BIOMECHANICAL PARAMETERS CHARACTERISING THE FOOT DURING NORMAL GAIT

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ABSTRACT. The biomechanical analysis allows to understand the normal and pathological gait, the mechanics of neuromuscular control, and last but not least, allows the visualisation of the effects of footwear on human gait or feet. Biomechanical analyses are very important for the footwear development process, as they can identify the incorrect loading of the foot or the incorrect gait pattern, thus avoiding the occurrence of deformations. This paper aims to create an average representative model of barefoot loading based on an extended group of participants by applying an optimal procedure for measuring biomechanical parameters. The variation of four basic biomechanical parameters, namely force, pressure, contact time and contact area, was measured using a pressure platform and a specialised software system. The data was collected from 32 healthy females, without particularities regarding foot health and the practice of performance sports, aged between 18 and 30 years, divided into three size groups – 36, 37 and 38. The T-Student test was applied to verify if there are significant differences between the left and right foot. Statistical indicators for each parameter were calculated, in order to characterize and establish the degree of variation of the obtained values, as follows: mean, standard deviation, minimum and maximum values, the amplitude of variation and coefficient of variation (CV). The study results confirm that the obtained mean values can be used as input data to load the foot and perform virtual simulations of footwear products.

KEYWORDS: foot, biomechanics, normal gait

PARAMETRII BIOMECANICI CARE CARACTERIZEAZĂ PICIORUL ÎN TIMPUL MERSULUI NORMAL

REZUMAT. Analiza biomecanică permite înțelegerea mersului normal și patologic, mecanica controlului neuromuscular și, nu în ultimul rând, permite vizualizarea efectelor încălțămintei asupra mersului uman și a picioarelor. Analizele biomecanice sunt foarte importante pentru procesul de dezvoltare a încălțămintei, deoarece permit identificarea încărcării incorecte a piciorului sau depistarea modelului incorect al mersului, evitând astfel apariția deformațiilor. Această lucrare are drept scop crearea unui model mediu reprezentativ de încărcare a piciorului desculț bazat pe un grup extins de participanți prin aplicarea unei proceduri optime pentru măsurarea parametrilor biomecanici. Variația a patru parametri biomecanici de bază, și anume forța, presiunea, timpul de contact și suprafața de contact, a fost măsurată utilizând o platformă de presiuni plantare și un sistem software specializat. Studiul s-a realizat pentru un eșantion de 32 de persoane de sex feminin, fără anumite particularități referitoare la starea de sănătate a picioarelor și practicarea sporturilor de performanță, cu vârsta cuprinsă între 18-30 de ani, împărțite pe 3 grupuri de mărimi, respectiv 36, 37 și 38 în sistem francez. Testul T-Student a fost aplicat pentru a verifica dacă există diferențe semnificative între valorile pentru piciorul stâng și cel drept. Au fost calculați indicatorii statistici pentru fiecare parametru analizat în vederea caracterizării și stabilirii gradului de variație a valorilor obținute, și anume: media aritmetică, abaterea standard, minimul, maximul, amplitudinea variației și coeficientul de variație. Rezultatele studiului confirmă faptul că valorile medii obținute pot fi utilizate ca date de intrare pentru a încărca piciorul și a simula comportamentul încălțămintei.

CUVINTE CHEIE: picior, biomecanica mersului, mers normal

LES PARAMÈTRES BIOMÉCANIQUES QUI CARACTÉRISENT LE PIED PENDANT LA DÉMARCHE NORMALE

RÉSUMÉ. L'analyse biomécanique permet de comprendre la démarche normale et pathologique, la mécanique du contrôle neuromusculaire et, enfin et surtout, permet de visualiser les effets des chaussures sur la démarche et les pieds humains. Les analyses biomécaniques sont très importantes pour le processus de développement de la chaussure, car elles permettent l'identification de la charge incorrecte du pied ou la détection du modèle de démarche incorrect, évitant ainsi l'apparition de déformations. Cet article vise à créer un modèle moyen représentatif de la charge des pieds nus basé sur un groupe étendu de participants en appliquant une procédure optimale pour mesurer les paramètres biomécaniques. La variation de quatre paramètres biomécaniques de base, à savoir la force, la pression, le temps de contact et la surface de contact, a été mesurée à l'aide d'une plate-forme de pression plantaire et d'un système logiciel spécialisé. L'étude a été menée pour un échantillon de 32 femmes, sans aucune particularité concernant la santé des pieds et les sports de performance, âgées de 18 à 30 ans, réparties en 3 groupes de taille, respectivement 36, 37 et 38 dans le système français. Le test T-Student a été appliqué pour voir s'il y avait des différences significatives entre les valeurs pour le pied gauche et le pied droit. Des indicateurs statistiques ont été calculés pour chaque paramètre analysé afin de caractériser et d'établir le degré de variation des valeurs obtenues, à savoir : la moyenne arithmétique, l'écart type, le minimum, le maximum, l'amplitude de variation et le coefficient de variation. Les résultats de l'étude confirment que les valeurs moyennes obtenues peuvent être utilisées comme données d'entrée pour charger le pied et simuler le comportement de la chaussure.

MOTS CLÉS: pied, biomécanique de la démarche, démarche normale

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INTRODUCTION

The foot has a complex anatomical and biomechanical structure, which ensures the transmission of the forces created during its interaction with the ground [1] and fulfils multiple functions such as support, balance, thermoregulation [2, 3] force absorption, impact attenuation and body displacement [4]. These aspects are considered and evaluated by biomechanics – the study of human movement.

The biomechanical analysis allows understanding the normal and pathological gait [5], the mechanics of neuromuscular control [6], and visualising the effects of footwear on human gait or feet. Biomechanical analyses are very important for the footwear development process, as they can identify the improper loading of the foot or the incorrect gait pattern, thus avoiding the occurrence of deformations [7].

Specific studies include two components: kinematic and kinetic analyses. The kinematic analysis evaluates movement patterns, including body movement and specific angles [8], ignoring the generated forces [9]. Kinematic components of the foot evaluated during movement are width, foot deformation under the influence of the load while walking, medial longitudinal arch length, the angle between the ankle and the foot at the initial contact, ankle movement, etc. [10].

The term kinetics is used in biomechanics to describe the relationship between forces and movement produced in the joints. These movements are produced by both internal forces (derived mainly from muscle activity and bone contact) and external forces (derived mainly from body weight or reaction forces). Kinetic studies correlate joint's angles and movements in dynamics with joint moments [11]. The main kinetic parameters are force, pressure and centre of pressure.

Human movement is composed of different rotational and translational movements, which are the result of the action of a complex field of forces - normal (perpendicular) and tangential (parallel) or torques acting on the body [1, 9, 12].

