BIOMECHANICAL FOOT ANALYSIS IN CASE OF FOUR TYPOLOGIES: NORMAL FOOT, PES CAVUS, PES PLANUS AND HALLUX VALGUS

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ABSTRACT. As each person is different in terms of conformation of the foot and temporal and spatial peculiarities of the individual gait pattern, an extended biomechanical analysis was performed for four categories of foot identified by the authors in a previous research study, namely normal, pes cavus (high arched), pes planus (flat) and hallux-valgus foot, in the case of young people aged 20-30 years. A representative case study was selected and the plantar pressures obtained in dynamics were analysed, following the next sequence: framing the subject in the appropriate category, simultaneous visualisation of the footprint for the left and right foot, impulse analysis, recording the variation of plantar pressures and the forces exerted on the foot as a function of time, calculating the percentage values of balance on the rear-foot, heel and medial areas, positioning of the foot axis according to the direction of movement, identification of individual characteristics of walking phases and their temporal / spatial characterisation parameters, highlighting the hysteresis for heel and rear-foot areas, recommendations for the application of orthotic devices. These results are significant in the modelling and design of the bottom shoe assembly, thus proposing solutions for balancing the pressures on the plantar surface by choosing the appropriate dimensional and shape characteristics of the components of this assembly.
KEY WORDS: foot biomechanics, gait analysis, customized footwear

ANALIZA BIOMECANICĂ A PICIORULUI ÎN CAZUL A PATRU TIPOLOGII: PICIOR NORMAL, PICIOR SCOBIT, PICIOR PLAT ȘI PICIOR CU HALLUX VALGUS

REZUMAT. Pentru că fiecare persoană este diferită de celelalte prin conformația piciorului său și prin particularitățile temporare și spațiale ale tiparului individual de mers, a fost realizată o analiză biomecanică extinsă pentru patru categorii de picior identificate într-o cercetare anterioară, respectiv picior normal, picior scobit, picior plat și picior cu hallux-valgus, în cazul tinerilor cu vârsta cuprinsă între 20 și 30 de ani. A fost astfel selectat câte un studiu de caz reprezentativ și au fost analizate presiunile plantare obținute în dinamică, parcurgându-se următoarea succesiune: încadrarea subiectului în categoria corespunzătoare, vizualizarea simultană a amprentelor pentru piciorul stâng și piciorul drept, analiza impulsului, înregistrarea variației presiunilor plantare și a forțelor exercitate asupra piciorului în funcție de timp, calcularea valorilor procentuale ale echilibrului pe zonele anterioară, posterioară și mediană, poziționarea axei piciorului în raport cu direcția de deplasare, identificarea caracteristicilor individuale ale fazelor mersului și a parametrilor temporali/spațiali de caracterizare a acestora, evidențierea histerezelor călcâiului și pe cele ale părții anterioare, recomandări pentru aplicarea dispozitivelor ortotice. Aceste rezultate sunt extrem de importante în etapa modelării și proiectării ansamblului inferior al încălțămintei propunându-se astfel soluții pentru echilibrarea presiunilor pe suprafața plantară prin alegerea corespunzătoare a caracteristicilor dimensionale și de formă ale componentelor acestui ansamblu.
CUVINTE CHEIE: biomecanica piciorului, analiza mersului, încălțăminte personalizată

ANALYSE BIOMÉCANIQUE DU PIED DANS LE CAS DES QUATRE TYPES : LE PIED NORMAL, LE PIED CREUX, LE PIED PLAT ET LE PIED AVEC HALLUX-VALGUS

RÉSUMÉ. Parce que chaque personne diffère des autres par la forme de son pied et les caractéristiques temporelles et spatiales du modèle de marche individuel, une analyse biomécanique étendue a été réalisée pour quatre catégories de pied identifiées dans une étude précédente, à savoir le pied normal, le pied creux, le pied plat et le pied avec hallux-valgus, chez les jeunes de 20 à 30 ans. Un cas d'étude représentatif a été sélectionné et les pressions plantaires obtenues en dynamique ont été analysées en suivant la séquence suivante : cadrage du sujet dans la catégorie appropriée, visualisation simultanée des empreintes digitales du pied gauche et droit, analyse des impulsions, enregistrement de la variation des pressions plantaires et les forces exercées sur le pied en fonction du temps, le calcul des pourcentages d'équilibre sur les zones antérieure, postérieure et médiane, le positionnement de l'axe du pied par rapport à la direction du mouvement, l'identification des caractéristiques individuelles des phases de marche et leurs paramètres temporels/spatiaux, mettant en évidence l'hystérésis du talon et celles de la partie antérieure, recommandations pour l'application des orthèses. Ces résultats sont extrêmement importants dans l'étape de modélisation et de conception de l'ensemble inférieur de la chaussure, proposant ainsi des solutions pour équilibrer les pressions sur la surface plantaire en choisissant les caractéristiques dimensionnelles et de forme appropriées des composants de cet ensemble.
MOTS CLÉS : biomécanique du pied, analyse de la marche, chaussures personnalisées

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INTRODUCTION

Plantar footprint has often been studied in the past for various reasons [1-2]. Many scientists around the world have focused their attention on the analysis of traces of hominid fossils, orthopaedic and other medical studies, such as anatomical, anthropological, genetic, dermatological, biomechanical, ergonomic and forensic studies [3].

Biomechanical studies have progressed, by comparing the existence, lack or dimensions of the typological parameters of the foot between groups with or without pathologies under investigation [4]. Despite the widespread use of these parameters, it has been recognized that objective and quantitative analysis of foot typologies remains elusive [5-6]. The absence of an absolute dimension of the foot typology led to considerable variations in the choice of the type of measurements in order to determine the type of foot [7-8]. This is in antithesis with the suggestion that in order to identify the relations between the typology and the pathology of the foot, it is first necessary to use a classification system that allows the accurate recognition of each situation [9-10].

People can be distinguished from each other by their unique gait pattern. This gait pattern is used to recognise people at a distance [11-13]. Because each step is slightly different from the other while walking, due to differences in walking parameters, such as heel contact, speed and angle of rotation, force and effort, variation in human locomotion exists for each individual, even in walking on the same type of ground [14-16].

This article continues the research undertaken by the authors, namely the biomechanical analysis for the four typologies of the foot of young people aged between 20-30 years. Using the Chippaux-Simark index (CIS), vault angle (α), and thumb deflection angle (β), subjects were divided into 4 categories, as follows: subjects with normal, pes cavus (high arched), pes planus (flat), and hallux-valgus foot [17].

