is rated from -2 to +2 points, based on clinical manifestations. The addition of the points allows for an interpretation of the type of foot: the lowest score (-12) suggests a highly supinated foot, while the highest score (+12) indicates a highly pronated foot (Figure 2).

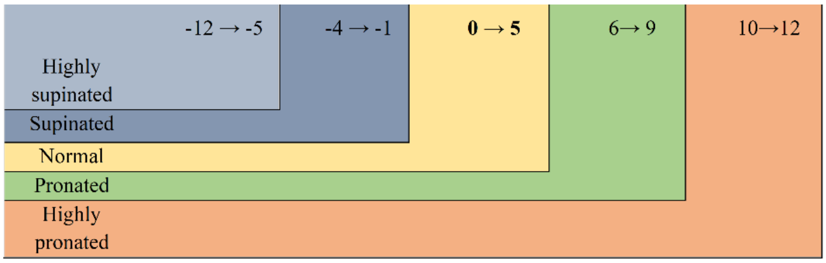

Figure 2. Rating system FPI 6

b) Podata is a device that allows the recording of images in real-time of the division of the body load on the plantar surface. The platform allows the analysis of the foot from the viewpoint of its morphology, thus helping classify the type of foot (normal/arched foot/flatfoot). As part of the GPS – Global Postural System, the platform can offer a complete evaluation of the body posture. About the technical specifications, the platform has a metallic base covered with a hardened glass surface, and a mirror positioned obliquely to facilitate the extraction of data from the plantar surface. This device uses the Global Postural System software, which runs on any computer with a Windows operating system in English.

4.3. Procedures

a) Foot analysis- FPI 6

The subjects were standing with arms relaxed along their trunk, double limb support, and looking straight ahead at a target. Before performing the assessment, each subject was asked to take 10 steps in place (with alternative leg support), then to position themselves with their feet (no shoes) on the testing surface, represented by a wooden platform (dimensions: 40cm width x 44cm length x 20 cm height). To make the assessment more efficient and prevent extra movements from the subjects, they were asked to focus on a visual target, placed on a wall at a height of 2 meters from the floor and 10m away from the place of testing.

The assessment was conducted by one person according to the FPI 6 rating system, and the interpretation was made according to the criteria presented in Figure 2.

b) Plantar print analysis - Podata

The participants were instructed to take two steps before standing on the Podata device to evaluate their weight distribution on their plantar surface. For access to the device, the Podostabil 2 was used, and then the subjects were asked to stand still but relax, while data was gathered regarding the plantar surfaces. The subjects were asked to position themselves on the platform and to try to stand still throughout the assessment. The system recorded the image of the plantar surface that was analyzed through the highlight of the plantar print. Then, the load areas for each foot were estimated through a pixel measurement of the forefoot area and the medial longitudinal arch area. The forefoot area describes the line connecting the external points in the metatarsal bones area, while the medial longitudinal arch area delineates the narrowest area on the plantar surface.

4.4. Statistical analysis

Statistical analysis was conducted using the IBM SPSS software package (Version 25). The significance threshold was set at $p \leq 0.01$, with all the analyses and tests being done 2-tailed [30]. The independent variables were represented by the Foot Posture Index 6 values for the right foot (FPI 6 rf) and for the left foot (FPI 6 lf). In contrast, the dependent variables were represented by the plantar pressure exerted in the forefoot area, right and left foot, the plantar pressure exerted in the midfoot area, right and left (forefoot area - rf., forefoot area - lf, midfoot area - rf., midfoot area - lf.).

To establish the relationship and the intensity of the link between the independent and the dependent variables, the Pearson correlation coefficient was calculated.

Also, to determine the ability of the FPI 6 score to influence the distribution of plantar pressures, the linear regression model was tested.

5. Conclusions

The results of this study indicate a strong intensity relationship between flatfoot and the distribution of plantar pressure in the midfoot area for the left foot. More than that, the statistical tests suggest that flatfoot has a strong ability to modify the values of the plantar pressures exerted in the midfoot area.

This finding provides a foundation for further research in this area. We recommended investigating that the modifications of this area can significantly alter the projection of the center of pressure, and consequently, affect balance and posture in static conditions. Additionally, we suggest examining the same variables, but in dynamic conditions. We supposed that the structural modifications of the flatfoot, which result in misalignment of the foot and ankle, in static conditions, are more susceptible to internal and external forces during gait phases, leading to increased pressure distribution on specific plantar surfaces. Regardless of these conditions (static or dynamic), flatfoot during a child's sensitive developmental period becomes a risk factor for future pathological conditions, which necessitates investigating the long-term effects of flatfoot on plantar pressure distribution.

Supplementary Materials: No applicable.

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