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Original paper

Analysis of the plantar pressure distribution in children with foot deformities

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This paper describes the method of measuring and assessing the pressure distribution under typical feet and the feet of patients with deformities such as: planovalgus, clubfoot, and pes planus using a pedobarograph. Foot pressure distribution was measured during static and walking at individual normal walking speed. Time-series pressure measurements for all sensors were grouped into five anatomical areas of human foot. In typical subjects, the heel was the first part of the foot receiving the loading of the body. Then it moved to the toe through the midfoot and the metatarsal area. The highest mean pressure in typical subjects was found under the heel and the metatarsal heads. The lowest pressure distribution was under the cuboid bone. In the planovalgus subjects, a higher pressure distribution was found under cuboid bone compared to typical one. In the pes cavus subjects, the pressure distribution was lower under all parts of foot. In the clubfoot subjects, the pressure distribution, the contact area of each mask, and the time of foot contact area in left and right foot are respectively different.

Key words: *locomotion, pressure distribution, planovalgus, pes cavus, clubfoot*

1. Introduction

One of the most commonly discussed topics in pediatric practice are the static and dynamic postural changes of the feet. The foot deformity is the most common condition seen in the clinical practice (around 70–80% of human population) [1]. For many people it is recognized as a cause of foot pain and fatigue. Diagnosis of foot dysfunction must go beyond clinical observation and visual inspection [2]. There are many additional methods for foot posture assessment such as: radiological examination, contour graphic, anthropometry, force plates, and pedobarograph. Most of the techniques are labour-intensive, time consuming, and insufficient for collecting reliable data. In the last years, the information about the plantar pressure distribution in static and during walking is considered to be an important basis for the practice of neurology and pediatric. It was accepted as a good tool for an assessment of normal and abnormal foot posture, because it provides a useful information to diagnose foot deformities. The high plantar foot pressure is an important risk factor for the development of foot, which has been associated with callus, foot deformities, reduced plantar tissue thickness, and limited joint mobility. The reduction of peak plantar pressure on the forefoot during walking has become a primary focus of the prevention and treatment of this condition [14]. However, the effect of foot structure characteristics on plantar pressure in different kinds of foot dysfunctions is not clearly defined. The objective of the present work is to monitor the plantar pressure distribution during human walking in typical foot and in patho-

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logical conditions such as: the planovalgus, the clubfoot, and the pes cavus with the aim of exploring foot load abnormality due to foot complication by comparing the results between the groups examined.

2. Material and methods

2.1. Subjects

The evaluation was carried out on 37 schoolchildren with foot deformities (20 planovalgus, 10 pes cavus, and 7 clubfoot) and 20 age-matched children as a control group taken from a total population of 450 primary schoolchildren. The local ethics committee approved the study. All parents received full information about the study before giving signed consent. The sample group was between the ages of 10–15 years. All subjects were screened with a detailed medical history. Clinical diagnosis of planovalgus was based on the observation of valgus position of the heel and a poor formation of the foot arch. Clinical diagnosis of clubfoot and pes cavus was based on heel position, calf wasting, foot size, bimalleolar angle and the range of motion in triplane. Inclusion criteria were: age range of 10–15, arch height of bilateral feet, skin condition, knee and hip position, and body symmetry. Exclusion criteria were any other disorders that may have impact on subject's plantar pressure distribution such as those suffering from cerebral palsy, etc.

2.2. Measurement protocol

Plantar pressure distribution was performed with a pedobraograph (T&T medilogic Medizintechnik, GmbH Munich, Germany) based on shoe insoles with capacitive sensors with static and dynamic data collected for both feet. Dynamic data were collected with the patient walking at their natural self-selected speed. The data for each sensor were sampled with the frequency of 60 Hz and transferred to a computer via a wireless connection. To assess plantar pressure spatial distribution, the time-series of the measured pressure amplitudes of all sensors were grouped into five anatomical masks [12] (figure 1). These masks corresponded to the following anatomical areas: the toes; the metatarsal heads; the navicular bone; the cuboid bone; and the heel.

During the experiment the pressure distribution, the contact area of each mask, and the time of surface contact of each anatomical area were measured. The pressure distribution value P^t is a quantitative parameter that depends on body mass, a real contact area of foot with the surface with time as below:

$$P^t \propto f(m, s, t)\,, \qquad (1)$$

where:

P^t – the instantaneous value of plantar pressure,

m – the body mass,

s – the surface contact of each anatomical area,

t – the time of surface contact of each anatomical area.