EXPERIMENTAL

Methods and Equipment

As the investigated subjects (volunteers) stated that they were not in the records of any specialist and did not report that they were suffering from any condition affecting the health of the foot (e.g., diabetes, rheumatoid arthritis, irreversible structural abnormalities of the foot), the preliminary condition of the study was met, namely the taking of plantar footprint from subjects who are apparently healthy or who declare a good state of health. Under these conditions, by elimination, the only factor that could influence the presence of the flat, the high arched or hallux valgus foot in young people is the wearing of inappropriate footwear. The study highlighted the need to inform consumers about the risks they are exposed to when wearing inappropriate footwear.

In order to establish the typology of the foot, the plantar footprints were taken from a number of 76 subjects, of which 60 are women and 16 men, aged between 20-30 years, and weighing between 45-100 kg.

For all investigated subjects, the following working hypotheses were considered:

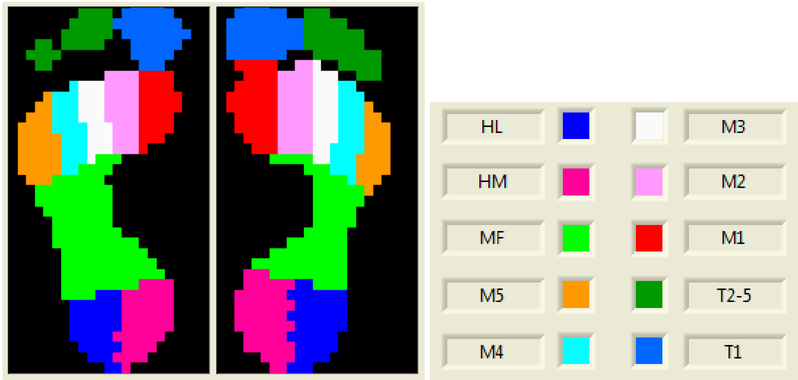
- No abnormal gait patterns were observed;
- No structural abnormalities in the foot;
- No systemic conditions that may affect gait.

All experimental protocols were approved by a named institutional review committee. The subject was informed and consented to the test and publishing the results. All methods were carried out in accordance with relevant guidelines and regulations.

RESULTS AND DISCUSSIONS

Comparative Analysis of Plantar Pressure Distribution

Using the RSscan pressure plate and the associated system - Footscan 7 Gait, 2nd Generation, 0.5 Gait Scientific System, the dynamic pressures were measured for all 76 subjects, women and men. The sole of the foot was divided into 10 significant areas (Figure 1) and the distribution of the plantar pressure was obtained.



HL – Lateral heel
HM – Medial heel
MF – Middle foot
M1 – Metatarsal 1
M2 – Metatarsal 2
M3 – Metatarsal 3
M4 – Metatarsal 4
M5 – Metatarsal 5
T2-5 – Toes 2-5
T1 – Toe 1

Figure 1. Anatomical division of the plantar footprint

Following the classification of subjects, women and men, in the four groups: normal, high arched, flat and hallux valgus foot, resulted the average pressures on each area of the plantar surface, presented in the following Table 1.

Table 1: Mean plantar pressure values (N / cm^2) for each group: normal foot, flat foot, high arched foot, hallux-valgus foot

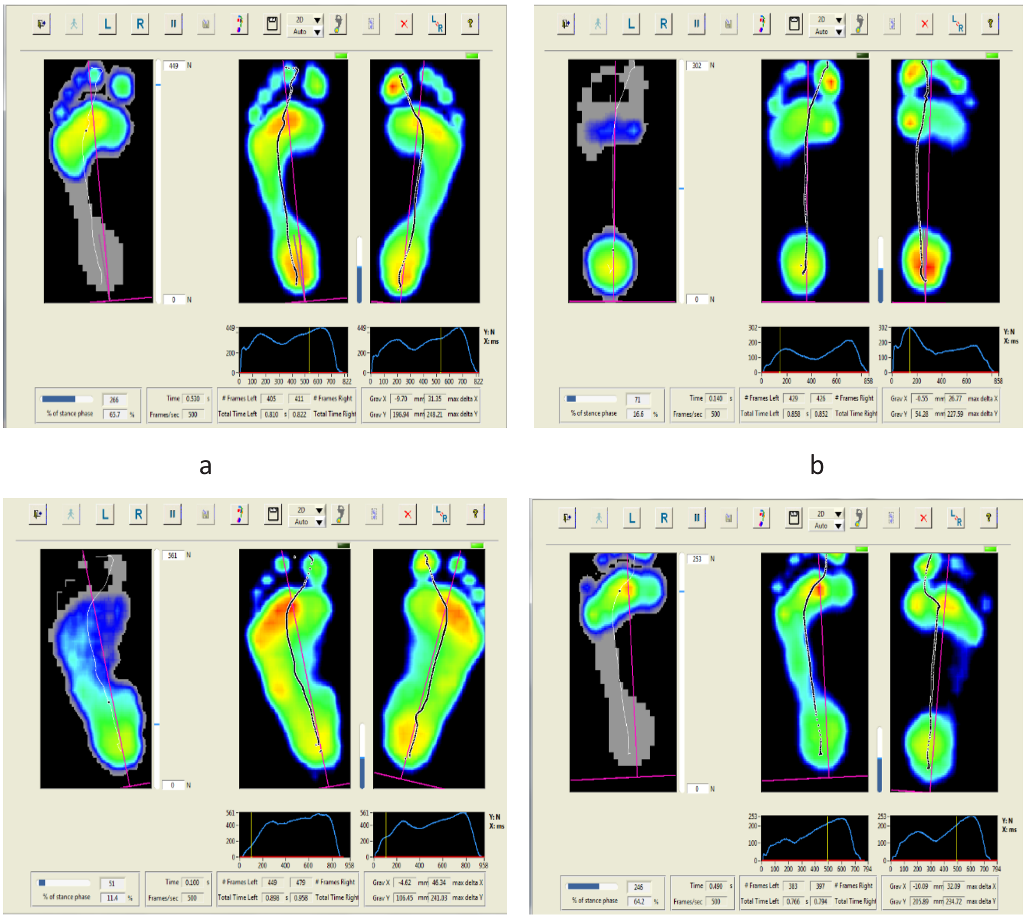
Foot			Toe 1	Toes 2-5	Metatarsal 1	Metatarsal 2	Metatarsal 3	Metatarsal 4	Metatarsal 5	Middle foot	Lateral heel	Medial heel
			Plantar pressure (N/cm^2)									
Normal	Women	Left	5	1.20	1.46	4.22	6.81	4.98	4	1.36	4.57	4.61
		Right	3.75	1.19	2.38	4.79	5.71	3.37	1.41	1.34	4.17	4.40
	Men	Left	3.31	0.96	2.82	6.48	8.44	6.56	3.54	0.66	7.36	6.36
		Right	3.6	3.18	0.98	5.54	6.84	4.3	2.4	1.8	6.68	5.76
High arched	Women	Left	3.51	1.57	2.75	5.18	7.31	3.52	2.60	1.37	5.88	5.05
		Right	3.62	0.82	2.02	5.41	5.74	2.74	1.37	0.83	4.55	4.62
	Men	Left	2.51	0.29	3.66	7.69	9.89	6.95	3.52	1.23	6.72	6.20
		Right	3.54	0.35	4.17	7.16	7.72	4.76	2.45	0.77	6.52	5.68
Flat	Women	Left	4	0.28	2.78	5.14	6.99	5.04	1.89	0.81	6.19	5.56
		Right	3.54	1.8	2.68	5.25	6.08	3.19	0.88	1.26	4.79	5.26
Hallux-Valgus	Men	Left	2.84	0.95	2.65	5.93	6.84	3.78	1.47	1.13	4.37	3.78
		Right	3.16	0.72	2.88	6.33	5.9	3.5	1.55	0.71	4.85	4.73

