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Differences in pediatric vertical ground reaction force between planovalgus and neutrally aligned feet

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Ground reaction forces (GRF) reflect the force history of human body contact with the ground. The purpose of this study was to explore human gait abnormalities due to planovalgus by comparing vertical GRF data between individuals with planovalgus and those with neutrally aligned feet. Second we estimated associations between various measurements and vertical GRF parameters in a pediatric population. Boys and girls between the ages of 4 and 18 years (72 planovalgus feet and 74 neutrally aligned feet) took part in this study. Ground reaction forces were recorded by two Kistler platforms and normalized to body weight. Comparison of vertical GRF between planovalgus and neutrally aligned feet suggests that the first and the second peaks of vertical force (F_{z1}, F_{z2}) are most affected by planovalgus. The results also indicate that neutrally aligned feet display a different ground reaction force pattern than planovalgus, and that differences between boys and girls may be observed. The shape of the vertical GRF curve can help in clinical interpretation of abnormal gait.

Key words: *force platforms, planovalgus, neutrally aligned feet, ground reaction forces*

1. Introduction

Locomotion is defined as bipedal, biphasic forward propulsion of the center of gravity of the human body in which there are alternating sinusoidal movements of different segments of the body with expenditure of energy. Walking is one of infant's greatest achievements. Development of balance and locomotion of children depends on age [1], [2], [6], [13]. The dynamics of human body segments during locomotion are affected by muscle activity, joint position, and the ground reaction force [18]. The forces acting on the foot by the ground are known as ground reaction forces (GRF) [8] and reflect the force history of the human body contact with the ground. A person standing motionless on the ground exerts a contact force on it and at the same time an equal and opposite ground reaction force is exerted by the ground on the person [37]. The GRF is quantified by three vectors in vertical, anterior-posterior and medial-lateral planes [25], [33]. The vertical force can be characterized by a double bump pattern. Body mass and acceleration play a role on the first peak whereas ankle plantarflexors play a role on the second peak of GRF [36]. The maximum amplitude of the vertical ground reaction force is about 120% of body weight (BW) during the double stance phase and about 80% BW during the single stance. The anterior-posterior reaction force is a shear force exerted by force platforms on foot that starts as a braking force from the onset of the stance phase to midstance, and it turns into the propulsion force. The amplitude of the anterior-posterior shear force is usually about 25% BW. It represents two phases: braking phase (approximatelly 50% of the contact time) and propulsion phase. Medial-lateral forces are related to balance during gait. It acts in medial direction with a maximum amplitude about 10% BW and then acts laterally during the rest of the stance phase [17]. In recent decades researchers have

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analyzed the ground reaction force in relation to different factors [2], [31] such as: age, style of walking, stepping surfaces and footwear type. Greer et al. [13] observed ground reaction force patterns during walking in children. The results indicate that 3 to 4 year old children contact the ground with greater vertical force measures relative to body mass than adults. Additionally, the minimum vertical force was lower, and the transition from braking to propulsion occurred earlier. However, the mediolateral force excursions were higher in children than in adults. They also found differences between genders; boys exhibited a greater difference in the vertical peak forces, a lower minimum force, a greater braking force, and a higher mediolateral force excursion value [13]. Many investigators presented data on GRFs during running and walking [4], [5], [14], [16], [20], [22], [26], [35] in healthy adults [14], [28], [35] and also in subjects with pathology [5], [15].

The purpose of this study was first to explore gait abnormality due to planovalgus by comparing the vertical GRF data between planovalgus individuals and neutrally aligned feet and second to estimate the associations between various measurements and vertical GRF parameters in a pediatric population.

