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BIOMECHANICAL ASPECTS OF STATIC FOOT LOAD IN PHYSICALLY ACTIVE AND INACTIVE STUDENTS

BIOMEHANIČKI ODNOSI STATIČKOG OPTEREĆENJA STOPALA KOD FIZIČKI AKTIVNIH I NEAKTIVNIH STUDENATA

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Summary
Introduction. This study investigated the parameters of foot load, as one of the dimensions of foot biomechanics, using a new method of objectification of the measured values. The examined biomechanical parameters directly affect correct gait and posture. The aim of this research was to determine if there was a statistically significant difference in the forefoot and rearfoot load, as well as the load on the whole foot between physically active and inactive students. **Material and Methods.** The study included 91 students, of whom 44 were physically inactive and 47 were physically active. Measurements were performed by using a baropodometry platform (FreeMed Maxi, Sensor Medica, Rome, Italy) used for the first time in our population for objectification of the morpho-physiological parameters. All reference values were provided by the manufacturer as a part of the Freestep version 1.4.01 software. **Results.** Our results showed that physically active students have statistically significantly higher forefoot load values. Physically inactive students have statistically significantly higher rearfoot load values. Also, physically inactive students have statistically significantly higher deviations in most parameters from the reference values compared to physically active students. The percentage of physically inactive students with non-physiological values is higher in every parameter compared to the percentage of physically active students. However, this difference is statistically significant only for the load on the right forefoot in relation to both feet. **Conclusion.** Physically active students showed a physiologically better foot load distribution than physically inactive students.
Key words: Biomechanical Phenomena; Foot; Gait; Students; Exercise; Sedentary Behavior; Pressure; Posture

Sažetak
Uvod. U ovom istraživanju ispitivani su parametri opterećenja stopala, kao jedne od dimenzija biomehanike stopala, novom metodom objektivizacije merenih vrednosti. Izmereni parametri biomehanike imaju direktan uticaj na ispravan hod i pravilnu posturu. Cilj istraživanja bio je da se utvrdi da li postoji statistički značajna razlika u opterećenju prednjeg i zadnjeg dela stopala, kao i stopala u celini između fizički aktivnih i neaktivnih studenata. **Materijal i metode**. Uzorak je činio 91 student, od kojih je bilo 44 fizički neaktivinih, a 47 fizički aktivnih. Merenja su vršena na aparatu *freeMed Maxi* proizvođača *Sensor Medica*, *Italy*, koji je prvi put upotrebljen u našoj populaciji za objektivizaciju morfo-fizioloških parametara. Sve referentne vrednosti je dao proizvođač u okviru svog *freeStep v.1.4.01* programa. **Rezultati.** Rezultati istraživanja ukazuju na to da fizički aktivni studenti imaju statistički značajno veće vrednosti opterećenja prednjeg dela stopala. Fizički neaktivni studenti imaju statistički značajno veće vrednosti opterećenja zadnjeg dela stopala, a takođe, imaju statistički značajno veća odstupanja u većini parametara od referentnih vrednosti u odnosu na fizički aktivne studente. Procenat fizički neaktivnih studenata sa nefiziološkim vrednostima je za sve parametre veći nego kod fizički aktivnih studenata, iako je ova razlika statistički značajna samo za opterećenje prednjeg dela desnog stopala u odnosu na oba stopala. **Zaključak.** Fizički aktivni studenti su pokazali fiziološki bolju raspodelu opterećenja od fizički neaktivnih studenata.
Ključne reči: biomehanički fenomeni; stopalo; hod; studenti; fizička aktivnost; sedentarna aktivnost; pritisak; postura

Introduction

Despite a high incidence of foot deformities in the general population [1], they are not treated with the necessary attention. Foot deformities affect one of the basic foot functions – maintenance of the physiological relationship between the static load and its distribution on the ground. For better understanding of these deformities, one needs good knowledge of the foot anatomy and gait mechanics.

The foot (*pes*) is a distal part of the lower extremity which is in contact with the ground and forms a

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Abbreviations

F – forefoot
R – rearfoot
PIS – physically inactive students
PAS – physically active students
D – right foot
S – left foot
DF – right forefoot
DR – right rearfoot
SF – left forefoot
SR – left rearfoot

right angle with the shin. It can be divided into three regions: forefoot (F), midfoot and rearfoot (R). The F consists of toe bones and metatarsal bones; the midfoot consists of the navicular, cuboid and three cuneiform bones; the R includes the talus and calcaneus bones. In addition to the bones, each of these regions consists of muscles, tendons and other soft tissues [2, 3].