It can be seen from the previous table that there are no significant differences between the groups of subjects, the maximum pressure being recorded each time on the metatarsal 3, and the following, as values, on the metatarsal 2 and on the heel. Consequently, when designing the lower shoe assembly, the balance of plantar pressure distribution by the shape of the parts and the type of materials used must be taken into account.

Case Studies on Biomechanical Foot Analysis

From each category previously identified by applying the classification criteria based on plantar parameters (indices and angles), a representative subject was selected. For each case presented, the plantar pressures obtained on dynamics are analysed, following the next sequence: classification of the subject in the appropriate category, simultaneous visualisation of the footprint for the left and right foot, impulse analysis, recording the variation of plantar pressures and the forces exerted on the foot as a function of time, calculating the percentage values of balance on the rear-foot, heel and medial areas, positioning of the foot axis according to the direction of movement, identification of individual characteristics of walking phases and their temporal / spatial characterisation parameters, highlighting the hysteresis for heel and rear-foot areas, recommendations for the application of orthotic devices.

Subject S74 did not have health problems and did not have lower limb disorders (Figure 2a). According to the previous analysis, the presented subject is part of the category of those with normal foot. A brief analysis of plantar pressures will reveal deviations from the pattern of normal gait. Subject S57 (Figure 2b) has no health problems or lower limb disorders, but has lower back pain. Subject S65 (Figure 2c) does not present health problems. At the level of the foot, a structural anomaly of the flat foot type is identified. In case of prolonged physical exertion, the subject shows pain in the foot. Subject S26 (Figure 2d) has no health problems and has never had lower limb disorders. At a first investigation, there is a tendency of the big toe to deviate outwards, a situation associated with a structural anomaly of the hallux-valgus type.



a b c d

Figure 2. Simultaneous visualisation of the left and right foot and tracking the projection of the center of gravity (a-normal foot, b-high arched foot, c-flat foot, d-hallux-valgus foot)

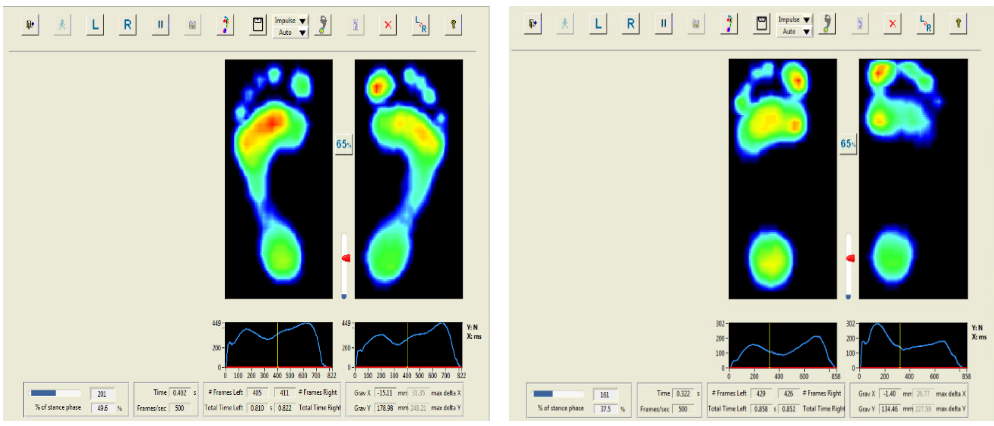
Figure 2a shows that there is a slight difference between the contact surfaces of both feet. Thus, in the middle area of the left foot, the contact area is smaller. The center of gravity displacement curve is lateral to the axis of symmetry of the foot, with a larger difference in the left foot. The highest-pressure points can be observed, on the left foot, in the area of the metatarsals 2-4, and on the right foot, under the thumb. Both the left and the right foot move at about the same speed, and as can be seen from the force graphs over time, the gait pattern for the two feet is similar.

The subject shown in Figure 2b has both feet strongly arched, the middle area does not make contact at all with the ground while walking. The displacement curve of the center of gravity is located inwards with respect to the longitudinal axis of the right foot. In the case of the left foot, it follows the axis of the foot until push off moment, when it changes direction inwards due to excessive loading of the toe 1. The highest-pressure points can be observed on the left foot in the area of the metatarsal 1 and toe 1, and on the right foot, under the metatarsal 1 and the big toe. The variation in strength as a function of time shows graphs that have different shapes for the right foot compared to the left one. If for the left foot, the shape of the curve approaches a shape specific to the normal gait pattern, for the right it is observed that in the first phases of gait (heel strike and mid-stance), the forces exerted on the heel area of the foot are much greater than those exercised on the rear-foot.

The footprint for the subject presented in Figure 2c suggests the flat foot. From the 2D view it can be seen that there is a slight difference between the contact surfaces of both feet, the contact surface being slightly smaller in the middle area of the left foot. The highest-pressure points can be observed on the heel area, on the medial-outer area of the foot, under the metatarsals 2-5 and under the toe 1.

In the case of the subject from Figure 2d, the middle area of the right foot does not come into contact with the support surface while walking, which indicates a high arched foot. The pronounced outward orientation of the toe 1 is also observed. The displacement curve of the center of gravity is lateral to the longitudinal axis of the foot. For the left foot it is positioned outside the longitudinal axis, and for the right foot it is located inwards. The highest-pressure points are observed on the left foot, in the area of the metatarsals 2-3, and on the right foot, under the big toe, the metatarsals 1-3 and in the area of the heel. Each foot has a movement close to the normal gait pattern.

