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Mechanical loading on plantar surface in children

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1. Introduction

Flat-foot is the common dysfunction seen in school children [1, 2]. It is very often associated with foot abnormalities which can lead to higher loading on plantar surface, foot discomfort, pain and other pathologies [3, 4]. Foot as the part of musculoskeletal system expose to large forces, particularly when the activity is dynamic. It has been estimated that a subject with a mass of 72 kg absorbs 64.5 tonnes on each foot during overcoming the distance of 1 mile. Examining the GRF allows to assess abnormal foot loading due to a flat-foot disorders. Bertani et al. [5] studied children with idiopathic flat-foot. They found significant abnormal ground reaction force parameters during the terminal stance phase. Children with flat-feet tend to walk with a reduced compliance in the loading response phase due to the impaired function of the hindfoot. Pauk et al. [6] showed that the peak of the vertical force appeared earlier in flat-feet children than in control subjects. The amplitude of the force in posterior direction was lower in flat-feet children compared to the control subjects.

Plantar pressure measurement is an important research tool in gait analysis, because provide valuable information about the structure, function of the foot, and loading on plantar surface [3, 7]. Many factors have been reported for higher foot loading such as: age, gender, body weight, etc [8]. Hennig and collegues [9] determined peak pressure and relative loads under the feet of typical children and adults. School children showed lower peak pressure under all anatomical structures compared to adults. Riddiford-Harland et al. [10] concluded that excess body mass appeared to negatively affect the foot structure.

Despite of many investigations in the area of plantar pressure distribution in adults with foot complication, still little is known about the loading on plantar surface in typical and flat fee children during walking. The purpose of the study was to exploring the foot load abnormality between flat-foot individuals and control group.

2. Testing procedures

The evaluation was carried out on 42 flat-foot children and 70 age-matched children as a control group. Inclusion criteria for flat feet group stated that subjects must be aged between 9-16 years, have lower arch height. Exclusion criteria were any other disorders different than flat foot that may impact on subject’s gait and plantar pressure distribution. The local ethics committee approved the study. All parents/legal guardians received full information about the study before giving signed consent. Subject’s body weight was measured using a scale with resolution of 100 g. The subject’s height was measured by stadiometer.

2.1. Measurement protocol

Foot parameters were estimated from radiographs taken during full weight-bearing position (Xray at both anterior-posterior and medial-lateral plans). For measuring plantar pressure distribution, subjects were instructed to walk a distance of approximately 10 m at their habitual speed inside of a gait laboratory. Plantar pressure distribution during walking was measured with a pedobraograph (T&T medilogic Medizintechnik, GmbH Munich, Germany) based on shoe insoles with capacitive sensors (max. 240 SSR sensors per insole, depending on size and shape). A small portable datalogger attached to the waist of particiapnt allowed data sampling for each sensor at sample frequency of 60 Hz and transfer to a computer via a wireless connection. Each insole was calibrated using a calibration device (T&T medilogic Medizintechnik, Munich, Germany) before each measurement. Trial replications were done tree times for left and right foot separately. To quantify plantar pressure distribution, the maximum magnitude of plantar pressure (peak pressure) under seven anatomical masks was measured using a commercially available toolbox (Fig. 1).

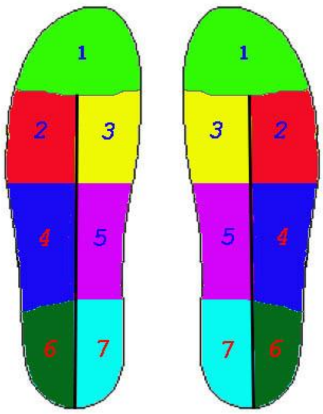


Fig. 1 The definition of different masks used in this study: mask *1* = the toes; mask *2* = the metatarsal heads; mask *3* = the head of first metatarsal; mask *4* = the cuboid bone; mask *5* = the navicular bone; mask *6* = the lateral heel; mask *7* = the internal heel

These masks corresponded to the following anatomical areas: the toes; the first metatarsal head, the other metatarsal heads; the cuboid bone; the navicular bone; the lateral heel, and the inside heel. The following variables were calculated for each mask: the pressure distribution

(*P*), the time of foot contact (*T*), and the area of foot contact (*S*) of each mask. Maximum pressure was defined as the greatest pressure in each anatomical area of foot in a single step, and these values were averaged separately for each mask over 10 steps. Mean pressure, time of foot contact, and the area of foot contact were defined as the average of all activated sensors in a mask for a single step as follow:

$$P = \frac{F}{S}, \qquad (1)$$

where P is pressure distribution, N/cm^2; F is ground reaction force, N, S is contact area, cm^2.