From morphological and physiological aspects, the feet are the foundation for both standing and walking. In a healthy foot, three main support points are distal extremities (heads) of the first and the fifth metatarsal bone, and the calcaneal tuberosity. Together, they make up the vertices of the so called "sustentation triangle" **(Figure 1)** [4]. The three vertices are connected by arches of the foot: transverse, medial longitudinal and lateral longitudinal. The most prominent arch is the medial longitudinal, with its highest point 15 – 18 mm above the surface, while the lateral longitudinal is 3 – 5 mm above the surface at its highest point [5]. In

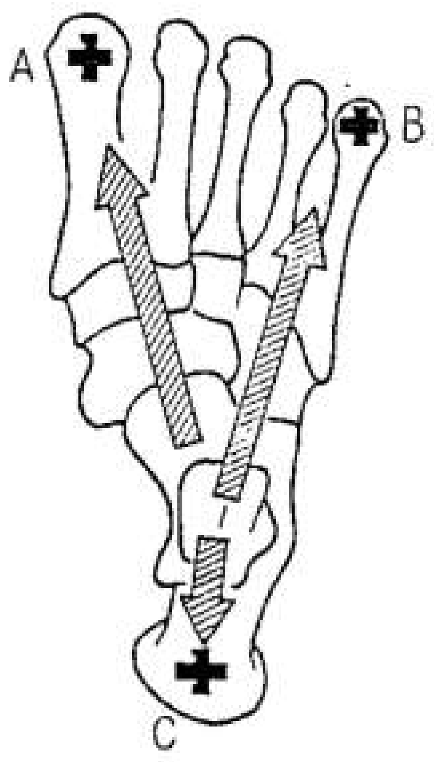


Figure 1. Sustentation triangle (drawing by the author)
Slika 1. *Trougao sustentacije (crtež autora)*

adults, the arches form an indentation on the medial plantar side of the foot called the plantar vault [4].

The morphology of the foot must be preserved in order to perform its function adequately. The shape is defined by the bones, the soft tissues and the forces that affect the foot. These morphological elements resist the pressure that is transferred from the shin and has a tendency to flatten the foot. They may be divided into passive and active components. Passive components or passive tensors of the foot vault are ligaments, while muscles are the active components [5]. Physical activity during the warm-up exercises significantly contributes to the tautness of the active tensors of the foot vaults, and thus maintains the morphology of the foot.

The foot is a key element of biomechanics of the human body because it has the following functions [6]:

- it maintains appropriate weight distribution and its transfer to the ground,
- it supports the body and allows maintenance of posture without extensive muscle use,
- it adapts to the irregularities of the surface while standing and walking,
- it acts like a spring and therefore can be separated from the surface while walking.

The most important forces which enable body movement are muscle activity, body weight and connective tissue elasticity. While analyzing gait biomechanics one should take into account both foot statics and dynamics.

The foot statics includes the influence of all forces that affect the foot while standing. The trabecular system of the bones follows the direction of these forces. One of these forces is the body weight, by which the body puts pressure on the surface. The body weight is transferred to the plantar vault via the tibiotalar articulation, in the direction of the mechanical axis of the leg, which is located between the medial two thirds and the lateral third of the articular surface of the tibiotalar joint. Half of the force is transferred to the subtalar joint, then to the sustentaculum tali, from which it is transferred to the plantar side of the calcaneal tuberosity and finally across the soft tissues to the ground. The rest is directed to the ground across the neck and the head of the talar bone to the navicular bone, then to the cuneal, cuboid and all five metatarsal bones, with the help of the soft tissues [4, 7, 8].

According to the Newton's third law of motion, there are forces by which the surface reactively affects the foot while it is on the ground. They are called ground reaction forces and are crucial in the development of the deformities of the locomotor apparatus. Each of these forces has three components: vertical, anteroposterior, mediolateral. The vertical component is of the highest magnitude, and can reach up to 150% of the body weight [9].

Foot dynamics includes the study of biomechanical forces on the foot in motion. From the aspect of dynamics, the foot is a 2nd class lever, which means that the resistive force to the body weight is located between the fulcrum (heads of the metatarsal bones) and the effort (Achilles tendon).