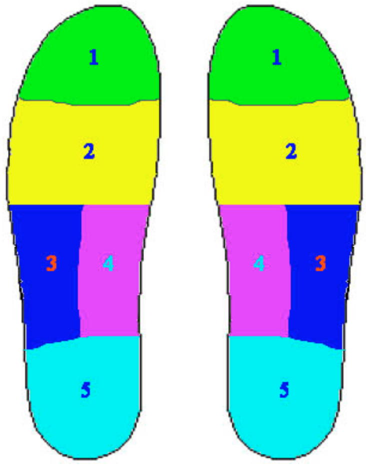


Fig. 1. Anatomical areas of human foot

The pressure value should fit to the full range from zero to the absolute maximum determined by the body mass and the contact area of one sensor [11], [12]. 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.

The center of pressure was found by a ratio of the sum of products of the element values to the radius-vector, which depended on their coordinates, versus the sum of these values. This center specifies the point of projection onto the pressure vector plane. The configurations may be in the form of spots, graphic primitives or isobaric lines. The anatomic phase of a step is a sequence of the sets of instantaneous values of the plantar pressure during one step limited by the appearance of certain configurations within the frames of anatomic representations [11], [13]. Step is considered to be a sequence of the sets of instantaneous values of the plantar pressure constrained by reiteration of certain element configurations from the moment $t1$ till $t2$:

$$S = \bigcup_{t=t1}^{t2-1} P^t\,, \qquad (2)$$

where:

S – the step;

P^t – the instantaneous value of plantar pressure.

Mean time of contact area and the mean contact area of foot were defined as the average of all activated sensors for each mask over 10 steps.

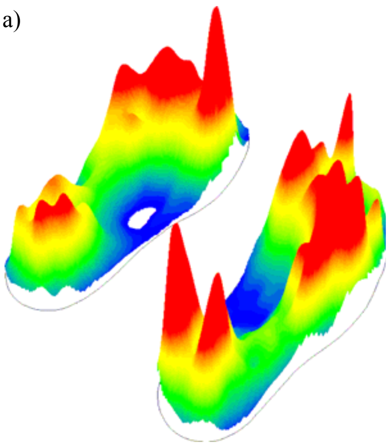
2.3. Statistical analysis

The differences in pressure distribution, the contact area of each mask, and the time of surface contact of each anatomical area were tested with t-test. Means and standard deviations were calculated for the total subject sample for the data from the pedobarograph.

3. Results

The average body mass was 52.2±6.6 kg and 50.4±6.7 kg, respectively, for children with foot dysfunctions and control subjects. Figure 2 presents the pressure distribution in typical subjects. The foot pressure distribution is mainly shared by central part of heel, the metatarsal heads and big toe. A significant part of the load is taken by forefoot, but the peak pressure is located in the central part of the heel. The pressure values under the metatarsal heads are more or less the same as that under central heel. The medial part of the foot takes a very small part of a load due to skeletal structure of the foot.

a)



b)

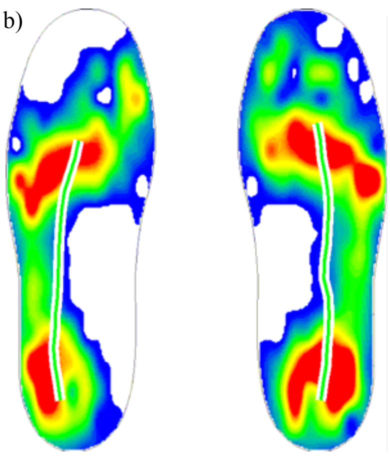
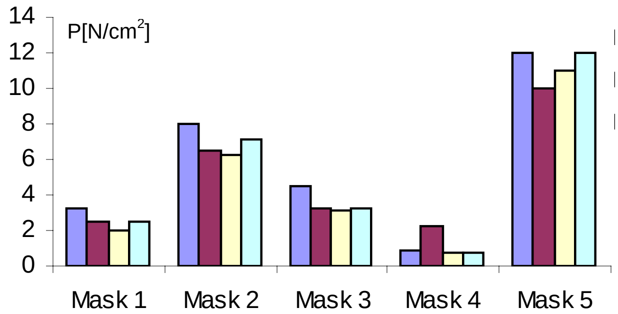