The field consists of two categories of forces: external and internal. The tensions in the muscle groups represent the active internal forces. During walking, muscle forces are added to inertia forces, which occurs due to the interaction of different body elements [2]. The most common external force applied to the human body while walking is the reaction force. This force is a three-dimensional vector comprising a vertical component and two horizontal components. In the mid-stance phase, the foot exerts an exchange of forces with the ground. In the heel strike phase, the human foot touches the support, generating two forces in the x-direction and the y-direction. The foot passes through the mid-stance phase immediately after the entire plantar surface touches the support. In the next stage, the foot exerts the most significant force to ensure that the body moves forward. The support reacts with the same amount of force in the opposite direction [13]. The magnitude of the ground reaction forces depends on the speed and body weight [14].

The extent and direction of the internal forces are significant. According to Jacob [15], the force applied on the first metatarsal reaches about 119% of body weight, while the second metatarsal is subjected to a high bending moment, with a resulting force of about 45% of the body weight acting on foot.

In the first 100 ms of each step, the force acting in the Z direction reaches a maximum of 120% of body weight, decreasing to about 60-80% of body weight during support on one foot. The centre of gravity is located in the middle of the pelvis and makes a sinusoidal movement while walking. The horizontal reaction forces are considerably smaller than the vertical reaction force. The horizontal reaction force acting in the Y direction has an amplitude of 25% of the body weight [14].

Wiedemeijer and Otten [16] and Stefanyshyn *et al*. [17] have analysed the distribution of forces while walking in high-heeled shoes. This condition significantly influences angles and force distributions. The maximum vertical reaction force is about 5% higher than walking with a low heel in the impact phase. The reaction force, in this case, is higher in the forward and rearward directions and corresponds to an increase in deceleration and acceleration forces in the vertical direction.

During walking barefoot or with low heel shoes, the heel takes on a load of about 57% of body weight and the metatarsals 43%. During walking with a 10 cm heel, about 100% of the weight is applied to the metatarsals. The most balanced weight distribution is made on a 2 cm heel (approximately 50% on each vector). The calcaneus is loaded on 25-43% of body weight. The metatarsals carry 57-75% of body weight for medium-high heels [7].

The distribution of force also changes during running. A lower load and a more evenly distributed force were identified in the heel strike phase [18].

Body weight, speed, step length, type and structure of footwear are the factors that influence the distribution of plantar pressure [19].

Biomechanical measurements of the pressure distribution between the plantar surface of the foot and the support plane provide valuable information on the structure and function of the foot [14], which can indicate the impact of footwear or the necessary shape of the insole [7] and provide suggestions for improving design structure of footwear [19, 20].

During human walking, the centre of pressure advances during each step, creating a rolling motion between the foot and the support [21]. The average pressure distribution determines the centre of pressure. It could be standardised according to the length of the foot [22].

During the mid-stance phase, the maximum plantar pressure is transferred from the heel area to the rear-foot area [3].

The contact pressure at the metatarsophalangeal joints intensifies and reaches its maximum value in the push-off phase. The maximum contact pressure in the metatarsal area during push-off increases at least four times (third metatarsophalangeal joint) and up to 11 times (first metatarsophalangeal joint) compared to the heel strike phase [23].

Both peak plantar pressure and ground reaction forces can vary at similar walking speeds, as they can be produced by different combinations of length and cadence [14]. In general, maximum pressures and total force increase with walking speed.

The type of footwear influences the pressure distribution. Comfortable footwear contributes significantly to a balanced distribution of pressure on the plantar surface of the foot. Shoes with flexible soles reduce the plantar pressure and contribute to the proper functioning of the foot [19].

Several studies have investigated the influence of the heel on pressure distribution. During high-heeled walking, the joints showed different loading patterns [23]. This condition influenced the increase in pressure in the peak area compared to the barefoot. The maximum pressure is observed in the rear-foot area (hallux), followed by the midfoot and forefoot. Walking in high-heeled shoes resulted in a 30% increase in peak pressures in the II-IV metatarsal area compared to walking in low-heeled shoes [16, 24].

The 3D biomechanical analysis that includes a description of the movement of different anatomical segments of the foot is the most common assessment of the foot and gait. A motion capture system and a force plate must perform both kinematic and kinetic (dynamic) analysis.

Plate [13, 3] and insole systems with in-shoe sensors [14, 15] are used to register plantar pressures, both of which allow the determination of maximum pressures, weight distribution, surface and contact time, the position of the centre of pressure in both static and dynamic conditions [22, 25].

External forces, i.e., ground reaction forces, are measured using a force plate [3]. Intramuscular forces and Achilles' tendon forces are taken from electromyography and sensitive analysis of the centre of pressure [26, 27].

Kinematic parameters, such as the contact time, can be measured using high-speed cameras (i.e., MotionBLITZ EoSens® mini) [28].

There are complex systems with sensors (i.e., Vicon) [27, 29], which allow the simultaneous capture and determination of kinetic and kinematic parameters, such as: walking or running speed, duration of heel strike, mid-stance and push-off, cadence, impact index, maximum reaction force, average load rate, initial speed, initial tibia angle, initial ankle flexion angle.

This paper investigates the biomechanical parameters to create an average representative model of foot loading for an extended target group.

EXPERIMENTAL

Materials and Methods

Equipment

The biomechanical parameters were registered using the Footscan system produced by RS Scan International. The equipment consists of a pressure platform and a software system (Figure 1), ensuring the collection, visualisation, and processing of static and dynamic biomechanical measurements. This system is mentioned in several research studies [28, 30], and is also used by various institutions and specialised laboratories. The platform incorporates 5 mm x 7 mm sensors that ensure the variation analysis of the pressures and forces for all the regions of the plantar footprint.

Figure 1. Footscan system

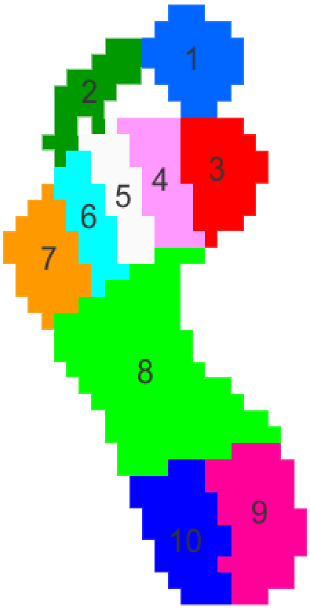
Subjects

The biomechanical study was made based on data collected from 32 volunteer subjects, female, representing students from the “Gheorghe Asachi” Technical University of Iasi, 18-30 years old, wearing footwear size numbers 36 (group 1), 37 (group 2), 38 (group 3) in the French system. None of the subjects practice performance sports or other activities that could significantly influence the gait pattern. The subjects are included in the height range of 153-175 cm and weight range of 40-72 kg.