2.Method

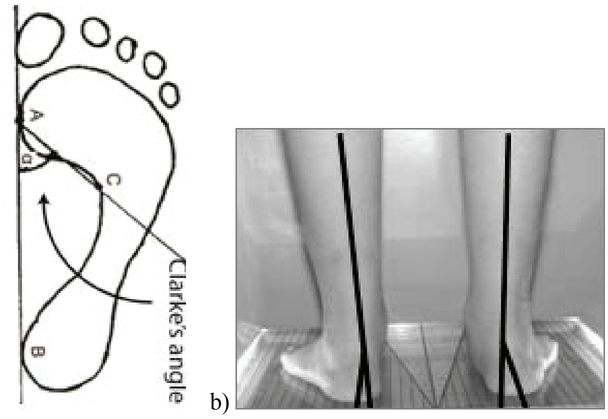
2.1. Subjects diagnostic

Seventy two planovalgus and seventy four neutrally aligned feet (men and women, ages 4–18 years) were studied. All participants filled out a history form which included questions about their history of knee and ankle injuries, age, and gender. Inclusion criteria for planovalgus subjects were: age range 4–18 years, arch height below 42 degrees of Clarke angle, ankle valgus above 5 degrees. Subjects with any current musculoskeletal complaint or if they had any health problems that would affect their gait were excluded from the study. Clinical diagnosis was based on observation of ankle dorsiflexion and plantarflexion, rearfoot, midfoot, and forefoot ranges of motion in triplane. Gait observation was conducted with the child barefoot. Control subjects were defined as individual having no known musculoskeletal disease or abnormality and having not had any prior musculoskeletal manipulation, such as a surgical procedure. All subjects were from Podlasie province and gave written consent to participate in this study. The protocol was approved by the local Ethical Committee.

2.2. Measurement protocol

Criteria for diagnoses of planovalgus

Subject's height and weight were measured using a physician's scale. Participants were screened with the use of podoscope (QMS-396) for inclusion of the planovalgus or neutrally aligned feet. We assessed both feet at the same time. The Clarke angle was calculated from a photo taken with an SLR camera and defined as the angle between the tangent at the medial margin of the foot print and the line connecting the greatest depression and the point at which the medial tangent crosses the margin of the front foot (Fig. 1a). Foot prints, de-identified, were tested in random order to minimize memory recall. During this experiment the Clarke angle was assessed from one image per foot and analyzed once. The accuracy for Clarke angle and ankle valgus was 1 degree. The valgus was calculated from a photo and defined as the angle between the line through the middle of the calf and the center of the heel (Fig. 1b). Deviation of up to 5 degrees was considered as normal. Criteria for planovalgus were as follows: Clarke angle < 42 degrees and ankle valgus > 5 degrees [30], [32].



a) b)

Fig. 1. Foot arch measurement:
(a) Clarke angle, (b) ankle valgus

Measuring ground reaction force (GRF)

Ground reaction forces were recorded by two Kistler platforms (model 9286AA-A, Kistler Instruments, Switzerland), and processed and plotted on a PC computer using the SMART Workstation and software (BTS, Italy) as a function of time, at a sampling frequency of 1000 Hz (Fig. 2).