Figure 3 shows the impulse exerted on the foot during the walking phases. Impulse is the product of force and time, measured in percentages. The longer the period of time in which a pressure is applied to a particular area, the greater the risk.



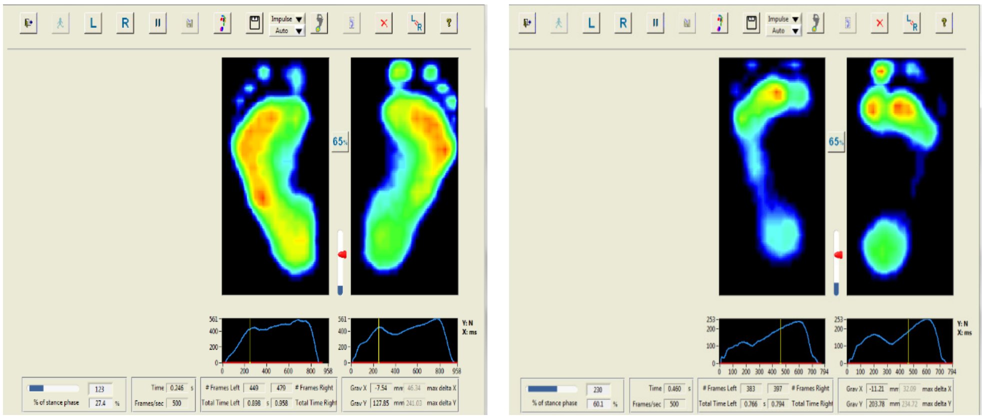
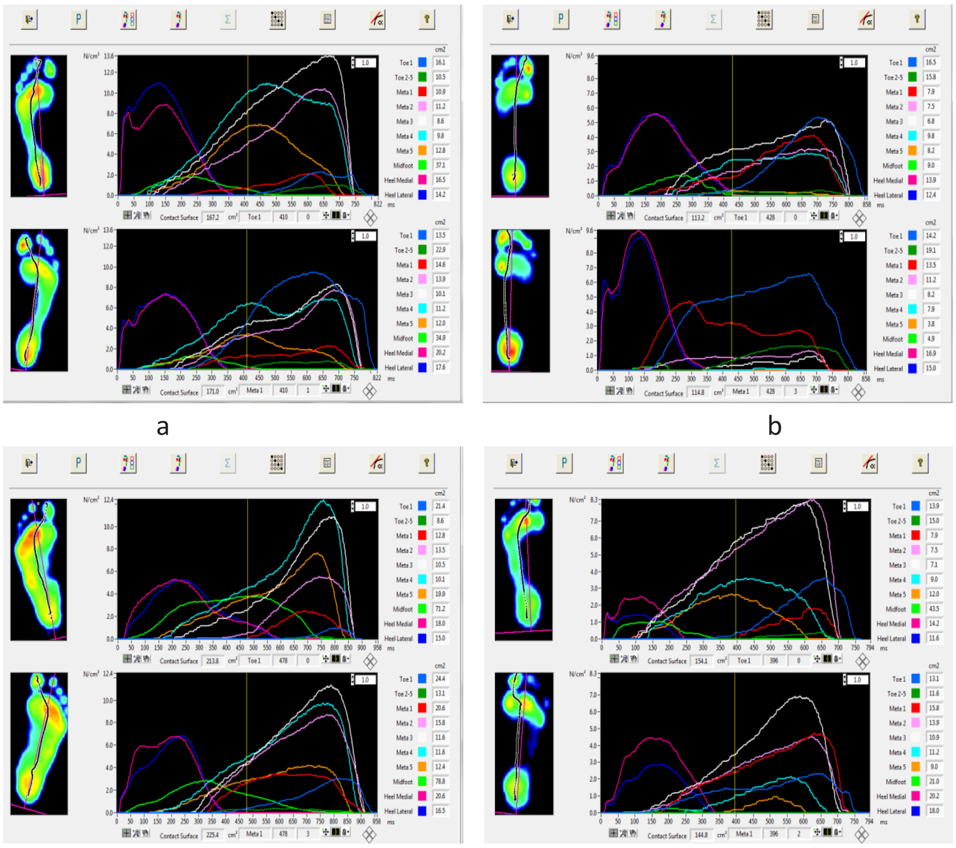


Figure 3. Impulse analysis (a-normal foot, b-high arched foot, c-flat foot, d-hallux-valgus foot)

In the case of the subject presented in Figure 3a, the risk areas are the metatarsal 3 and the toe 1; while from Figure 3b, the risk areas are the metatarsal 1 and the toe 1; for the subject in Figure 3c, these are the metatarsals 2-5 and the lateral-medial area of the foot; the subject presented in Figure 3d shows high pressures in the area of the metatarsal 2, for the right foot and the toe 1, respectively, the metatarsals 1, 2 and 3 for the left foot.

If from the previous figure (Figure 3), the risk areas have been established based on the impulse, using Pressure / Time graphs presented in Figure 4 the values of the pressures for each area can be calculated exactly.



a b

c d

Figure 4. Variation of pressure as a function of time
(a-normal foot, b-high arched foot, c-flat foot, d-hallux-valgus foot)

The line of net force, the purple line, in Figure 5 represents the variation of the force as a function of time and it can be seen that it consists of the loads which appear in heel, medial and rear area of the foot and the times at which these loads occur.