Method. Recording and Analysis of Biomechanical Parameters in Dynamics

To obtain the most accurate results, a working methodology was developed. Each subject was asked to reproduce three types of barefoot gait: normal gait (N), slow gait (L) and fast gait (R). The subjects established by themselves the specific speed for all three types of gait, considering the following ranges for total step time: normal gait 700-900 ms, slow gait 900-1100 ms, fast gait 500-700 ms. The subjects were tested using the three-step approach considered the most suitable in terms of results [31, 32]. According to this protocol, the subjects contact the platform on the third step after initiating gait and walk a few more steps after platform contact. The invalid trials in which the contact between the foot and platform were not made correctly were not saved. The subjects repeated the same procedure with the opposite foot, thus recording values specific to the right and left foot. For each condition, three trials were recorded, resulting in 9 measurements/subject.

The plantar footprint is divided into 10 distinct regions (Figure 2) 242 [35]: 1 –toe I (Z1); 2 - toe II-V (Z2); 3 – metatarsal I (Z3); 4 – metatarsal II (Z4); 5 –metatarsal III (Z5); 6 - metatarsal IV (Z6); 7 - metatarsal V (Z7); 8 - midfoot (Z8); 9 – heel medial (Z9); 10 – heel lateral (Z10).



Toe I	Z1
Toe II-V	Z2
Meta I	Z3
Meta II	Z4
Meta III	Z5
Meta IV	Z6
Meta V	Z7
Midfoot	Z8
Heel medial	Z9
Heel lateral	Z10

Figure 2. Anatomical division of the plantar footprint in 10 regions

The force (N), contact area (cm^2), contact time (ms), and pressure (N/cm^2) for the 10 regions of the plantar surface were recorded and analysed using the Footscan system. Deviant values were excluded from the list, so the average of the tests was done with the remaining values.

The results were divided into three groups, according to the subjects' foot size, and the average values for the three trials for each analysed parameter were centralised in a table.

This paper presents the analysis of the biomechanical parameters during the normal gait.

RESULTS AND DISCUSSIONS

Verification of the Statistical Significance of the Differences between the Biomechanical Parameters of the Left and Right Foot Using the Student's Test and the Fisher's Test

The T-Student test was applied to confirm that there are no significant differences between the left and right foot. The averages of the set of values for the left and right foot for each of the 10 regions of the plantar footprint were compared, taking into account the following biomechanical parameters: force (N), contact area (cm^2), contact time (ms) and pressure (N / cm^2).

The calculated values are compared with p = 0.05 for a probability of 95% to determine if the results obtained are statistically significant. The values must be greater than p = 0.05 to confirm the null hypothesis.

The Fisher test was used with p = 0.05 to verify that the variances in terms of biomechanical parameter values for the left foot did not differ significantly from the variances for the right foot.

According to both tests (Table 1), the null hypothesis for the contact area parameter was not confirmed, which highlights that most subjects have differences between the gait patterns of the left (L) foot compared to the right (R) foot in terms of the area of the plantar surface that contacts the ground. While in the case of force, pressure, and contact time parameters, the opposite is demonstrated – namely, there are no significant differences between the left and right foot. As a result, using the averages between the two feet in the next stage is possible. These hypotheses validate that the values are representative of the population.

Table 1: T and F Test results

Size 36		Z1	Z2	Z3	Z4	Z5	Z6	Z7	Z8	Z9	Z10
Force	Test T	0.279	0.382	0.321	0.480	0.890	0.759	0.485	0.013	0.314	0.532
	Test F	0.691	0.501	0.795	0.269	0.429	0.858	0.532	0.264	0.102	0.184
Contact area	Test T	0.135	0.044	0.002	0.000	0.000	0.001	0.002	0.814	0.000	0.000
	Test F	0.012	0.060	0.429	0.354	0.559	0.579	0.985	0.981	0.803	0.922
Contact time	Test T	0.316	0.971	0.743	0.446	0.944	0.999	0.839	0.350	0.294	0.519
	Test F	0.392	0.967	0.315	0.425	0.625	0.710	0.323	0.340	0.732	0.958
Pressure	Test T	0.499	0.712	0.039	0.669	0.215	0.526	0.896	0.005	0.048	0.434
	Test F	0.619	0.512	0.039	0.903	0.997	0.744	0.850	0.147	0.028	0.155

Size 37		Z1	Z2	Z3	Z4	Z5	Z6	Z7	Z8	Z9	Z10
Force	Test T	0.263	0.202	0.212	0.392	0.938	0.220	0.413	0.005	0.707	0.548
	Test F	0.448	0.094	0.003	0.925	0.247	0.080	0.856	0.175	0.058	0.045
Contact area	Test T	0.105	0.605	0.002	0.000	0.000	0.007	0.001	0.339	0.000	0.000
	Test F	0.982	0.942	0.282	0.968	0.080	0.137	0.040	0.837	0.981	0.413
Contact time	Test T	0.420	0.473	0.809	0.681	0.794	0.744	0.075	0.247	0.836	0.650
	Test F	0.343	0.603	0.194	0.945	0.672	0.632	0.000	0.532	0.581	0.594
Pressure	Test T	0.648	0.147	0.601	0.922	0.145	0.073	0.697	0.006	0.489	0.724
	Test F	0.741	0.061	0.012	0.984	0.408	0.173	0.693	0.072	0.112	0.086

Size 38		Z1	Z2	Z3	Z4	Z5	Z6	Z7	Z8	Z9	Z10
Force	Test T	0.096	0.795	0.596	0.287	0.555	0.533	0.517	0.364	0.638	0.896
	Test F	0.317	0.896	0.224	0.577	0.636	0.812	0.436	0.229	0.539	0.527
Contact area	Test T	0.003	0.789	0.009	0.006	0.001	0.013	0.228	0.432	0.050	0.002
	Test F	0.378	0.321	0.099	0.833	0.842	0.129	0.852	0.544	0.123	0.445
Contact time	Test T	0.587	0.881	0.726	0.667	0.630	0.297	0.583	0.525	0.668	0.396
	Test F	0.761	0.411	0.632	0.343	0.174	0.139	0.904	0.236	0.212	0.307
Pressure	Test T	0.276	0.724	0.761	0.994	0.468	0.347	0.634	0.295	0.346	0.633
	Test F	0.822	0.712	0.567	0.954	0.136	0.510	0.766	0.596	0.839	0.853

Statistical Indicators for Characterisation and Variation of Biomechanical Parameters

The statistical indicators [33] which characterise the set of values are mean, standard deviation (S), the minimum, maximum, amplitude of variation (A), and the coefficient of variation (CV). The values of statistical indicators of measured biomechanical parameters are presented in Tables 2-5.