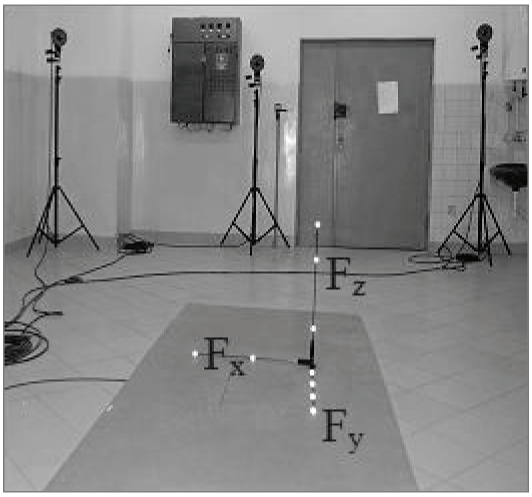


Fig. 2. Ground reaction force measurement with force platforms

The platforms were hidden from the subject's view so that the children would not attempt to alter their gait as they stepped on the platform. Before conducting any tests with subjects present, the platforms were calibrated using special markers. Subjects were asked to walk barefooted across the lab at their comfortable (normal) walking speed over force platforms. Before the data acquisition session, subjects executed several trials to get used to the procedures. The children had to step entirely on the force platforms with one foot only. If the subject missed the force platform completely or partially, or had contact of both feet on the force platform, the measurement was not included in the study. The data included walking speed and GRF parameters for individual lower limbs. Subjects walked a minimum of 9 steps at a self-paced velocity across Kistler force platforms for 5 trials [23]; the force platforms was reset before each trial. Any trial that generated indiscernible oscillations was excluded from our analysis. Consequently, after visual inspection, approximately 3 trials for each subject were accepted for further analysis. The forces were normalized to body weight. Figure 3 represents a typical pattern of vertical ground reaction force. The *z*-axis is normal to the floor.

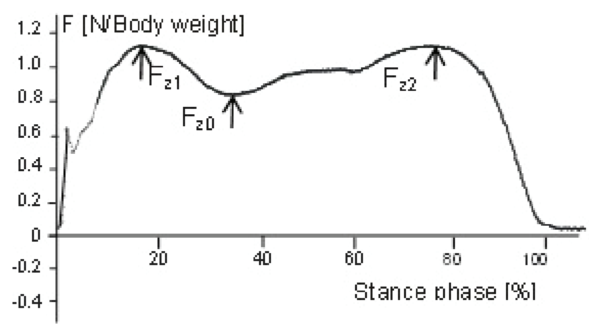


Fig. 3. Typical pattern of vertical ground reaction force normalized to body weight

The vertical force can be characterized by a double bump pattern. The first peak is related to body weight loading and the second peak is due to push off [14], [17], [24]. The events were taken at the first peak (F_{z1}), second peak (F_{z2}), and at the minimum vertical ground reaction force (F_{z0}). Force data were low-pass filtered at 50 Hz. Reliability of measurements of GRF magnitude had correlation coefficient (ICC) of 0.89. Average walking speed for each subject was calculated using the time recorded from the three selected trials.

2.3. Statistical analysis

Analysis of the measurements included values obtained from the three trials for each subject. Means and standard deviations were calculated for the total subject sample for the data from the Kistler platforms. Several graphs were generated to uncover trends in the neutrally aligned feet and planovalgus data and determine appropriate statistical tests to analyze the data. The correlations between Clarke angle, ankle valgus and vertical GRF were examined using Spearman's rank correlation. The normality of the data was verified using the Shapiro–Wilk test. Gender differences were assessed by parametric independent *t*-test. A paired *t*-**test** was also used to determine differences between GRFs in particular trials. Statistical significance was set to $p < 0.05$. Computer software Statistica 10 (StatSoft, Tulsa, OK, USA) was used for computations.

3. Results

3.1. Subjects demography

Table 1 summarizes the demography of participants. Subjects were classified as planovalgus or neutrally aligned feet based on Clarke angle and ankle valgus. Feet with Clarke angles between 25 and 42 degrees and ankle valgus above 5 degrees were assumed as planovalgus [32]. No significant difference was observed between planovalgus and neutrally aligned feet for age, body mass, height, and gender ratio ($p > 0.05$).

There were no differences between groups in height (neutrally aligned feet = 1.52 m, planovalgus = 1.39 m, or weight (neutrally aligned feet = 41.6 kg, planovalgus = 37.8 kg). Table 2 summarizes Clarke angles and ankle valgus for each group.