Means and standard deviations were calculated for the total subject sample for the data from the pedobarograph. All of the variables were statistically analyzed using an independent *t*-test to detect any differences between the left and right foot and between the male and female groups. Computer software Statistica 8.0 (StatSoft, Tulsa, OK, USA) was used for computations.

3. Results

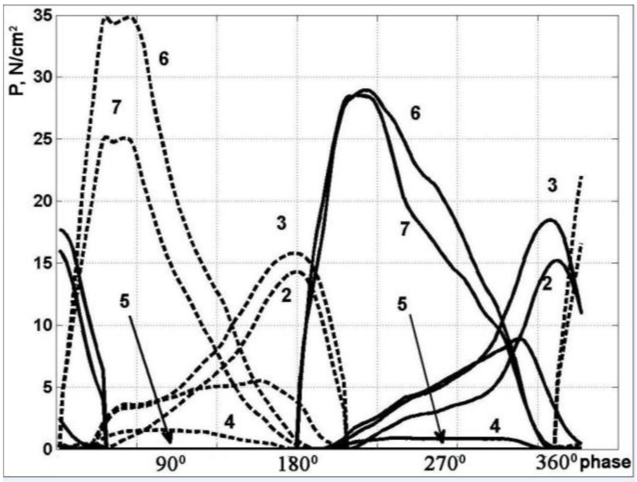
Table 1 summarizes the demography of participants. Subjects were classified as flat foot and control group based on data from radiograms. No significant difference was observed between flat feet and control group for age, body mass, height, and gender ratio ($p > 0.05$).

Table 1

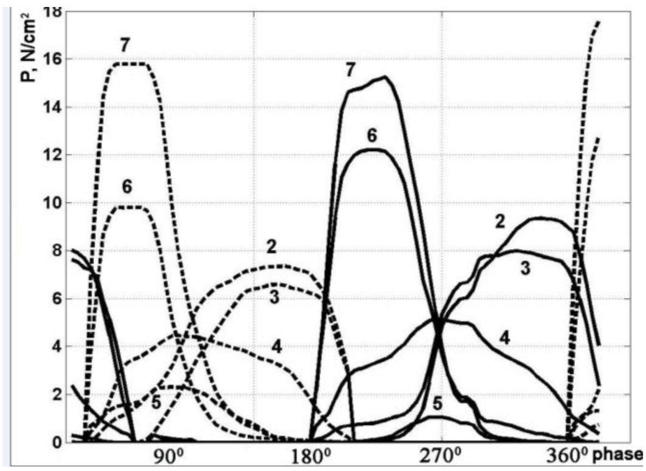
Subject characteristic (±SD)

Group	Control	Flat feet	Comparison control v. Flat feet	
Number	70	42	Difference	*p*-value
Age, years mean(SD)	12.2 (3.2)	12.6 (1.9)	0.4	0.19
BMI	19.4 (2.6)	19.9 (3.0)	0.5	0.16
Height, cm mean(SD)	153.6 (12.7)	152.5 (9.3)	-1.1	0.51
Gender ratio (%female)	54.3%	51.9%	-2.4	0.79

Each subject wore the insoles in their shoes for 10 min to allow insole acclimatization and potentially increase the reliability of measurement. Fig. 2 illustrates plantar pressure distribution for flat-foot subjects and control subject respectively during dynamic (walking with habitual speed) plantar loading. The axis *X* is a time in second, as the result of measuring. The time is mapping to a step phase by means of mapping function. During the heel contact the center of gravity moves outwards in control subjects, and the center of pressure moves to the first toe. However the center of gravity moves inwards during stance, and the center of pressure is moved to the third toe in flat feet subjects. Additional, during the foot loading the higher pressure distribution was under navicular bone and under cuboid bone in flat feet subjects. The shape and duration of substituted signals, generated by the dependences of pressure on a step phase can become the important data for the analysis. The shape of the signals for the *2* and *3* mask becomes more symmetrical in flat-foot subjects. However the signal for *6* and *7* mask becomes less long-term in flat-foot subjects.



a



b

Fig. 2 The average pressure distribution in each mask for the left (dashed line) and right foot (solid line) during walking: a) control subject; b) flat feet subject