Table 2: Statistical indicators for characterising the force distribution during normal gait

Size 36	Number of subjects	10	Z1	Z2	Z3	Z4	Z5	Z6	Z7	Z8	Z9	Z10
Force (N)	Mean value		159.4	9.2	54.7	125.2	156.5	113.3	42.0	38.3	244.3	186.7
	Min		63.2	0.0	16.6	18.9	80.7	38.6	1.0	5.1	160.9	133.2
	Max		241.3	26.1	96.7	202.9	229.0	220.7	84.0	69.6	326.9	272.9
	A		178.1	26.1	80.1	184.0	148.3	182.1	83.0	64.5	166.0	139.7
	S		60.4	7.6	28.9	50.3	41.2	52.9	31.4	23.3	63.8	46.0
	CV %		37.9	83.0	52.8	40.2	26.3	46.7	74.8	60.9	26.1	24.6
Size 37	Number of subjects	13	Z1	Z2	Z3	Z4	Z5	Z6	Z7	Z8	Z9	Z10
Force (N)	Mean value		141.9	19.0	40.8	142.9	163.2	92.2	34.0	34.0	184.4	170.8
	Min		57.8	0.0	0.4	50.8	76.6	40.3	5.1	4.1	106.0	75.0
	Max		247.1	42.2	144.2	340.6	253.0	170.5	142.7	55.6	262.7	278.4
	A		189.3	42.2	143.8	289.9	176.4	130.2	137.6	51.5	156.8	203.3
	S		62.9	14.3	36.7	83.8	52.6	33.8	36.5	15.2	49.0	61.7
	CV %		44.3	75.3	89.9	58.7	32.2	36.6	107.5	44.8	26.6	36.1
Size 38	Number of subjects	9	Z1	Z2	Z3	Z4	Z5	Z6	Z7	Z8	Z9	Z10
Force (N)	Mean value		201.2	48.2	79.9	166.7	180.2	115.5	40.1	44.9	256.7	215.6
	Min		9.9	6.2	11.2	83.7	115.9	51.1	0.0	5.8	107.0	94.8
	Max		345.7	177.5	188.8	270.4	282.7	273.9	111.7	133.5	471.5	381.8
	A		335.9	171.3	177.6	186.7	166.9	222.8	111.7	127.7	364.5	287.0
	S		109.1	54.5	66.3	61.4	56.3	71.3	38.6	37.0	137.7	102.0
	CV %		54.2	113.2	83.0	36.9	31.2	61.7	96.3	82.3	53.7	47.3

Table 3: Statistical indicators for characterising the contact time during normal gait

Size 36	Number of subjects	10	Z1	Z2	Z3	Z4	Z5	Z6	Z7	Z8	Z9	Z10
Contact time (ms)	Mean value		618.2	541.9	519.9	586.4	589.8	565.1	496.9	207.4	178.9	180.8
	Min		542.7	296.0	394.3	499.8	474.8	454.0	393.5	181.0	140.7	151.5
	Max		685.0	726.0	644.3	662.5	703.3	711.2	644.5	264.5	221.0	218.2
	A		142.3	430.0	250.1	162.7	228.5	257.2	251.0	83.5	80.3	66.7
	S		53.0	138.1	67.7	55.5	67.5	83.9	82.7	27.6	28.4	22.8
	CV %		8.6	25.5	13.0	9.5	11.5	14.8	16.7	13.3	15.9	12.6

Size 37	Number of subjects	13	Z1	Z2	Z3	Z4	Z5	Z6	Z7	Z8	Z9	Z10
Contact time (ms)	Mean value		612.4	504.9	501.1	585.8	587.2	575.5	488.4	199.0	173.1	178.5
	Min		563.5	0.0	93.0	531.5	521.8	508.0	238.5	107.7	86.5	120.0
	Max		675.0	672.5	650.0	650.0	658.5	664.5	614.5	338.8	215.5	235.5
	A		111.5	672.5	557.0	118.5	136.7	156.5	376.0	231.1	129.0	115.5
	S		38.2	207.9	137.2	40.2	42.3	44.7	107.5	53.1	37.2	32.2
	CV %		6.2	41.2	27.4	6.9	7.2	7.8	22.0	26.7	21.5	18.0
Size 38	Number of subjects	9	Z1	Z2	Z3	Z4	Z5	Z6	Z7	Z8	Z9	Z10
Contact time (ms)	Mean value		633.0	625.6	575.4	616.2	611.9	605.5	463.7	228.6	184.7	183.6
	Min		561.0	542.3	479.0	535.0	537.5	520.5	0.0	190.3	148.2	158.0
	Max		795.0	721.3	766.0	781.5	700.0	738.0	599.0	315.5	266.5	244.3
	A		234.0	178.9	287.0	246.5	162.5	217.5	599.0	125.2	118.3	86.3
	S		79.2	65.7	95.2	77.7	51.4	74.8	180.5	40.7	37.0	27.3
	CV %		12.5	10.5	16.6	12.6	8.4	12.4	38.9	17.8	20.0	14.9

Table 4: Statistical indicators for characterising the contact area during normal gait