Table. 1. Demography of participants

Group	Neutrally aligned feet	Planovalgus	Comparison of neutrally aligned feet vs. planovalgus	
Number	74	72	Difference	p-value
Age, years Mean(SD)	11.5 (4.5)	10.8 (3.6)	0.7	0.17
BMI Mean(SD)	19.4 (3.9)	19.7 (4.2)	–0.3	0.34
Height, cm Mean(SD)	152.1 (19.2)	139.5 (10.8)	12.6	0.08
Gender ratio (% female)	52.7%	55.5%	–2.8	0.12

Table 2. Foot posture assessment using Clarke angle and ankle valgus

Group	Neutrally aligned feet	Planovalgus	Comparison p-value
Clarke angle, deg Mean (SD)	45.8 (1.9)	31.7 (4.6)	$p < 0.05$
Ankle valgus, deg Mean (SD)	2.9 (1.3)	7.4 (1.2)	$p < 0.05$

Average Clarke angle was 45.8 ± 1.9 and 31.7 ± 4.6 for neutrally aligned feet and planovalgus respectively, whereas ankle valgus was 2.9 ± 1.3 for neutrally aligned feet and 7.4 ± 1.2 for planovalgus.

3.2. Assessing vertical ground reaction force during walking

The Shapiro–Wilk tests showed that the data were normally distributed allowing the use of parametric statistics methods. Results showed that the planovalgus subjects walked at a natural speed of 1.14 m/s ± 0.09 whereas the subjects with neutrally aligned feet walked at 1.24 m/s ± 0.15. There was moderate correlation between the F_{z1}, F_{z2}, and F_{z0} for each subject in three trials according to the Pearson correlations ($r > 0.8$, $p < 0.05$). The mean value of vertical GFR for neutrally aligned and planovalgus feet is presented in Table 3.

Table 3. Vertical GRF for neutrally aligned and planovalgus feet

VGRF [N/Body weight]	Neutrally aligned feet	Planovalgus	Comparison p-value
F_{z1} Mean(SD)	1.202 (0.106)	1.142 (0.213)	$p < 0.05$
F_{z0} Mean(SD)	0.772 (0.073)	0.849 (0.196)	
F_{z2} Mean(SD)	1.147 (0.072)	0.993 (0.169)	

The magnitudes of first and second peak vertical GRF were both smaller in planovalgus subjects compared to neutrally aligned feet. Force absorption causes an amplitude reduction for the second peak compared to the first one for both planovalgus and neutrally aligned feet (average reduction value was 13% for planovalgus, $p < 0.05$ and about 5% for neutrally aligned feet, $p < 0.05$). Table 4 presents VGRF according to age. The subjects were divided into four age groups: 4–6 years; 7–10 years; 11–13 years; 14–18 years. The difference between the four groups was statistically significant ($p < 0.05$).

It was found that the young children produce relatively larger vertical GRF maxima during walking

Table 4. Verical GRF according to age

Group	Age (y)	F_{z1} [N/Body weight] Mean (SD)	F_{z0} [N/Body weight] Mean (SD)	F_{z2} [N/Body weight] Mean (SD)	p
Neutrally aligned feet	4–6	1.242 (0.11)	0.775 (0.08)	1.160 (0.07)	$p < 0.05$
	7–10	1.190 (0.08)	0.754 (0.07)	1.149 (0.06)	
	11–13	1.170 (0.07)	0.752 (0.06)	1.139 (0.07)	
	14–18	1.083 (0.05)	0.738 (0.05)	1.124 (0.04)	
Planovalgus	4–6	1.221 (0.13)	0.759 (0.09)	1.155 (0.06)	$p < 0.05$
	7–10	1.182 (0.07)	0.746 (0.08)	1.142 (0.09)	
	11–13	1.161 (0.06)	0.738 (0.05)	1.135 (0.08)	
	14–18	1.059 (0.08)	0.730 (0.06)	1.121 (0.08)	

Table 5. Vertical GRF according to gender

Group	Males/ Females	F_{z1} Mean(SD)	F_{z0} Mean(SD)	F_{z2} Mean(SD)	p
Neutrally aligned feet	Males	0.196 (0.11)	0.760 (0.08)	1.144 (0.07)	$p < 0.05$
	Females	1.150 (0.09)	0.782 (0.08)	1.127 (0.07)	
Planovalgus	Males	1.149 (0.21)	0.843 (0.19)	1.022 (0.16)	$p < 0.05$
	Females	1.100 (0.20)	0.885 (0.21)	0.835 (0.12)	

than older children ($p < 0.05$). The analysis showed that males demonstrate greater F_{z1} and F_{z2} of VGRF and lower F_{z0} than females with neutrally aligned and planovalgus feet (Table 5), ($p < 0.05$).