The analysis of four specified pedobarographic signals shows, that the phases of pressure distributions are defined by both left and right foots contacts with a surface. These are the moments of the ultimately minimums of the pressure distributions. It is possible to recognize the phase shifts of the local peaks of the pressure distributions in the intervals between this moments. The beginning of the support phases two feet is a phase 0º (Fig. 2). Next a plantar pressure starts to grow under a hindfoot in control group – mask *6* and *7* (Fig. 2, a). The averaged plantar pressure distributions under a hindfoot in the flat-foot subjects can be explained by its variance in the steps sequence which were averaged – mask *6* and *7* (Fig. 2, b). Almost at once plantar pressure grows under midfoot – mask *4*, *5* in flat-foot subjects (Fig. 2, b). This growth begins with value of a phase 30º- 40º only in control group (Fig. 2, a). The maximum of signals (*2* and *3* masks) come practically earlier by 35º in flat-foot subjects compared to typical. The support phases on two feet comes to the end in around 210º for both control and the flat-foot subjects. Then a plantar pressure growth under a midfoot – mask *4*, *5* in control group; a hindfoot is already weighted (Fig. 2, a). By this moment a hindfoot and a midfoot are already weighted in flat-foot subjects (Fig. 2, b).

Paired *t*-test results indicated there were no significant differences between each variable when comparing right and left limbs, all variables were pooled across test limbs in subsequent analyses. During walking in both groups, the heel was the first part of the foot receiving the load of the body. Then the plantar loading moved to the toe through the midfoot and the metatarsal area. For control subjects, the highest pressure amplitudes were found under the heel and the metatarsal heads, while the lowest pressure distribution was under the medial arch. Similar pattern was observed for flat feet patients except for the medial arch area. Tables 2-4 summarizes the parameters extracted from pedobarograph insoles during walking for control and flat-foot subjects.

Table 2

The time of foot contact in control and flat feet subjects (±SD)

Group	*1* mask, s	*2* mask, s	*3* mask, s	*4* mask, s	*5* mask, s	*6* mask, s	*7* mask, s
Control	0.12 ± 0.04	0.29 ± 0.07	0.31 ± 0.06	0.30 ± 0.1	0.16 ± 0.04	0.25 ± 0.05	0.30 ± 0.06
Flat feet	0.08 ± 0.03	0.30 ± 0.06	0.29 ± 0.05	0.55 ± 0.12	0.40 ± 0.08	0.27 ± 0.05	0.28 ± 0.05

No significant difference was observed between control and subjects with flat foot for the time of foot contact (*T*) for anatomical area related to toes (mask *1*), metatarsal heads (mask *2*), first metatarsal head (mask *3*), lateral heel (mask *6*), and internal heel (mask *7*), $p > 0.05$. However, the time of foot contact for the mask *5* (navicular bone) was in average 150% higher in flat-foot subjects (0.16 ± 0.04 s in control subjects vs. 0.40 ± 0.08 s in flat-foot subjects, $p < 0.05$). Additional, results suggest 83.3% reduction for the contact time of cuboid bone in control group (0.30 ± 0.1 s in control subjects vs. 0.55 ± 0.12 s in flat-foot subjects, $p < 0.05$).

Table 3

The area of foot contact in control and flat feet subjects (±SD)

Group	*1* mask, %	*2* mask, %	*3* mask, %	*4* mask, %	*5* mask, %	*6* mask, %	*7* mask, %
Control	18.3 ± 2.4	20.1 ± 1.2	10.5 ± 0.9	17.8 ± 1.7	6.3 ± 1.3	13.2 ± 0.9	13.8 ± 1.3
Flat feet	17.4 ± 1.4	16.1 ± 0.6	9.6 ± 0.8	19.5 ± 1.3	12.5 ± 2.4	12.2 ± 1.7	12.7 ± 1.1

The highest area of foot contact was for the metatarsal heads (20.1 ± 1.2%), the toes (18.3±2.4%), and the cuboid bone (17.8±1.7%) in control group. However in flat feet subjects the foot contact area was higher for cuboid bone (12.5 ± 2.4%), and for navicular bone (19.5 ± 1.3%).