Table 1. Measured foot loads in PAS and PIS
Tabela 1. *Izmerene vrednosti opterećenja stopala PAS i PIS*

		N/*B*	$\overline{x}$	SD/*SD*	Minimum/*Minimum*	Maximum/*Maksimum*	t	p/*p*
R/F % DF	PIS	44	40.05	11.759	17	73	3.216	0.002
	PAS	47	47.13	9.164	27	66		
R/F % DR	PIS	44	59.95	11.759	27	83	3.216	0.002
	PAS	47	52.87	9.164	34	73		
R/F % SF	PIS	44	38.66	11.344	20	62	3.000	0.004
	PAS	47	44.85	8.188	23	62		
R/F % SR	PIS	44	61.34	11.344	38	80	3.000	0.004
	PAS	47	55.15	8.188	38	77		
load % DF	PIS	44	20.09	6.049	9	36	3.093	0.003
	PAS	47	23.66	4.931	13	35		
load % DR	PIS	44	30.09	6.261	13	43	3.114	0.002
	PAS	47	26.47	4.782	17	36		
Load % D	PIS	44	50.18	3.725	41	59	0.345	0.942
	PAS	47	50.13	3.340	40	58		
load % SF	PIS	44	19.23	5.701	10	32	2.931	0.004
	PAS	47	22.23	3.985	11	30		
load % SR	PIS	44	30.59	6.032	18	43	2.623	0.010
	PAS	47	27.64	4.660	18	37		
Load % S	PIS	44	49.82	3.725	41	59	0.073	0.942
	PAS	47	49.87	3.340	42	60		

Legend: F - forefoot; R – rearfoot; R/F % - F or R load percentage in relation to the whole foot; load % - F or R load percentage in relation to both feet; Load % - whole foot load percentage in relation to both feet; PAS - physically active students; PIS - physically inactive students; D – right foot; S – left foot; SD - standard deviation
Legenda: F - prednji deo stopala; R - zadnji deo stopala; R/F % - procenat opterećenja prednjeg. odnosno zadnjeg dela stopala u odnosu na celo stopalo; load% - procenat opterećenja prednjeg. odnosno zadnjeg dela stopala u odnosu na oba stopala; Load% - procenat opterećenja celog stopala u odnosu na oba stopala; PAS - fizički aktivni studenti; PIS - fizički neaktivni studenti; D - desno stopalo; S - levo stopalo, SD - standardna devijacija

Gait is a complex biomechanical process of refraction of force vectors. Apart from motion of the feet, this process includes both vertical and horizontal oscillations of the body and the head, which are followed by the postural adaptation. During gait, the gravity lines move a few centimeters from the center of gravity (located anteriorly to the promontorium). Although small, these movements are crucial during the absorption of reaction forces of the ground [10–12].

Material and Methods

The study included 91 students (n = 91, aged from 19 to 23 years) of the University of Novi Sad attending the Faculty of Medicine and the Faculty of Sport and Physical Education. A study on daily physical activities was conducted; each participant was asked if they got at least 150 minutes of moderate-intensity aerobic activity per week (this is the minimal weekly activity recommended by the World Health Organization) [13]. Based on their answers, the participants were divided into two categories: physically inactive students (PIS) of the Faculty of Medicine (n = 44) and physically active students (PAS) of the Faculty of Sport and Physical Education (n = 47). The PIS were active less than 150 minutes per week, while PAS had at least 150 minutes of physical activity per day. Of the total number of PIS, 21 were male and 23 female. Of the total number of PAS, 32 were male and 15 female.

All the participants were given detailed instructions regarding the research and all signed a written informed consent for participation in the study. Ethics Committee of the Faculty of Medicine in Novi Sad issued a written approval for this research.

Feet measurements were performed by using a baropodometry platform (FreeMed Maxi, Sensor Medica, Rome, Italy, owned by company "Dunav ortopedsko") and the included Freestep version 1.4.01 software. The platform is equipped with pressure sensors that can determine biometric parameters related to foot statics and dynamics. Measured data were transferred to a computer with the installed Freestep software. Numerical data of the examined parameters were processed in the software, as well as the isochromatic map of the foot sole, based on the foot load. Alongside the measured values, the software shows physiological data with a reference range recommended by the manufacturer.