4. Discussion

Despite of many investigations in the area of ground reaction forces during walking, little is known about the ground reaction force in children with planovalgus feet. Most of the measurements presented in the literature are connected to GRFs measured during running [4], [16], [20], [26].

Walking velocity has previously been shown to affect temporal and spatial parameters [27], and the magnitudes of peak and mean GRF during walking [4], [11], [12]. Nilsson and Thorstensson [22] investigated the variation in GRF parameters with respect to adaptations to speed, mode of progression and type of foot-strike. The study found that the F_z peak in walking and running increased with speed, F_y peak amplitude and that F_x peak-to-peak time doubled with speed in walking and increased 2–4 times in running. However, White et al. [34] compared F_z walking overground with vertical foot-belt forces during walking. In this study, 24 subjects were asked to walk overground at three velocities: slow, normal and fast speeds, and at similar cadences and stride lengths at each of the speeds. The study found that the patterns of reaction forces were similar. However, small but significant differences (5–9%) in force magnitude for the two forms of locomotion were detected during midstance for normal and fast walking speeds and in late stance for normal and fast trials. The researchers concluded that the patterns of the vertical reaction forces for the two forms of locomotion were nearly identical. In addition, authors [19] hypothesized that the neuromuscular locomotor system is best stabilized at the usual walking speed. Subjects walked at a self-paced velocity across force platforms in the present study, so the differences in walking speed compared to previous studies have not affected the GRF ($p > 0.05$). Also, the results presented in [34] show that velocity has no effect on the GRF. In our opinion, the differences in F_{Z1}, F_{Z0} and F_{Z2} between the neutrally aligned and planovalgus feet are caused by gait parameters such as kinematics or foot anatomy.

Few studies have examined the three-dimensional trajectory of GRF during walking in children with flatfeet. Bertani et al. [3] studied 20 children (aged between 9–14 years) with idiopathic flatfeet. They suggest that children with flatfeet tend to walk with a reduced compliance in the loading response phase due to the impaired function of the hindfoot. We observed that the peak of the vertical force appeared earlier in planovalgus children than in neutrally aligned feet. Neely [21] observed that pronation and supination play a vital role in decreasing forces during foot contact. Our results suggest that the pattern of vertical ground reaction force during normal walking is almost similar between planovalgus and neutrally aligned feet. In a previous paper [24], we observed no significant difference between the second peak vertical GRF. Moreover, in the anterior-posterior plane, the amplitude of the force in the posterior direction was significantly lower for the flatfooted group. Our results show that the magnitudes of first and second peak vertical GRF are both smaller in planovalgus subjects compared to neutrally aligned feet. This is in agreement with previous findings [7] that peak vertical GRFs are lower in the low-arched group compared to high arched group.

Age of the test subjects is a factor which should be considered because the younger children produce larger vertical GRF maxima during walking than older children. It is similar to [35], they observed that younger age group walk faster and produce larger vertical GRF maxima during level walking than the middle and older aged groups. In study [29], authors suggest that age influences vertical ground reaction forces and it should be considered when comparing normal subjects with patients.

Although kinematic lower body differences between genders have been documented [9], [10] gender-related force differences in children with planovalgus have yet to be established. This study found that vertical ground reaction forces in both neutrally aligned and planovalgus feet for males demonstrated greater F_{z1} and F_{z2} VGRF and lower F_{z0}. This is similar to [13], where differences were observed between boys and girls. Boys exhibited a greater difference in the vertical peak forces and a lower minimum force.