Size 36	Number of subjects 10	Z1		Z2		Z3		Z4		Z5		Z6		Z7		Z8		Z9		Z10	
		S	D	S	D	S	D	S	D	S	D	S	D	S	D	S	D	S	D	S	D
Contact area (cm^2)	Mean value	14.2	12.7	11.8	9.4	7.3	10.1	7.8	9.6	7.1	8.4	7.6	8.5	10.7	7.8	19.9	19.3	12.2	14.3	10.8	12.7
	Min	12.8	8.5	6.0	6.1	5.6	7.1	6.4	8.6	6.4	7.6	6.9	7.6	7.3	3.4	9.8	9.4	11.2	13.0	9.8	11.3
	Max	16.1	17.1	15.6	11.3	10.3	12.6	10.0	10.7	8.0	9.2	8.5	9.4	13.0	9.2	26.5	27.4	14.2	15.8	12.4	14.1
	A	3.4	8.6	9.6	5.1	4.7	5.4	3.6	2.1	1.6	1.6	1.6	1.8	5.7	5.9	16.7	18.0	3.0	2.8	2.7	2.8
	S	1.1	2.8	3.0	1.6	1.5	1.9	1.0	0.8	0.4	0.5	0.6	0.5	1.7	1.7	6.0	6.0	0.9	0.8	0.8	0.8
	CV %	7.8	21.7	25.9	16.6	20.0	18.9	13.5	7.9	6.3	6.5	7.5	5.5	16.0	21.5	30.0	31.3	7.0	5.5	7.8	6.4
Size 37	Number of subjects 13	Z1		Z2		Z3		Z4		Z5		Z6		Z7		Z8		Z9		Z10	
		S	D	S	D	S	D	S	D	S	D	S	D	S	D	S	D	S	D	S	D
Contact area (cm^2)	Mean value	14.0	12.7	12.3	11.4	7.1	10.6	8.2	10.2	7.0	8.7	8.0	8.6	10.5	8.4	24.4	22.0	13.2	15.3	11.4	13.6
	Min	10.9	9.0	4.5	4.6	3.6	4.0	6.4	7.7	5.6	7.7	7.4	7.5	9.0	7.5	10.3	12.6	11.3	13.7	10.5	12.2
	Max	18.2	16.0	17.6	17.2	10.0	14.6	11.1	11.8	8.1	9.4	8.6	9.6	14.7	9.9	32.2	35.3	15.0	17.1	13.2	14.8
	A	7.4	7.0	13.1	12.6	6.3	10.6	4.7	4.1	2.5	1.7	1.2	2.1	5.7	2.4	22.0	22.6	3.8	3.4	2.7	2.7
	S	1.9	1.9	4.5	4.4	2.2	3.0	1.2	1.1	0.7	0.4	0.4	0.6	1.7	0.9	6.0	6.4	1.1	1.1	0.7	0.9
	CV %	13.9	15.2	36.8	38.9	30.9	28.4	14.1	11.3	10.4	5.0	5.1	7.3	15.8	10.5	24.6	28.9	8.4	7.3	6.4	6.9
Size 38	Number of subjects 9	Z1		Z2		Z3		Z4		Z5		Z6		Z7		Z8		Z9		Z10	
		S	D	S	D	S	D	S	D	S	D	S	D	S	D	S	D	S	D	S	D
Contact area (cm^2)	Mean value	14.4	10.6	14.3	14.7	9.5	12.1	8.1	9.3	6.5	7.1	6.8	7.6	9.1	7.5	22.9	22.0	11.7	12.6	10.0	11.3
	Min	11.8	1.9	4.5	4.4	2.2	3.0	1.2	1.1	0.5	0.2	0.2	0.4	1.7	0.8	6.0	6.4	1.1	1.1	0.5	0.9
	Max	16.5	15.2	36.8	38.9	30.9	28.4	14.1	13.1	10.4	10.3	8.9	10.2	15.8	11.4	35.9	40.6	15.8	18.2	13.4	15.6
	A	4.7	13.3	32.2	34.4	28.7	25.4	13.0	12.0	9.9	10.1	8.7	9.7	14.2	10.6	29.9	34.2	14.6	17.1	12.8	14.7
	S	1.7	3.9	8.1	8.8	7.1	6.2	3.7	3.9	3.0	3.4	3.2	3.4	4.2	3.7	8.6	8.9	5.3	6.0	4.7	5.4
	CV %	12.0	37.0	56.8	60.0	74.8	51.1	45.8	42.1	45.5	48.2	47.3	44.9	45.5	48.8	37.4	40.5	45.0	47.6	47.6	47.4

Table 5: Statistical indicators for characterising the pressure distribution during normal gait

Size 36	Number of subjects	10	Z1	Z2	Z3	Z4	Z5	Z6	Z7	Z8	Z9	Z10
Pressure (N/cm²)	Mean value		11.6	0.9	6.4	14.4	20.7	14.2	4.2	1.8	18.6	15.9
	Min		5.7	0.0	1.6	2.5	9.6	5.0	0.1	0.5	12.7	12.1
	Max		18.0	2.1	10.5	23.5	30.3	28.3	9.8	3.0	26.9	20.6
	A		12.3	2.1	8.9	21.0	20.7	23.3	9.7	2.5	14.3	8.5
	S		3.9	0.7	3.2	5.9	5.7	6.8	3.2	0.9	4.8	3.0
	CV %		33.5	84.3	49.6	41.2	27.6	47.7	75.6	49.8	26.0	19.0
Size 37	Number of subjects	13	Z1	Z2	Z3	Z4	Z5	Z6	Z7	Z8	Z9	Z10
Pressure (N/cm²)	Mean value		10.8	1.4	4.2	15.3	21.0	11.1	3.6	1.4	13.1	13.8
	Min		4.5	0.0	0.1	6.3	10.4	4.9	0.5	0.4	7.8	5.9
	Max		19.8	3.4	12.4	31.3	31.3	20.2	17.0	2.5	19.3	21.0
	A		15.4	3.4	12.3	25.0	20.9	15.3	16.5	2.1	11.5	15.1
	S		5.0	1.0	3.1	8.1	6.3	3.9	4.3	0.6	3.6	4.8
	CV %		46.7	72.7	74.1	53.1	29.9	35.2	119.9	44.5	27.9	34.9
Size 38	Number of subjects	9	Z1	Z2	Z3	Z4	Z5	Z6	Z7	Z8	Z9	Z10
Pressure (N/cm²)	Mean value		14.8	4.7	7.3	16.7	22.4	13.2	3.7	2.0	16.8	16.2
	Min		0.8	0.5	1.6	11.0	14.4	5.7	0.0	0.2	7.2	7.0
	Max		24.9	22.4	16.5	26.4	35.0	30.5	8.7	3.9	28.4	27.2
	A		24.1	22.0	14.9	15.4	20.5	24.8	8.7	3.7	21.1	20.3
	S		7.4	6.9	5.5	5.0	6.9	8.1	3.1	1.2	8.0	7.1
	CV %		49.8	145.7	75.0	29.9	30.7	61.3	83.2	59.8	47.6	44.1

The highest values of force are highlighted in the region of the medial heel (Z9), lateral heel (Z10), toe I (Z1), followed by the metatarsal II, III and IV (Z4, Z5, Z6). The lowest values of the force are registered for the region of toes II-V (Z2), metatarsal V (Z7) and midfoot (Z8) of the plantar surface of the foot (Figure 3). The same trend could be seen in the case of pressure (Figure 4). Regarding the mean values for the contact time (Figure 5), higher values are recorded at the toe I, metatarsal II, III and IV, while in the heel area, these values decrease significantly. This distribution is specific to all three groups of analysed subjects. The highest contact area mean values (Figure 6) are recorded in the case of the midfoot, followed by the inner region of the heel for both left and right foot. The lowest values for contact area are noted in the region of metatarsal III and IV (Z5 and Z6).

The analysis of the chromatic maps generated by Footscan software and the evaluation of diagrams demonstrate that the most loaded, in terms of force and pressure, are toe I, metatarsal II-IV, lateral and medial heel, being in the same time the regions with the minimum contact areas. This conclusion is supported by previous studies, which confirm that the maximum loading and plantar pressure are transferred from heel to rear-foot. Thus, in the barefoot gait, the heel takes a load of about 57% and metatarsals 43% of the body weight, while the stresses in midfoot and toe II-V regions are not significant [3, 34]. Some studies have reported that the highest pressure has been identified in the area of the toe I [35]; others highlighted the metatarsal II and III regions [32]. These differences in pressure distributions could be caused by the rules used to divide the plantar surface into regions, the software used for the analysis, the subjects involved in the study, the protocols, the experimental conditions, the characteristics of the sensor and the measurement technologies.