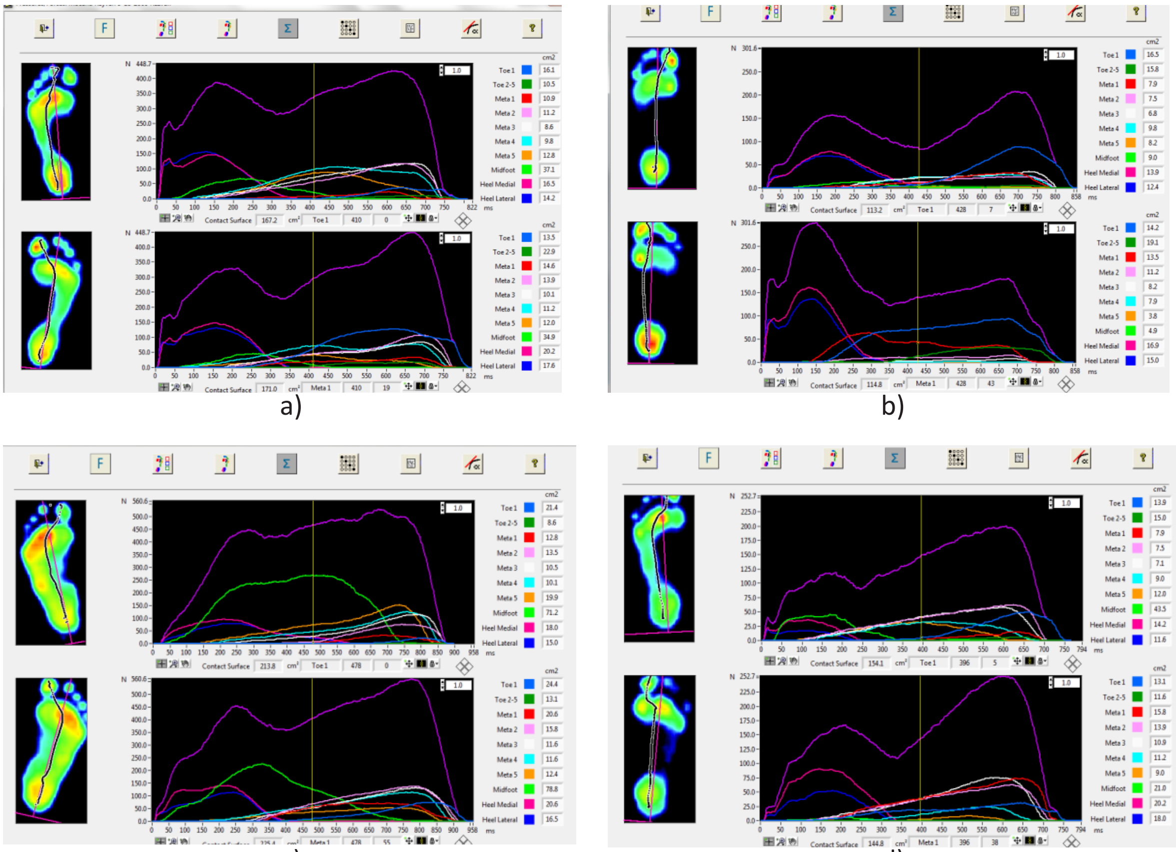
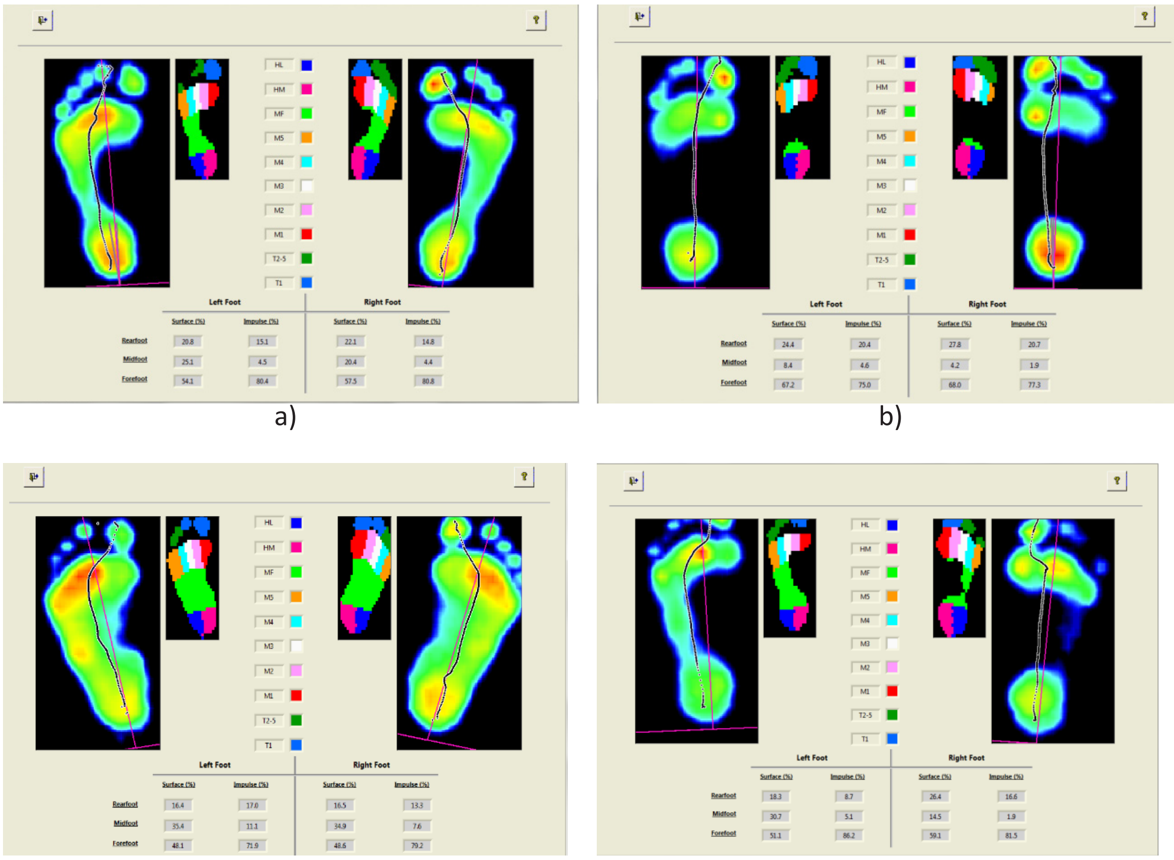


Figure 5. Variation of force as a function of time (a-normal foot, b-high arched foot, c-flat foot, d-hallux-valgus foot)

For each of the four categories of foot studied, the walking patterns show that in the impact phases, both for the right foot and for the left foot, the pressures exerted by the foot in the heel area have values that would require the presence of additional elements in the shoe structure with shock damping role. For these subjects, the force-time curve does not have a normal shape due to high pressures under the heel and under the metatarsals, in the case of the left foot and the heel and toe 1, in the case of the right foot.