5. Conclusion

This study explored human gait abnormalities due to planovalgus by comparing the vertical GRF data between individuals with planovalgus and individuals with neutrally aligned feet. We also estimated associations between various parameters such as: age, gender and vertical GRF components in a pediatric population. Comparison in vertical GRF between planovalgus children and neutrally aligned feet suggest that GRF parameters, which reflect more GRF modification due to planovalgus are F_{z1}, F_{z0} and F_{z2}. The results indicate that neutrally aligned feet display a different ground reaction force pattern than planovalgus, and that differences between boys and girls may be observed. The shape of the vertical GRF curve demonstrates gait abnormalities, and can helpful in the clinical interpretation of gait and lead to more effective treatment of gait disorders.

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References

[1] ADOLPH K.E., *Learning to keep balance*, [in:] *Advances in child development and behavior*, R. Kail (ed.), Elsevier Science, 2002, 30, 1–40.
[2] ADOLPH K.E., VEREIJKEN B., SHROUT P.E., *What changes in infant walking and why*, Child Development, 2003, 74(2), 475–497.
[3] BERTANI A. et al., *Flat foot functional evaluation using pattern recognition of ground reaction data*, Clin. Biomech., Bristol, Avon, 1999, 14, 484–493.
[4] CAVANAGH P.R., LAFORTUNE M.A., *Ground reaction forces in distance running*, J. Biomech, 1980, 13(5), 397–406.
[5] CHOCKALINGAM N., DANGERFIELD P., RAHMATALLA A., AHMED E., COCHRANE T., *Assessment of ground reaction force during scoliotic gait*, European Spine Journal, 2004, 13(8), 750–754.
[6] CRAIK R., *Changes in locomotion in the aging adult*, *Development of posture and gait across the life span*, Woollacott M.H., Shumway-Cook A., Columbia, 1989, 176–198.
[7] WILLIAMS D.S. et al., *Lower Extremity Kinematic and Kinetic Differences in runners With High and Low Arches*, Journal of Applied Biomechanics, 2001, 17, 153–163.
[8] ECKBURG M.C., *Sex and Foot Posture Affects Ground Reaction Forces During a Single-Leg Drop Landing*, Master Thesis, Ohio University, 2008.
[9] FERBER R., DAVIS I.M., WILLIAMS D.S., *Gender differences in lower extremity mechanics during running*, Clinical Biomechanics, Bristol, Avon, 2003, 18(4), 350–357.
[10] FORD K.R., MYER G.D., TOMS H.E., HEWETT T.E., *Gender differences in the kinematics of unanticipated cutting in young athletes*, Medicine and Science in Sports and Exercise, 2005, 37(1), 124–129.
[11] FREDERICK E.C., HAGY J.L., *Factors influencing peak vertical ground reaction forces in running*, International Journal Sport Biomechanics, 1986, 2(1), 41–49.
[12] GRABOWSKI M.A., KRAM R., *Effects of Velocity and Weight Support on Ground Reaction Forces and Metabolic Power During Running*, Journal of Applied Biomechanics, 2008, 24, 288–297.
[13] GREER N.L., HAMILL J., CAMPBELL K.R., *Ground Reaction Forces in Children's Gait*, Pediatric Exercis Science, 1989, 1(1), 45–53.
[14] HANKE A., ROGERS W., *Reliability of ground reaction force measurements during dynamic transitions from bipedal to single-limb stance in healthy adults*, Physical Therapy, 1992, 72(11), 810–816.
[15] KIM C.M., ENG J.J., *Symmetry in vertical ground reaction force is accompanied by symmetry in temporal but not distance variables of gait in persons with stroke*, Gait & Posture, 2003, 18, 23–28.
[16] KRAM R. et al., *Force treadmill for measuring vertical and horizontal ground reaction forces*, J. Appl. Physiol., 1998, 85(2), 764–769.
[17] KRUPICZ B. et al., *Foot dysfunction, biomechanics, diagnostics and treatment*, Monograph, 157, Bialystok, 2008.
[18] LEBIEDOWSKA M.K., WENTE T.M., DUFOUR M., *The influence of foot position on body dynamics*, Journal of Biomechanics, 2009, 42(6), 762–766.
[19] MASANI K., KOUSAKI M., FUKUNAGA T., *Variability of ground reaction forces during treadmill walking*, Journal of Applied Physiology, 2002, 92(5), 1885–1890.
[20] NACHBAUER W., NIGG B.M., *Effects of arch height of the foot on ground reaction forces in running*, Official Journal of the American College of Sport Medicine, 1992, 1264–1269.
[21] NEELY F.G., *Biomechanical risk factors for exercise-related lower limb injuries*, Sports Medicine, 1998, 26(6), 395–413.
[22] NILSSON J., THORSTENSSON A., *Ground reaction forces at different speeds of human walking and running*, Acta Physiol. Scand., 1989, 136(2), 217–227.
[23] OGGERO E., PAGNACCO G., MORR R., SIMON R., BERNE N., *Collecting valid data from force plates: how many subjects must alter their gait?* North American Congress on Biomechanics, Proceedings of NACOB, 1998, 147–148.
[24] PAUK J., GRISKEVICIUS J., *Ground reaction force and support moment in typical and flat feet children*, Mechanika, 2001, 17(1), 93–96.
[25] PAUK J., *Modeling and prediction parameters in flat feet children*, Monograph, 201, Białystok, 2011.