Fig. 2. Pressure distribution under typical feet:
a) during walking; b) in static standing

Figure 3 presents the average pressure distribution (P) and foot contact area (S) for typical, planovalgus, pes cavus, and clubfoot subjects under anatomical parts of children's foot in static standing.

a)



b)

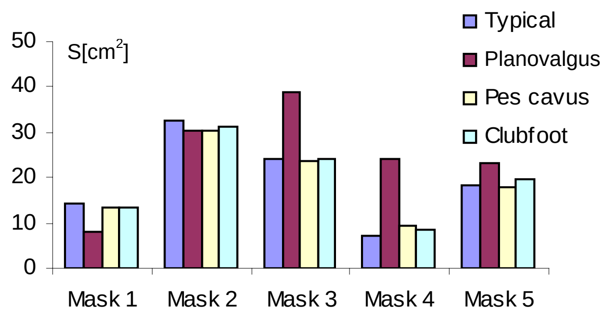


Fig. 3. The data obtained from pedobarograph in static standing for typical, planovalgus, pes cavus, and clubfeet:
a) the average pressure distribution;
b) the average foot contact area

Table 1 summarized the pressure distribution extracted from pedobarograph insoles during walking for control, planovalgus, pes cavus, and clubfeet subjects. For control subjects, the highest pressure amplitudes were found under the heel and the metatarsal heads, while the lowest pressure distribution was under the cuboid bone and navicular bone. The pressure distribution in anatomical area related to toe (mask 1) was the lowest in pes cavus subjects (2.8 ± 0.7 N/cm^2 in pes cavus subjects vs. 4.8 ± 2.8 N/cm^2 in typical subjects, $p < 0.05$). Additionally, the pressure distribution in anatomical area related to the navicular bone (mask 3) was reduced, on average, by 59.4% in pes

Table 1. The pressure distribution for control, planovalgus, pes cavus, and clubfeet subjects during walking (±SD)

Foot area	Typical	Planovalgus	Pes cavus	Clubfeet	
				Left	Right
1	4.8 ± 2.8	4.2 ± 2.2	2.8 ± 0.7	3.8 ± 0.9	3.2 ± 0.7
2	16.0 ± 2.6	14.8 ± 2.7	14.9 ± 0.9	16.1 ± 0.8	18.7 ± 0.7
3	6.4 ± 1.6	3.2 ± 1.1	2.6 ± 0.8	3.4 ± 1.1	5.8 ± 0.9
4	2.7 ± 0.6	4.2 ± 1.5	1.5 ± 0.7	2.7 ± 0.8	2.5 ± 0.7
5	21.6 ± 2.3	18.0 ± 1.8	16.7 ± 0.9	17.3 ± 0.5	18.7 ± 0.6

Table 2. The foot contact areas for control, planovalgus, pes cavus, and clubfeet subjects during walking (±SD)

Foot area	Typical	Planovalgus	Pes cavus	Clubfeet	
				Left	Right
1	18.3 ± 2.4	13.4 ± 1.4	16.28 ± 2.7	16.5 ± 1.5	15.2 ± 1.4
2	39.1 ± 1.8	35.7 ± 2.1	34.7 ± 5.5	36.2 ± 2.4	36.3 ± 2.6
3	17.8 ± 1.7	34.5 ± 1.3	15.1 ± 3.6	17.1 ± 1.9	16.4 ± 2.2
4	12.3 ± 1.3	38.5 ± 2.4	14.5 ± 1.9	13.5 ± 1.2	13.9 ± 1.4
5	20.0 ± 1.4	25.6 ± 1.1	19.8 ± 3.3	20.3 ± 2.3	21.9 ± 2.5

Table 3. The time of foot contact area for control, planovalgus, pes cavus, and clubfeet subjects during walking (±SD)