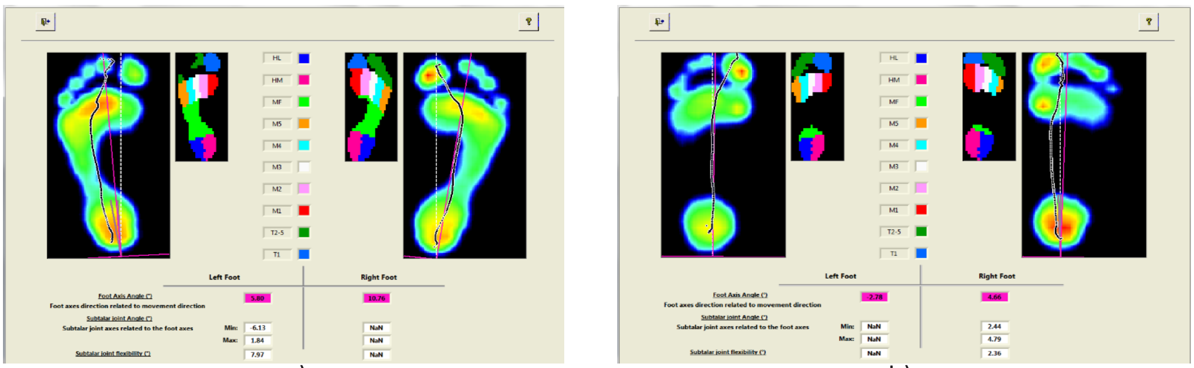
From Figure 6 can be observed the percentage values of the plantar surface corresponding to the heel, medial and rear-foot areas and the associated impulse. Based on these values, the category in which the foot is placed is automatically identified: normal (Figure 6a), flat (Figure 6b) or high arched (Figure 6c).



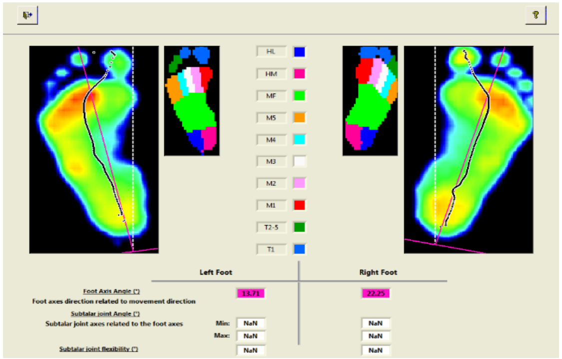
a) b) c) d)

Figure 6. Percentage value of rear-foot, medial and heel areas. Percentage value of the impulse (a-normal foot, b-high arched foot, c-flat foot, d-hallux-valgus foot)

In Figure 7, the white line indicates the direction of movement, the pink line represents the longitudinal axis of the foot, and the black curve, following the movement of the point of gravity. The value of the angle formed between the direction of movement and the longitudinal axis of the foot indicates the abduction position of the foot if it has a positive sign, and the adduction position if it has a negative sign, respectively.



a) b)



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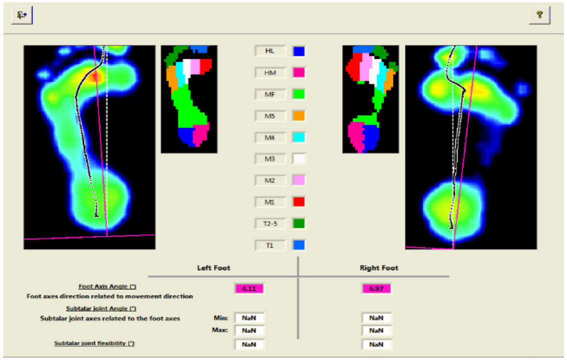
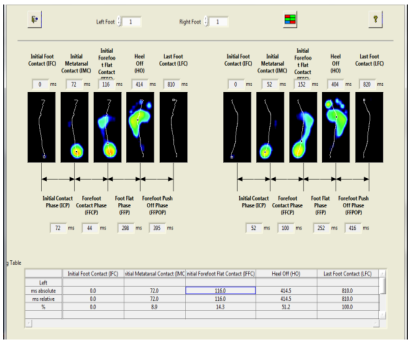


d)

Figure 7. Foot axis direction and direction of movement
(a-normal foot, b-high arched foot, c-flat foot, d-hallux-valgus foot)

In the case of the subjects presented in Figures 7a, c, d, the right foot has an angle of abduction greater than the left foot.

In the Figure 8 the times to complete a step are shown.



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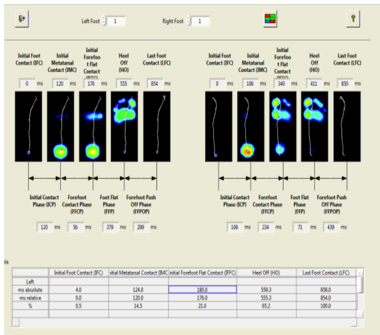

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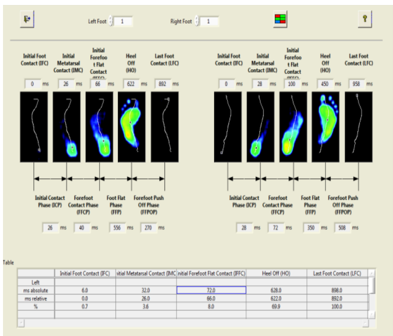

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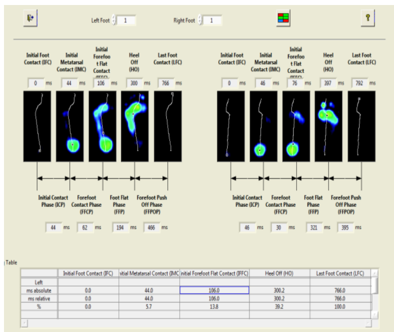


d)

Figure 8. Walking phases and time (ms) corresponding to each phase
(a-normal foot, b-high arched foot, c-flat foot, d-hallux-valgus foot)

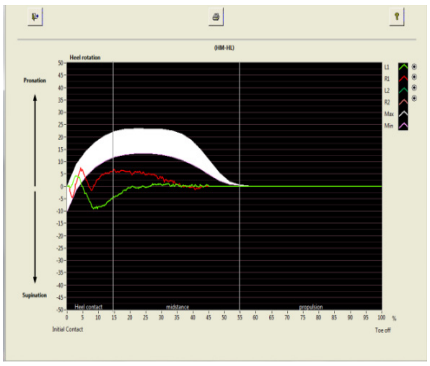
For the subject with a normal foot, Figure 8a, it can be seen that the time required for the left foot to complete a step is 10 ms less than that for the right foot (810 and 820 ms, respectively). Even if the right foot needs only 52 ms for the initial contact, compared to 72 ms in the case of the left foot, the push off phase is longer on this foot, thus explaining the high pressure on the toes.