In order to compare the load of participants' feet the following were used:

1. F or R load percentage in relation to the whole foot (R/F %),

Table 2. Deviation of measured values of the foot load from the reference values in PAS and PIS
Tabela 2. *Odstupanja izmerenih vrednosti opterećenja stopala od referentnih kod PAS i PIS*

		N/*B*	$\bar{x}$	SD/*SD*	Minimum/*Minimum*	Maximum/*Maksimum*	U/*U*	p/*p*
R/F % DF deviation	PIS	44	7.57	7.079	0	25	835.500	0.113
	PAS	47	4.91	5.081	0	18		
R/F % DR deviation	PIS	44	7.57	7.079	0	25	835.500	0.113
	PAS	47	4.91	5.081	0	18		
R/F % SF deviation	PIS	44	7.77	7.243	0	22	789.500	0.049
	PAS	47	4.57	5.274	0	29		
R/F % SR deviation	PIS	44	7.77	7.243	0	22	789.500	0.049
	PAS	47	4.57	5.274	0	29		
Load % DF deviation	PIS	44	2.93	3.302	0	11	657.500	0.003
	PAS	47	1.66	2.389	0	9		
Load % DR deviation	PIS	44	3.11	3.519	0	13	647.500	0.002
	PAS	47	1.55	2.124	0	7		
Load % D deviation	PIS	44	0.86	1.456	0	6	1024.00	0.936
	PAS	47	0.60	1.378	0	7		
Load % SF deviation	PIS	44	3.05	3.410	0	10	697.000	0.007
	PAS	47	1.06	1.686	0	9		
Load % SR deviation	PIS	44	3.20	3.488	0	13	721.000	0.013
	PAS	47	1.53	2.052	0	7		
Load % S deviation	PIS	44	0.86	1.456	0	6	1024.00	0.936
	PAS	47	0.60	1.378	0	7		

Legend: F - forefoot; R – rearfoot; R/F % - F or R load percentage in relation to the whole foot; load % - F or R load percentage in relation to both feet; Load % - whole foot load percentage in relation to both feet; PAS - physically active students; PIS - physically inactive students; D – right foot; S – left foot; SD - standard deviation; U - Mann-Whitney test

Legenda: F - prednji deo stopala; R - zadnji deo stopala; R/F % - procenat opterećenja prednjeg. odnosno zadnjeg dela stopala u odnosu na celo stopalo; load % - procenat opterećenja prednjeg. odnosno zadnjeg dela stopala u odnosu na oba stopala; Load % - procenat opterećenja celog stopala u odnosu na oba stopala; PAS - fizički aktivni studenti; PIS - fizički neaktivni studenti; D - desno stopalo; S - levo stopalo, SD - standardna devijacija, U - Man-Vitnijev test

2. F or R load percentage in relation to both feet (load %) and
3. Whole foot load percentage in relation to both feet (Load %).

The recommended reference range for the first parameter (R/F %) is 42 – 48% for F and 52 – 58% for R; for the second parameter (load %) it is 20 – 26% for F and 24 – 30% for R; the reference range for the third parameter (Load %) is 47 – 53%.

Measurements of height, weight and shoe size were conducted and these data were entered into the database. Then, the participants were submitted to baropodometry platform: they stood still for several seconds, until the machine finished reading the data.

After determining the parameters, the data were entered into the free program for statistical analysis of sampled data. The measured values were compared with the reference values. By doing so, we have established to what degree they deviated from the reference physiological values.

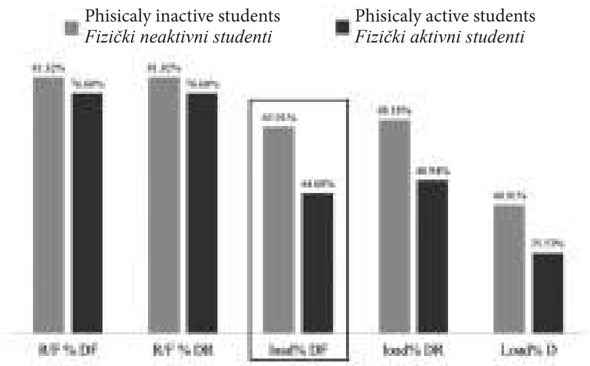
We examined:
- The percentage of participants with non-physiological values in each of the groups,
- If there was a statistically significant difference in measured values between PIS and PAS,
- If there was a statistically significant difference in deviation from the reference values between PIS and PAS.

Student’s t-test, Mann-Whitney U-test and Pearson’s χ^2-test were used for statistical analysis.