The mean values for the contact time are higher in the rear-foot regions and decrease on the heel area. A similar distribution is identified in the literature [36, 37]. The values obtained justify that the heel strike phase is shorter than the support and propulsion phase and confirm that the contact time between the heel region and the support increases pressure [34].

The contact area is an important variable which in alliance with the pressure, provides valuable information regarding the loading model of the foot. As can also be identified in other studies [32, 36], this parameter has higher values in the heel and midfoot regions, which have the function of force absorption and pressure redistribution. In contrast, the metatarsal region has a significantly smaller contact area and higher pressures.

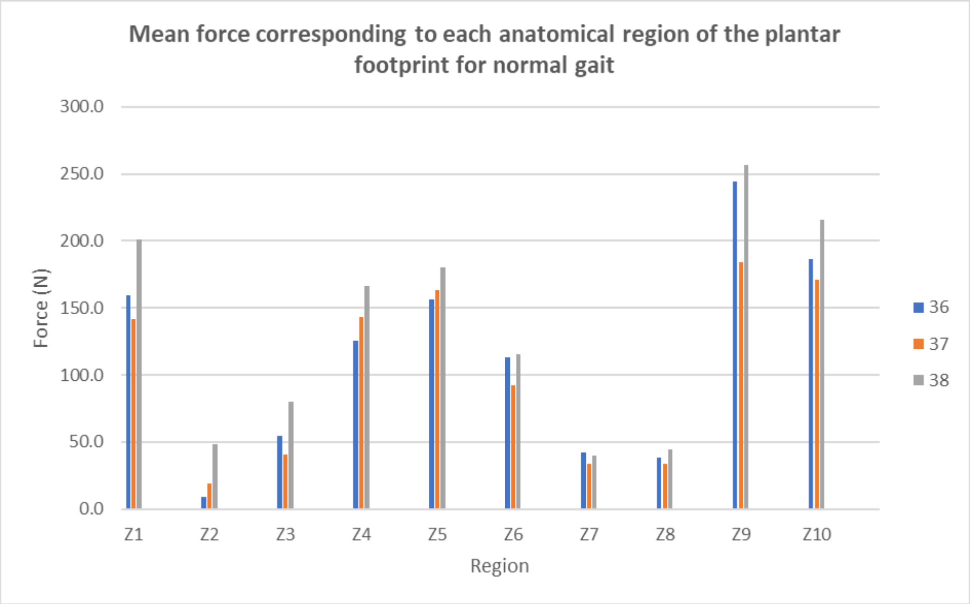


Figure 3. Mean force corresponding to each anatomical region of the plantar footprint for normal gait

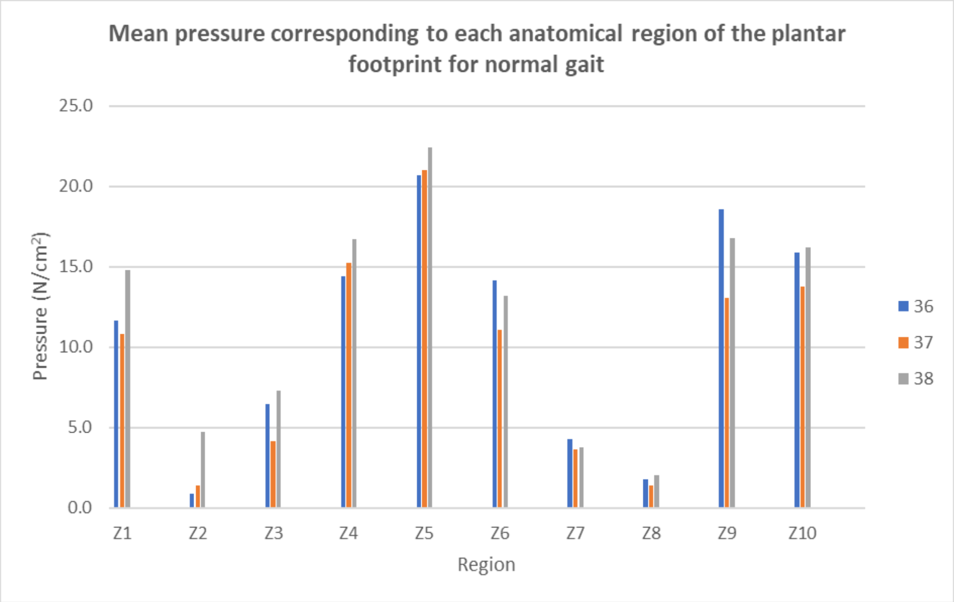


Figure 4. Mean pressure corresponding to each anatomical region of the plantar footprint for normal gait

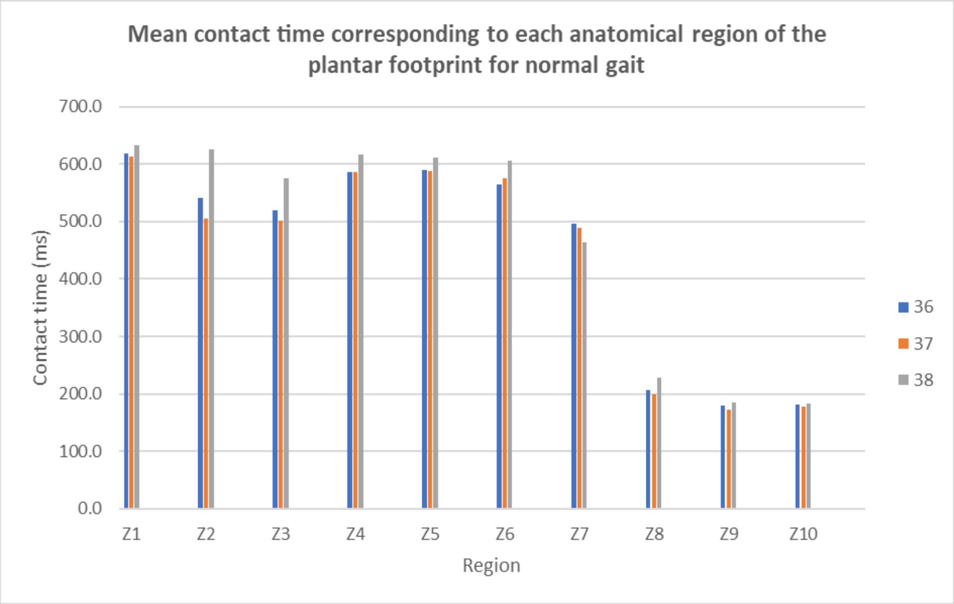


Figure 5. Mean contact time corresponding to each anatomical region of the plantar footprint for normal gait