In the case of the high arched foot, Figure 8b, the time required for the left foot to complete a step is 4 ms longer than that for the right foot (854, respectively 850), even if these values are very close, in areas they differ very much, the right foot needs 120 ms for the initial contact, compared to 106 ms for the left foot; 56 ms for metatarsal area contact on the left foot and 234 ms on the right foot; 379 ms for mid-stance on the entire plantar surface for the left foot and 71 ms for the right foot and the push off phase is longer on the right foot, 439 ms compared to 299 ms for the left foot, thus explaining the high pressure on the toes, in this case, the toe 1.

Regarding the flat foot, Figure 8c, it can be seen that the time required for the left foot to complete a step is 66 ms less than that for the right foot (892 and 958 respectively), in some areas the values differ greatly, the right foot needs 28 ms for the initial contact, compared to 26 ms for the left foot; 40 ms for medial area contact on the left foot and 72 ms on the right foot; 556 ms for mid-stance on the entire plantar surface for the left foot and 350 ms for the right foot; the push off phase is longer on the right foot, 508 ms compared to 270 ms for the left foot, thus explaining the high pressure on the toe area, in this case, the toe 1.

For the subject with the hallux-valgus anomaly, Figure 8d, it can be seen that the time required for the left foot to complete a step is 26 ms less than that for the right foot (766, respectively 792), in some areas the values differ greatly, the right foot needs 44 ms for the initial contact, compared to 46 ms for the left foot; 62 ms for medial area contact on the left foot and 30 ms on the right foot; 194 ms for mid-stance on the entire plantar surface for the left foot and 321 ms for the right foot; the push off phase is longer on the left foot, 466 ms compared to 395 ms for the right foot, thus explaining the high pressure on the toes.

In all analysed cases, the balance graph for the heel movement shows that the left foot is loaded less than the average in the mid-stance phase, suggesting a possible supination of the heel (Figure 9).



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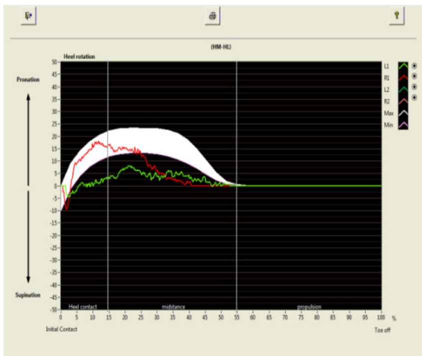

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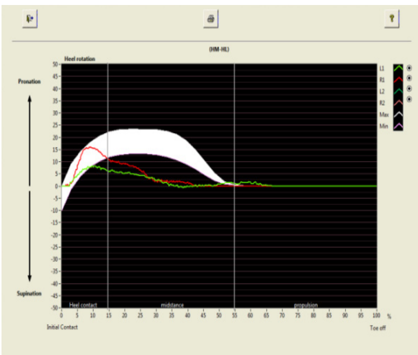

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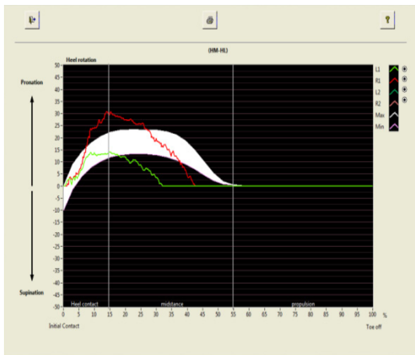
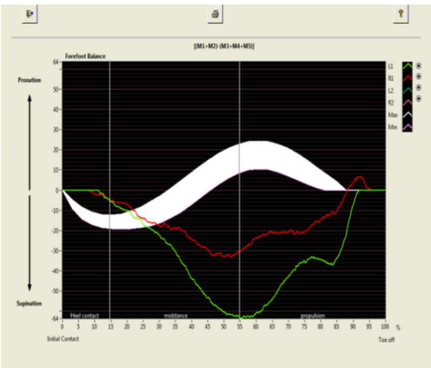


d)

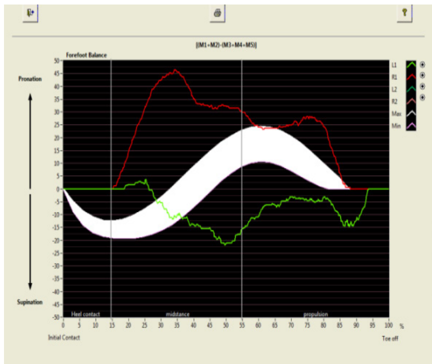
Figure 9. Heel hysteresis (a-normal foot, b-high arched foot, c-flat foot, d-hallux-valgus foot)

For subjects with normal, high arched, and flat feet, the balance graph for the rear-foot area shows that both feet (left and right) are loaded less than normal in the mid-stance phase on the entire plantar surface, thus suggesting a possible supination of them (Figures 10 a, b, c).

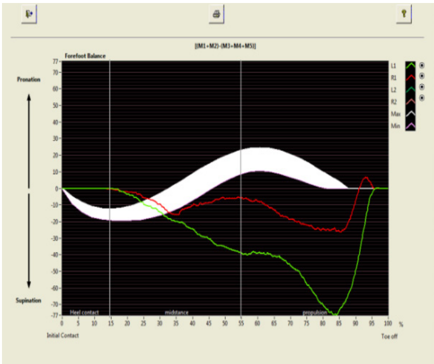
For the hallux-valgus foot, Figure 10d, the balance graph for the rear-foot area shows that the right is loaded more than normal in the mid-stance phase on the entire plantar surface, thus suggesting a possible pronation of it, and the left is loaded less than normal values, in the phase of mid-stance, suggesting supination in that area. Towards the push off phase, the loads increase due to the high pressure that is exerted on the toe 1.



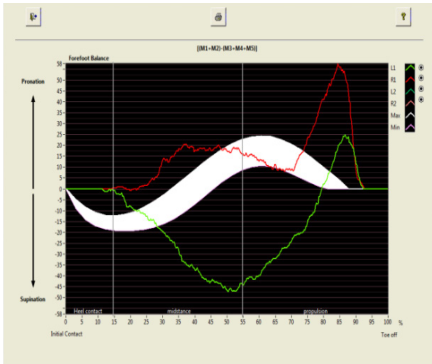
a)



b)



c)



d)

Figure 10. Rear-foot hysteresis (a-normal foot, b-high arched foot, c-flat foot, d-hallux-valgus foot)

Taking into account the contact areas of the foot while walking, the value of the impulse in those areas and the calculations made to obtain equilibrium graphs, orthotic devices may be recommended (Figure 11).