Results

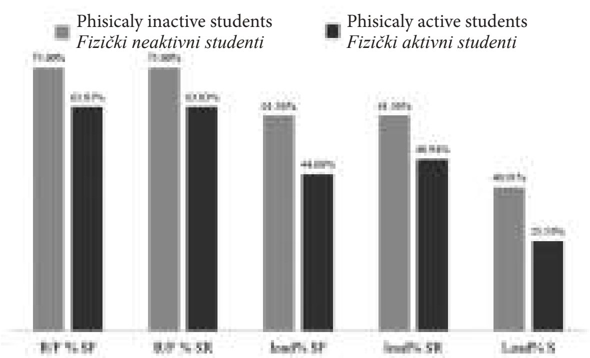
The statistical analysis showed that PAS have statistically significantly higher values of R/F % of the right forefoot (DF), R/F % of the left forefoot (SF), load % DF and load % SF. The PIS showed statistically significantly higher values of R/F % of the right rearfoot (DR), R/F % of the left rearfoot (SR), load % DR and load % SR. There were no statistically significant differences in values of Load % D and Load % S between PAS and PIS **(Table 1)**.

The PIS showed statistically significantly higher deviations from the reference values for the parameters R/F % SF, R/F % SR, load % DF, load % DR, load % SF and load % SR in comparison to PAS. There were no statistically significant differences in deviations from the reference values for parameters R/F % DF, R/F % DR, Load % D and Load % S in comparison to PAS **(Table 2)**.



Graph 1. Percentage of participants with non-physiological values for the right foot by groups; the selected part shows a statistically significant difference
Grafikon 1. *Procenat ispitanika sa nefiziološkim vrednostima po grupama ispitanika za desno stopalo. Označeni deo grafika pokazuje statistički značajnu razliku*

The percentage of PIS with non-physiological values was higher for all the parameters than in PAS. However, the difference was statistically significant only for the parameter load % DF **(Graphs 1 and 2)**.



Graph 2. Percentage of participants with non-physiological values for the left foot by groups
Grafikon 2. *Procenat ispitanika sa nefiziološkim vrednostima po grupama ispitanika za levo stopalo*

Discussion

The significance of this paper is reflected in the first attempt of representing objective parameters of the foot statics in our population using a new device - FreeMed Maxi. Such a sophisticated device was not accessible to researchers until now, therefore there was little to no possibility to compare our results with those of other researchers.

We have concluded that all the parameters of the F load (R/F % DF, R/F % SF, load % DF and load % SF) in PAS are statistically significantly higher in comparison to PIS. All the parameters of the R load (R/F % DR, R/F % SR, load % DR and load % SR) are statistically significantly higher in PIS than in PAS. According to these results, we may conclude that while standing, PAS use their F as the main support and PIS use their R as the main support. This can be partially explained by frequent exercise in PAS, mainly because during warm-up exerices (stretching and running) greater strain is exerted on the F, which was confirmed by authors who conducted research in this area [14–16].

We have established that there is a statistically significantly higher deviation for most parameters of foot load (R/F % SF, R/F % SR, load % DF, load % DR, load % SF and load % SR) in PIS in comparison to PAS. A possible explanation could be that physical activity significantly stretches the tendons of the muscles and the ligaments, and in that way contributes to maintaining healthy morpho-functional caracteristics of the foot [17, 18]. Apart from that, inadequate footwear and sedentary way of life of PIS are possible causes of these differences.

Even though a higher percentage of PIS deviates from physiological values in all the parameters in comparison to PAS, both groups showed a significant percentage of participants that deviated from the reference range. These results are quite unsatisfactory. The most probable causes for such results are genetic inheritance, damaging effects of inadequate footwear and differences in gait.

The limiting factor of this study is that there are no relevant data we can compare our results to. In addition, the significance of the inheritance factor for the development of foot deformities and load distribution was not taken into account, since the data regarding foot deformities of the participants' relatives were not acquired, as well as the type and quality of footwear and orthopedic aids which the participants may have used in their childhood. Finally, earlier foot and ankle injuries should have been taken into consideration.

Foot deformities are not only a medical but also a socioeconomic problem. Their early discovery and prevention is necessary, so that the damage to the locomotor apparatus, caused by inadequate force vector distribution, especially in young athletes and in older age, could be hindered. Consequently, it is crucial that medical professionals observe the development of child's feet through regular checkups and educate the population about the problems that may appear as a consequence of foot deformities.

Conclusion

Our study shows that physically active students have physiologically better foot load distribution than physically inactive students.

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