Foot area	Typical	Planovalgus	Pes cavus	Clubfeet	
				Left	Right
1	0.12 ± 0.05	0.08 ± 0.04	0.44 ± 0.02	0.42 ± 0.04	0.46 ± 0.04
2	0.33 ± 0.07	0.30 ± 0.08	0.59 ± 0.03	0.58 ± 0.03	0.61 ± 0.05
3	0.32 ± 0.12	0.53 ± 0.15	0.38 ± 0.03	0.46 ± 0.03	0.49 ± 0.04
4	0.18 ± 0.04	0.42 ± 0.12	0.47 ± 0.03	0.45 ± 0.04	0.47 ± 0.04
5	0.34 ± 0.03	0.28 ± 0.04	0.40 ± 0.02	0.42 ± 0.02	0.37 ± 0.03

cavus subjects (6.4 ± 1.6 N/cm^2 in typical group vs. 2.6 ± 0.8 N/cm^2 in pes cavus subjects, $p < 0.05$). The pressure distribution was higher, on average, by 55.5% for the cuboid bone (mask 4) in planovalgus subjects than in typical group (4.2 ± 1.5 N/cm^2 in planovalgus subjects vs. 2.7 ± 0.6 N/cm^2 in typical subjects, $p < 0.05$).

In table 2, there are presented the values of foot contact area for typical, planovalgus, pes cavus, and clubfeet subjects. The foot contact area was smaller, on average, by 213% under the cuboid bone in typical subjects than in planovalgus subjects (12.3 ± 1.3 cm^2 in typical subjects vs. 38.5 ± 2.4 cm^2 in planovalgus subjects, $p < 0.05$, vs. 14.5 ± 1.9 cm^2 in pes cavus subjects vs. around 13.5 ± 1.2 cm^2 (for the left foot) and 13.9 ± 1.4 cm^2 (for the right foot) in clubfoot subjects). Additionally, the larger of foot contact area was found under navicular bone (mask 3), on average, by 93.8% in planovalgus group (17.8.0 ± 1.7 cm^2 in typical subjects vs. 34.5 ± 1.3 cm^2 in planovalgus, $p < 0.05$, vs. 15.1 ± 3.6 cm^2 in pes cavus subjects vs. around 17.1 ± 1.9 cm^2 (for the left foot) and 16.4 ± 2.2 cm^2 (for the right foot) in clubfoot subjects, $p > 0.05$). No statistically significant differences were observed between all groups in the foot contact area under the toes (mask 1), the metatarsal heads (mask 2), and heel (mask 5).

Table 3 summarizes the time of foot contact area in typical, planovalgus, pes cavus, and clubfeet groups. No statistically significant differences were observed between control, planovalgus, pes cavus, and clubfoot subjects for the time of foot contact (T) in anatomical area related to navicular bone (mask 3) and the heel (mask 5). The time of foot contact was, on average, by 266% longer under toes (mask 1) in pes cavus and clubfoot subjects (0.12 ± 0.05 sec. in typical subjects vs. 0.44 ± 0.02 sec. in pes cavus group, vs. around 0.42 ± 0.04 sec. (for the left foot) and 0.46 ± 0.04 sec. (for the right foot) in clubfoot subjects, $p < 0.05$). Finally, the time of foot contact was, on average, by 133% longer under cuboid bone (mask 4) for planovalgus subjects (0.18 ± 0.04 sec. in typical subjects vs. 0.42 ± 0.12 in planovalgus subjects, vs. 0.47 ± 0.03 sec. in pes cavus group, vs. around 0.45 ± 0.04 sec. in clubfoot subjects, $p < 0.05$). Among the clubfoot subjects, no significant variations in the pressure, foot contact area, and time of foot contact area of right and left foot were found. In pathological subjects, the pressure varied depending upon the type and location of the pathology. The parameters in clubfoot subjects were similar to those in other subjects with foot dysfunctions such as: the planovalgus and the pes cavus. In the clubfoot subjects, the maximal pressure was observed under the metatarsal heads (mask 2) and the heel (mask 5), the lowest pressure was under the cuboid bone (mask 4).