For the normal foot, the recommendation is to lift the left foot outward to prevent supination. With regard to the high arched foot, it is recommended to use a custom orthosis on the inside of the hollow area, especially on the right foot, being more severely affected. In the case of the flat foot, it is suggested to insert the orthoses in the heel area for both feet and in the outer part of the middle area of the left foot. For the foot with hallux-valgus, the recommendation is an orthosis in the heel area but also for the release of the metatarsal areas 1-3.

a) b) c) d)

Figure 11. Areas of application of orthotic devices
(a-normal foot, b-high arched foot, c-flat foot, d-hallux-valgus foot)

CONCLUSIONS

In the stage of modelling and designing the component parts of the bottom assembly of footwear (insole, sole), it is necessary to consider balancing the distribution of plantar pressures by the shape of the component parts and by the type of materials used. The analysis of the distribution of plantar pressures on the surface of the sole of the foot showed for both categories of subjects, women and men, the presence of pressure peaks under the metatarsals 2 and 3 and in the heels. These areas were considered risk areas, and in the modelling and design of the bottom assembly, solutions were proposed to balance the pressures on the plantar surface by choosing the appropriate dimensional and shape characteristics of the components of this assembly.

For the biomechanics studies within this research, the RSScan plantar pressure recording system was used. Modern computer-aided equipment, assisted by specialised recording, measurement and analysis software, offers multiple advantages in terms of the possibility of integrating information obtained from simple analysis of plantar footprint configuration with exact values of plantar pressures and forces exerted on foot, in static and dynamic.

A direction for further research initiated in this article is the design of models to validate the results recorded for each of the analysis steps mentioned above through simulation models and techniques. Currently, through specialized studies undertaken by various research teams, it has been possible to simulate on simple models of the foot and validate the pressures and forces recorded on the plantar surface in a position of bilateral orthostatic support. The simulation of dynamic conditions and the validation of other parameters for characterizing gait is a topic for future studies, this paper initiating new research directions in this regard.

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REFERENCES

1. Leardini, A., Benedetti, M.G., Berti, L., Bettinelli, D., Nativo, R., Giannini, S., Rear-foot, mid-foot and fore-foot motion during the stance phase of gait, *Gait Posture*, **2007**, 25, 453–462, https://doi.org/10.1016/j.gaitpost.2006.05.017.
2. Wolf, P., Stacoff, A., Liu, A., Nester, C., Arndt, A., Lundberg, A., Stuessi, E., Functional units of the human foot, *Gait Posture*, **2008**, 28, 434–441, https://doi.org/10.1016/j.gaitpost.2008.02.004.
3. Kewal, K., Establishing correlation of footprints with body weight—Forensic aspects, *Forensic Sci Int*, **2008**, 179, 63–69, https://doi.org/10.1016/j.forsciint.2008.04.015.
4. Bruening, A.D., Cooney, K.M., Buczek, F.L., Analysis of a kinetic multi-segment foot model part II: Kinetics and clinical implications, *Gait Posture*, **2012**, 35, 535–540, https://doi.org/10.1016/j.gaitpost.2011.11.012.
5. Zheng, S., Huang, K., Tan, T., Evaluation framework on translation-invariant representation for cumulative foot pressure image, The 18th IEEE International Conference on Image Processing (ICIP), **2011**, 201–204, https://doi.org/10.1109/ICIP.2011.6115874.
6. Zheng, S., Huang, K., Tan, T., Tao, D., A cascade fusion scheme for gait and cumulative foot pressure image recognition, *Pattern Recognit*, **2012**, 45, 3603–3610, https://doi.org/10.1016/j.patcog.2012.03.008.
7. Felzenszwalb, P.F., Girshick, R.B., McAllester, D., Ramanan, D., Object detection with discriminatively trained part-based models, *IEEE Trans Pattern Anal Mach Intell*, **2010**, 32, 1627–1645, https://doi.org/10.1109/TPAMI.2009.167.
8. Bouchrika, I., Nixon, M., Model-based feature extraction for gait analysis and recognition, International Conference on Computer Vision/Computer Graphics Collaboration Techniques, **2007**, 150–160, https://doi.org/10.1007/978-3-540-71457-6_14.
9. Zhang, T., Li, X., Tao, D., Yang, J., Multimodal biometrics using geometry preserving projections, *Pattern Recognit*, **2008**, 41, 805–813, https://doi.org/10.1016/j.patcog.2007.06.035.
10. Mathieson, I., Upton, D., Birchenough, A., Comparation of footprint parameters calculated from static and dynamic footprints, *Foot*, **1999**, 9, 145-149, https://doi.org/10.1054/foot.1999.0544.
11. Shan, C., Gong, S., McOwan, P.W., Fusing gait and face cues for human gender recognition, *Neurocomputing*, **2008**, 71, 1931–1938, https://doi.org/10.1016/j.neucom.2007.09.023.
12. Tao, D., Li, X., Wu, X., Maybank, S.J., General tensor discriminant analysis and gabor features for gait recognition, *IEEE Trans Pattern Anal Mach Intell*, **2007**, 29, 10, 1700–1715, https://doi.org/10.1109/TPAMI.2007.1096.
13. Geng, X., Smith-Miles, K., Wang, L., Wu, Q., Context-aware fusion: a case study on fusion of gait and face for human identification in video, *Pattern Recognit*, **2010**, 43, 3660–3673, https://doi.org/10.1016/j.patcog.2010.04.012.
14. He, M., Horng, S., Fan, P., Performance evaluation of score level fusion in multimodal biometric systems, *Pattern Recognit*, **2010**, 43, 1789–1800, https://doi.org/10.1016/j.patcog.2009.11.018.
15. Chang, W.R., Matz, S., Chang, C.-C., A comparison of required coefficient of friction for both feet in level walking, *Saf Sci*, **2012**, 50, 240–243, https://doi.org/10.1016/j.ssci.2011.08.056.
16. Gravano, S., Ivanenko, Y.P., Maccioni, G., Macellari, V., Poppele, R.E., Lacquaniti, F., A novel approach to mechanical foot stimulation during human locomotion under

body weight support, *Hum Mov Sci*, **2011**, 30, 352–367, https://doi.org/10.1016/j.humov.2010.01.002.

17. Wrbaskic, N., Dowling, J.J., An investigation into the deformable characteristics of the human foot using fluoroscopic imaging, *Clin Biomech*, **2007**, 22, 230–238, https://doi.org/10.1016/j.clinbiomech.2006.09.006.

18. Mihai, A., Păştină (Costea), M., Classification of foot types, based on plantar footprint, Proceedings of the 4th International Conference on Advanced Materials and Systems (ICAMS 2012), Bucharest, **2012**, ISSN 2068-0783, 347-352.

19. http://www.rsscan.co.uk/