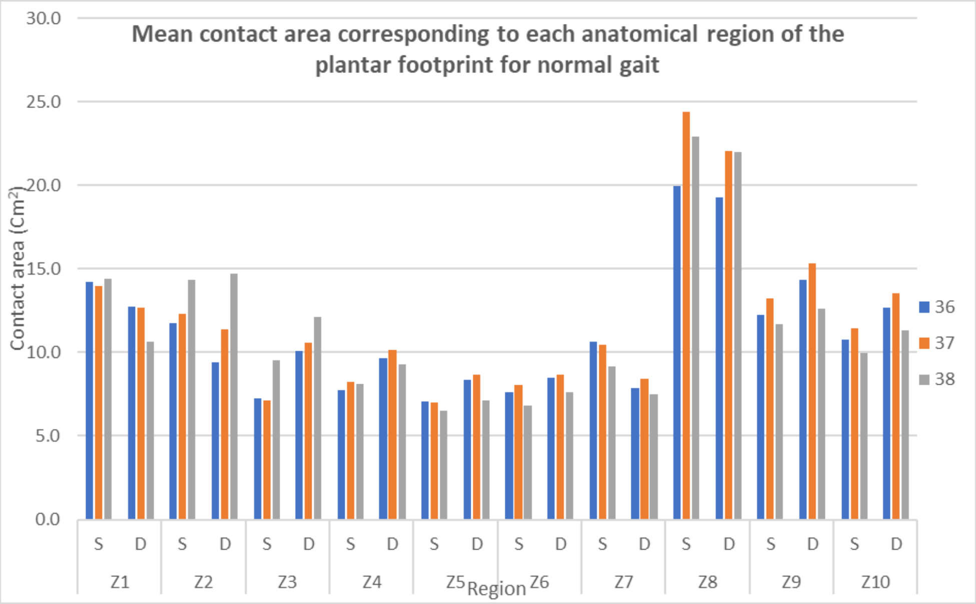


Figure 6. Mean contact area corresponding to each anatomical region of the plantar footprint for normal gait

Figures 7-10 represent the coefficients of variation of the studied biomechanical parameters graphically.

In the case of the group of subjects with size 36, the highest values of the coefficient of variation for force and pressure parameters are on Z2 (toe II-V) - 83%, Z7 (metatarsal V) - 74.8% and Z8 (midfoot) - 60.9%, while the lowest values are for the contact time parameter on the Z1 (toe I) -8.6% and Z4 (metatarsal II) - 9.5% regions.

The coefficient of variation with maximum value for the group of subjects with size 37 has the parameter force and pressure on the Z7 (metatarsal V) - 107.5%, Z3 (metatarsal I) - 89.9% and Z2 (toe II-V) - 75.3% regions, while the minimum values are observed for the contact time on Z1 (toe I) - 6.2%, Z4 (metatarsal II) - 6.9% and Z5 (metatarsal III) - 7.2%.

The highest values of the coefficient of variation for the group of subjects with size 38 in case of force and pressure are on Z2 (toe II-

V) - 113.2%, Z7 (metatarsal V) - 96.3% and Z8 (midfoot) -82.3%, while the lowest values are for the contact time parameter on Z1 (toe I) - 12.5%, Z2 (toe II-V) -10.5% and Z5 (metatarsal III) - 8.4%.

Regarding the contact surface, higher values of the coefficient of variation are detected in the case of subjects with size 38 on Z3 (metatarsal I) - 74.8%, Z2 (toe II-V), Z5 (metatarsal III) - 48.2% and Z7 (metatarsal V) - 48.8%. For the group of sizes 37 and 36, a minimum to medium dispersion over all 10 areas of the plantar footprint is highlighted.

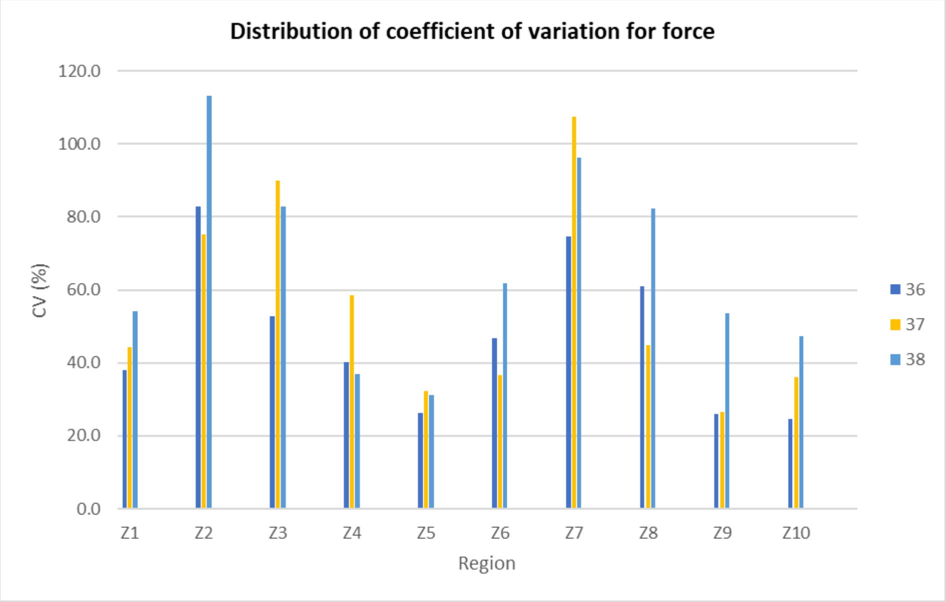


Figure 7. Distribution of coefficient of variation for force (normal gait)