[26] PAYNE A.H., *A comparison of the ground forces in race walking with those in normal walking and running*, Baltimore, University Park Press, 1978.
[27] PIETRASZEWSKI B., WINIARSKI S., JAROSZCZUK S., *Three-dimensional human gait pattern – reference data for normal men*, Acta of Bioengineering and Biomechanics, 2012, 14(3), 9–16.
[28] SIMPSON K.J., JIANG P., *Foot landing position during gait influences ground reaction forces*, Clinical Biomechanics, 1999, 14(6), 396–402.
[29] STACOFF A., DIEZI C., LUDER G., STUSSI E., KRAMERS-DE QUERVAIN I.A., *Ground reaction forces on stairs: effects of stair inclination and age*, Gait & Posture, 2005, 21, 24–38.
[30] TRZCIŃSKA D., *Plantographic pattern of foot structure in young volleyball players*, Physical Education and Sport, 2009, 52, 100–104.
[31] VASILESCU A.M., MICU A.C., BOGATU L., *Experimental determinations of the ground reaction force depending on the characteristics of sole materials and ground surface*, U.P.B. Sci. Bull., 2011, 73(2), 87–96.
[32] VEVES A. et al., *A study of plantar pressures in a diabetic clinic population*, The Foot, 1991, 2, 89–92.
[33] WATKINS J., *An introduction to biomechanics of sport and exercise*, Churchill Livingstone, New York, 2007.
[34] WHITE S.C., YACK H.J. et al., *Comparison of vertical ground reaction forces during overground and treadmill walking*, Med. Sci. Sports Exerc., 1998, 30(10), 1537–1542.
[35] WINIARSKI S., RUTKOWSKA-KUCHARSKA A., *Estimated ground reaction force in normal and pathological gait*, Acta of Bioengineering and Biomechanics, 2009, 11(1), 53–60.
[36] WINTER D.A., *Biomechanics and Motor Control of Human Movement*, Wiley Interscience, New York, 1990.
[37] WINTER D.A., *Kinematic and kinetic patterns in human gait: Variability and compensating effects*, Hum. Mov. Sci., 1984, 3(1–2), 51–76.