4. Discussion

Pedobarografic method shows the changes in the distribution of plantar pressure with the increases and decreases of pressure in certain regions of the foot. Several studies have reported that plantar pressure distribution is useful to determine the abnormal walking pattern [3], [6], [10], [15], [17], [20], [21] in such foot dysfunction as: rheumatoid foot, diabetic neuropathy, cerebral palsy, and foot deformities: flat foot, clubfeet [3], [23], [24]. Most of the previous studied were conducted on adults, still little is known about the plantar pressure distribution in children suffering from foot complication. The parameters of human plantar contact with a surface and the characteristics of gait were studied by WALCZAK et al. [7], SVIRIDENOK et al. [8], DUKWORTH et al. [9], and CAVANAGH at al. [4], [5]. The authors indicate the difference in the distribution of pressure on the surface of the sole of correctly arched feet and of flat feet as well. Our results suggest that flat-feet, planovalgus, pes cavus and clubfoot children as well as aged-matched control subjects show rather similar pattern of spatial distribution of plantar pressure during normal walking in the anatomical part of the foot, including metatarsal heads and toes. However, the properties of plantar pressure distribution in the area of contact as well as the amplitude of pressure were significantly different between planovalgus and typical, clubfoot and pes cavus children. The most significant difference was observed in the contact area of cuboid bone, which was, on average, by 213% larger in planovalgus group. This increase suggests that in planovalgus children, a higher pressure is localized under cuboid bone compared with age-matched children. This finding is confirmed by the results reported by SZCZYGIEL et al. [21], who analyzed the difference in the distribution of pressure on the surface of the sole of a correctly arched feet and flat feet in 22 subjects aged between 10 and 20 years. They demonstrated that the pressure distribution on the soles of planovalgus subject was concentrated in the middle of the foot. CYTOWICZ-KARPIŁOWSKA and KARPIŁOWSKI [16] by measuring plantar pressure in 25 children suggested that the amplitude of the pressure under the first metatarsal was significantly lower in planovalgus children. This confirms our findings that the plantar pressure amplitude is lower under metatarsal heads in plano-valgus, pes cavus, and clubfoot groups. LEDOUX and HILLSTROM [19] have a different opinion. They analyzed the pressure distribution in 19 subjects and reported that the pressure distribution under the first metatarsal head was higher in planovalgus than in control subjects. Our findings show that in pathological subjects pressure varied, depending upon the type and location of pathology. In pathological groups, we found a lower pressure distribution under the toes, the metatarsal heads, navicular bone, and under the heel compared to typical children. These findings are the same as the results of another studies [4], [7], [18]. We did not observe such differences between two lower limbs in typical group. The same opinion is expressed by ALVAREZ et al. [26], who analyzed 146 typical subjects aged between 1.6 and 14.9. No significant differences were found by comparing of right and left foot data. However, such differences we observed in clubfeet group. HERD at al. [22], who studied 13 children with 6 idiopatic clubfeet aged between 26 months and 13.5 years, shared this opinion. They found the differences in pressure distribution between affected and unaffected feet. We suggest that pressure distribution varied, depending upon the type and location of the pathology. We found the highest pressure distribution under the metatarsal heads and under heel in clubfeet subjects. Our findings are in agreement with those of ARANSON and PUSKARICH [25], who found an increased pressure under metatarsal heads in the treated group of clubfeet.

5. Conclusion

The measurement of foot pressure distribution proves to be useful for the assessment of foot and gait pathologies. The analysis gives a quantitative estimation of pressure distribution values and compares them to those of the significant and critical levels. The dynamic plantar pressure distribution seems to be an important parameter which provides information about changes in human posture during walking. The pressure measurement during subject's standing gives also an important information on the loading of human body on foot in persons that suffer from various postural deformities. The analysis of barometric data is aimed at describing subject's motion in space and the functioning of their movement system. It could be used in clinical practice or shoe making.

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References

[1] BASMAJIAN J.V., de LUCA C.J., *Muscles Alive – The Functions Revealed by Electromyography*, The Williams & Wilkins Company, Baltimore, 1985.

[2] ROSE G.K., WELTON E.A., MARSHALL T., *The diagnosis of flat foot in the child*, J. Bone Joint Surg., 1985, 67-B(1), 71–78.

[3] LIN C.J., LAI K.A., KUAN T.S., CHOU Y.L., *Correlating factors and clinical significance of flexible flatfoot in preschool children*, J. Pediatr. Orthop., 2001, 21, 378–382.

[4] SZCZYGIEŁ E., GOLEC E., GOLEC J., MAZUR T., SOBCZYK Ł., *Comparative analysis of distribution on the sole surface of arched feet and flat feet*, Przegląd Lekarski, 2008, 65 (1), 4–7.

[5] CAVANAGH P.R., RODGERS M.M., *The arch index: A useful measure from footprints*, J. Biomechanics, 1987, 20, 547–551.