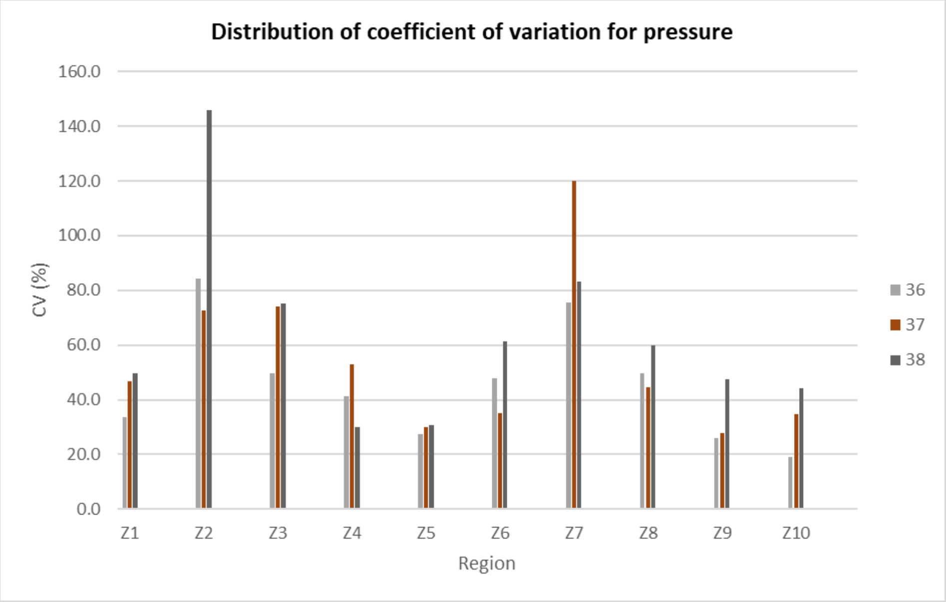


Figure 8. Distribution of coefficient of variation for pressure (normal gait)

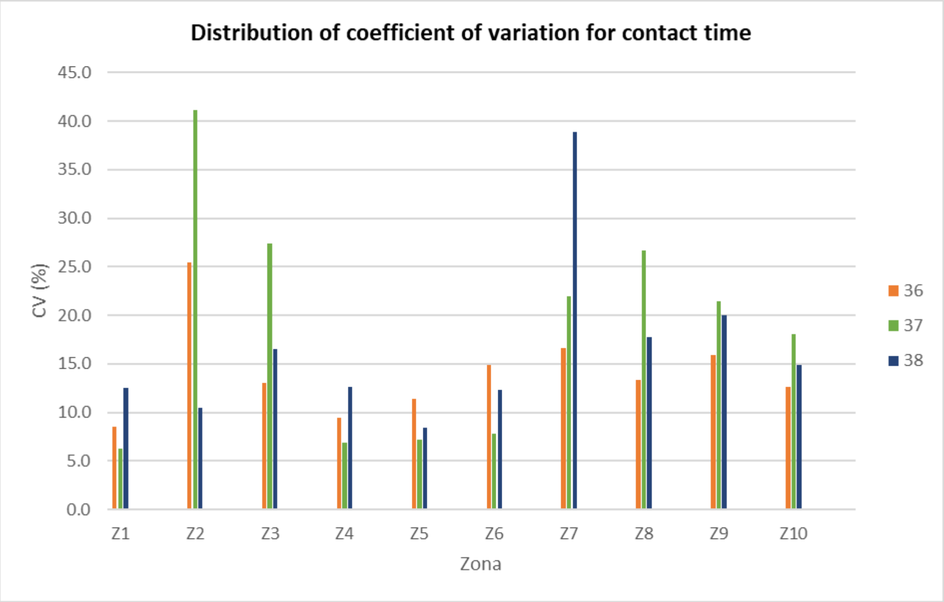


Figure 9. Distribution of coefficient of variation for contact time (normal gait)

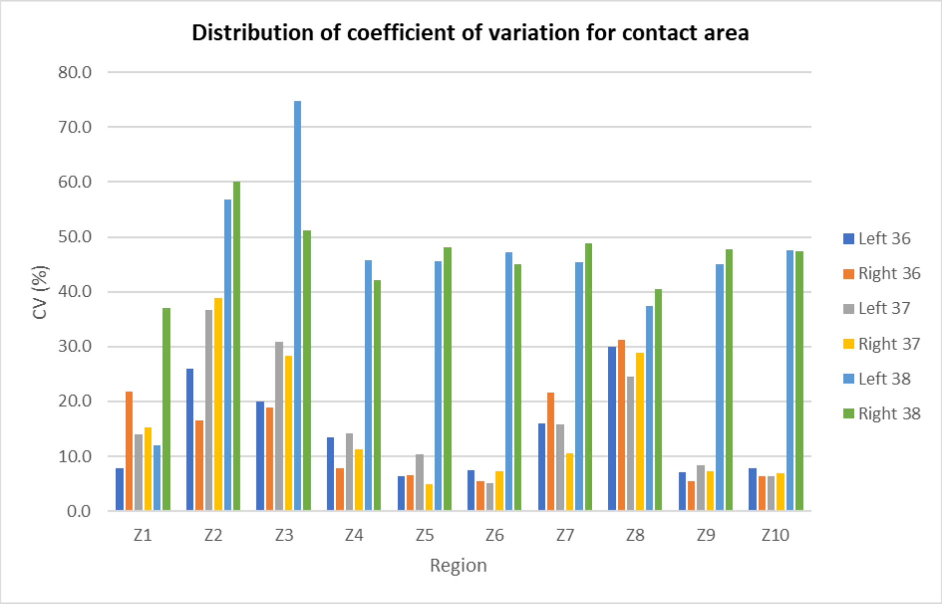


Figure 10. Distribution of coefficient of variation for contact area (normal gait)

CONCLUSIONS

The study evaluates the main variables in the biomechanical characterisation of gait – force, pressure, time and contact area. The research was performed based on the data collected from 32 healthy females, aged between 18 and 30 years, divided into three size groups – 36 (10 subjects), 37 (13 subjects), 38 (9 subjects).

Due to the division of the plantar surface on 10 distinct regions, toe I (Z1), toe II-V (Z2), metatarsal I (Z3), metatarsal II (Z4), metatarsal III (Z5), metatarsal IV (Z6), metatarsal V (Z7), midfoot (Z8), medial heel (Z9), lateral heel (Z10), the more and less loaded zones in terms of the forces acting during normal walking are identified. The obtained data were centralised and analysed from a statistical point of view.

The plantar pressures recorded in dynamics highlight the first toe, metatarsal II-IV, lateral and medial heel as the most loaded regions of the plantar surface. There are statistically significant differences between the left and right foot for the contact area parameter for all size groups in all plantar regions except midfoot. The analysis of statistical indicators for force variation highlights a medium and large dispersion, which describes the population as relatively homogeneous, and in some areas, even heterogeneous (CV is over 30%). It confirms that the forces generated during the impact with the ground vary from one subject to another, being a parameter influenced by many external and internal factors [38]. Considering the coefficient of variation for force and pressure variables, smaller distributions on the toe II-V, metatarsal I, V and midfoot regions are confirmed. In contrast, the areas with higher values of forces and pressures – toe I, metatarsal II-IV, medial and lateral heel have smaller distribution, nearby 30% – which characterise a moderately homogeneous population. In terms of time and contact area, the coefficient of variation highlights a small and medium spread of values, and the population is considered homogeneous.

Based on this research, the average model of foot loading for an extended target group was created to be further used in simulations of footwear behaviour in various loading conditions.

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