Table 4

The magnitude of plantar pressure distribution in control and flat feet subjects (±SD)

Group	*1* mask, N/cm^2	*2* mask, N/cm^2	*3* mask, N/cm^2	*4* mask, N/cm^2	*5* mask, N/cm^2	*6* mask, N/cm^2	*7* mask, N/cm^2
Control	4.9 ± 2.3	8.4 ± 1.5	12.3 ± 1.1	6.6 ± 1.3	2.6 ± 0.7	14.9 ± 1.9	7.5 ± 1.5
Flat feet	4.0 ± 1.9	11.2 ± 2.2	4.9 ± 0.9	3.3 ± 0.8	4.6 ± 1.2	9.6 ± 1.4	12.2 ± 0.9

Significant differences were also observed for the magnitude of plantar pressure under the first metatarsal heads (mask *3*), cuboid bone (mask *4*), and navicular bone (mask *5*). Specifically, under first metatarsal head, the magnitude of plantar pressure was significantly reduced in average by 151% in flat feet group (12.3 ± 1.1 N/cm^2 in control subjects vs. 4.9 ± 0.9 N/cm^2 in flat feet subjects, $p < 0.05$). On the same note, results showed a significant reduction for the magnitude of plantar pressure under cuboid bone in average by 100% in flat feet children (6.6 ± 1.3 N/cm^2 in control group vs. 3.3 ± 0.8 N/cm^2 in flat feet group, $p < 0.05$). Finally, the magnitude of plantar pressure distribution was higher under navicular bone in average by 77% in flat feet subjects (2.6 ± 0.7 N/cm^2 in control group vs. 4.6 ± 1.2 N/cm^2 in flat feet group, $p < 0.05$).

4. Conclusions

Loading on plantar surface was measure using in-shoe plantar pressure system while subjects wore their own sport shoes with almost identical characteristics. Authors [10, 11] suggest, that walking velocity can impact the magnitude of peak and mean plantar pressure measured during walking. Comparison in spatial distribution of plantar pressure between flat-feet children and aged-match control subjects suggest that the region of interest, which reflects more plantar loading modification due to flat-feet posture is under head of first metatarsal, and cuboid bone. Results suggest lower distribution under cuboid bone by 100% and under first metatarsal head by 151% in flat feet subjects. The plantar pressure reduction was under navicular bone by 77% in control group. The most significant difference was observed also for the contact area of cuboid bone and navicular bone. This finding is consistent with the results reported by Szczygiel et al. [11] in which they demonstrated that the pressure distribution on the soles of flat feet are concentrated in the middle of the foot. Our results suggest, that the time of foot contact for navicular bone was in average 150% higher in flat foot subjects. This information can be used to reducing the consequences of flat-feet complication by designing of appropriate foot orthoses.

Acknowledgements

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MECHANINIS VAIKŲ PĖDŲ PADO PAVIRŠIAUS APKROVIMAS

R e z i u m ė

Plokščiapėdystė dažnai siejama su nenormalia pėdos būsena, nes pado paviršius labai apkraunamas, o tai sukelia diskomfortą, skausmą ir kitas patologijas. Šio tyrimo tikslas – ištirti plokščiapėdystę turinčių ir kontrolinių to paties amžiaus tiriamųjų pėdos apkrovimo nenormalumą. Tyrime dalyvavo 42 vaikai, turintys plokščiapėdystę, ir 70 kontrolinių to paties amžiaus tiriamųjų. Buvo atliekami pėdos buvimo avalynėje trukmės, pėdos kontakto ploto bei pado slėgio pasiskirstymo ėjimo metu matavimai, naudojant septynias anatomines padines kaukes. Gauti rezultatai parodė, kad plokščiapėdystę turintiems asmenims maksimalus slėgis ypač padidėja po pirmąja padikaulio galva, klubikauliu ir laivakauliu. Tyrimų rezultatai gali būti naudingi mažinant didelio pado slėgio pasekmes plokščiapėdžiams vaikams.

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MECHANICAL LOADING ON PLANTAR SURFACE IN CHILDREN

S u m m a r y

Flat-foot is very often associated with foot abnormalities which can lead to high loading on plantar surface, foot discomfort, pain and other pathologies. The purpose of the study was to exploring the foot load abnormality between flat-foot individuals and aged-match group. Forty-two flat-foot children and 70 aged-matched control subjects were recruited. Measurements included in-shoe time of foot contact, area of foot contact, and plantar pressure distribution during walking under seven plantar anatomical masks. The results suggest increases peak pressure under the first metatarsal head, cuboid bone, and navicaular bone in flat feet subjects, especially. The results may be helpful in prevention the consequences of high plantar pressure in flat-foot children.

Keywords: flat feet, pressure distribution, pedobarograph.

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