[6] STAHELI L.T., *Corrective shoes for children: a survey of current practice*, Pediatrics, 1980, 65, 13–17.

[7] WALCZAK M., NAPIONTEK M., *The variability of plantar pressure pattern distribution in healthy children and its relation to flexible flatfoot*, J. Orthop. Trauma Surg. Related Research, 2007, 5(1), 4–9.

[8] SVIRIDENOK A., LASHKOVSKY V., *Biomechanical aspects of modern pediatrics development*, Proc. of the Inter. Conf. Biomechanics of Human Foot, 2008, 4–11.

[9] BETTS R.P., FRANKS C.I., BOULTON A.J.M., DUCKWORTH T., *Static and dynamic foot pressure measurements in the management of the incentive foot*, Proceedings of the International Conference on Biomechanics and Clinical Kinesiology of Hand and Foot, 1985.

[10] MAHESH M., BHATIA M.M., PATIL K.M., *New on-line parameter for analysis of a dynamic foot pressures in neuropathic feet of Hanison's disease subjects*, J. of Reh. Research and Develop., 1999, 36 (3), 43–46.

[11] IHNATOUSKI M., LASHKOVSKI V., *Biomechanical researches of children from Grodno area: the barometric measurement of the gait*, Proc. of the Inter. Conf. Biomechanics of Human Foot, 2008, 94–96.

[12] SVIRIDENOK A., LASHKOVSKY V., *Biomechanical aspects of modern podiatrics development*, Proc. of the Inter. Conf. Biomechanics of Human Foot, 2008, 4–11.

[13] CAPPOZZO A., *Measurement of human locomotion*, Journal of Biomechanics, 2002, 36 (1), 147–148.

[14] KNOW O.Y., MUELLER M.J., *Walking patterns used to reduce forefoot plantar pressure in people with diabetic neuropathies*, Phys. Ther., 2001, 81, 828–835.

[15] DZIUBA A., SZPALA A., *Foot kinematics in gait of children with cerebral palsy (CP)*, Acta of Bioengineering and Biomechanics, 2008, 10 (4), 3–6.

[16] CYTOWICZ-KARPIŁOWSKA W., KARPIŁOWSKI B., *Obciążenia w stopie płasko-koślawej u dzieci*. Postępy Rehabilitacji, 1997, 11(3), 123–135.

[17] BURNFIELD J.M., FEW C.D., MOHAMMED O.S., PERRY J., *The influence of walking speed and footwear on plantar pressures in older adults*, Clinical Biomechanics, 2004, 19(1), 78–84.

[18] FULLER E.A., *Center of pressure and its theoretical relationship to foot pathology*, J. Am. Podiatr. Med. Assoc., 1999, 89, 278.

[19] LEDOUX W.R., HILLSTROM H.J., *The distributed plantar vertical force of neutrally aligned and pes planus feet*, Gait and Posture, 2002, 15, 1.

[20] RAI D.V., AGGARWAL L.M., BAHADUR R., *Plantar pressure changes in normal and pathological foot during bipedal standing*, Foot, 2006, 40 (2), 119–122.

[21] GABRIEL R., MONTEIRO M., MOREIRA H., MAIA M., *Contribution of plantar pressure to the prevention and quantification of the muscle-skeletal injury risk in hiking trails – a pilot study*, Acta of Bioengineering and Biomechanics, 2008, 10 (3), 51–54.

[22] HERD F., RAMANATHAN A.K., COCHRANE L.A., MACNICOL M., ABBOUDA R.J., *Foot pressure in clubfoot – The development of an objective assessment tool*, The Foot, 2008, 18, 99–105.

[23] ABBOUD R.J., SWANSON A.J., *The role of foot pressure analysis in the assessment of relapsed clubfeet*, J. Bone Joint Surg., 2000, 82B (Suppl III), 204.

[24] HEE H.T., LEE E.H., LEE G.S.M., *Gait and pedobarographic patterns of surgically treated clubfeet*, J. Foot Ankle Surg., 2001, 40, 287–294.

[25] ARANSON J., PUSKARICH CL., *Deformity and disability from treated clubfoot*, J. Pediatr. Orthop., 1990, 10, 109–119.

[26] ALVAREZ Ch., De VERA M., CHHINA H., BLACK A., *Normative data for the dynamic pedobarographic profiles of children*, Gait and Posture, 2008, 28, 309–315.