Biomedical Signal Processing and Control 96 (2024) 106578

Contents lists available at ScienceDirect

Biomedical Signal Processing and Control

journal homepage: www.elsevier.com/locate/bspc

# Implications of plantar static pressure distribution among bilateral flatfoot patients: An analytical case-control research

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A R T I C L E I N F O

*Keywords:*
Adult
Foot disease
Flat foot
Musculoskeletal diseases
Pes planus
Gait
Plantar pressure

A B S T R A C T

*Background:* Adult pes planus is a highly prevalent condition characterized by the gradual or sudden appearance of fallen arches in adulthood, which is a recognized cause of difficulty with balance and stability, discomfort, pain, swelling, tired and achy feet and impairment. Accordingly, the main purpose of this analytical, case-control study was to evaluate the characteristics in foot morphology related to static plantar pressure distribution in adults with and without a bilateral condition.
*Methods:* Sixty-eight subjects were recruited by a laboratory in this analytical case-control study, involving thirty-four adults with a bilateral condition and thirty-four healthy controls. Static plantar pressure was measured in all participants using a specific portable pressure platform with multiple resistive sensors which was placed on the floor.
*Results:* Static plantar pressure distribution in the cases group showed significant increases in the right and left surface areas, in the right heel surface area and also in the left foot mean peak pressure ($p < 0.001$), as well as in the left heel surface area ($p = 0.003$).
*Conclusions:* Adults with bilateral flatfoot showed changes in the surface areas in both feet and recorded higher levels in static plantar pressures with respect to the control group, a feature which can be associated with this common bilateral condition.

## 1. Introduction

Adult flatfoot (AF), a very frequent foot condition, that has been found to have a high prevalence (11.4–29 %) in clinical settings and institutions in several investigations [1–3], is a syndrome that shows significant dynamic and static deformities characterized by the gradual or sudden appearance of fallen arches in adulthood; a recognized cause of difficulty with balance and stability, discomfort, pain, swelling, tired and achy feet, impairment and decrease in quality of life [4–6]. AF is a complex syndrome in which it is difficult to find two identical cases [7]. It is described by the loss of the natural arch on the inside of the foot, causing the entire sole to come into contact with the ground when standing [8,9].

Its evolution is unclear, showing a multifactorial, complex, and hard to understand etiology, [8,9] and it is associated with concomitant deformities that can be produced causing difficulties for putting on shoes, a slower walking speed, increased instability, and major poor posture, and can have potentially negative effects on the basic activities of daily life

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https://doi.org/10.1016/j.bspc.2024.106578
Received 20 December 2023; Received in revised form 5 June 2024; Accepted 22 June 2024
Available online 27 June 2024

[10–12].

According to previous research in patients with bilateral flatfoot linked with gait parameters performed by Casado-Hernández these patients evidence alterations in the symmetry index in the lateral load and in the initial contact and flatfoot contact phase [13] and Padrón et al show higher contact time data in the total stance phase compared to the control group, which seems to be linked to the presence of foot deformity in the adult population [14].

Furthermore, this medical foot problem is considered a major public foot health concern, because the potential impact on the individuals' health can create a burden on both public finances and personal health given the increasing risk of orthopedic surgery on the foot and ankle and its relation with discomfort and pain in other areas (legs, hips, knees and ankles), as well as walking problems, the possibility of falling and chronic disorders [15–17]. However, several features and measurements associated with the distribution of pressure and contact points on the plantar surface in people with and without AF, are unclear.

Based on previously available literature, we sought information to be able to predict other variables that alter the balance of static plantar pressure contact areas in people with and without AF, to find an adequate treatment and promote regular preventive foot care in order to achieve optimal health and improve well-being for the AF population.

Consequently, the purpose of this analytical case-control study was to evaluate the characteristics in foot morphology related to static plantar pressure distribution in adults with and without a symmetrical condition.

## 2. Materials and Methods

### 2.1. Design and sample

A descriptive, observational case-control study was conducted with an initial total sample of 73 participants (8 men and 65 women), aged between 18 and 64, who were recruited using a consecutive non-random technique in this national project registered with file identification number PID2019-108009RB-I00, in a biomechanics & motion analysis laboratory at the University of A Coruña, in the city of Ferrol, in the region of Galicia in northwest Spain, between May 2022 to September 2022.

Of the 73 adults chosen for this research, 34 had bilateral flatfoot. Left flatfoot was shown in 35 subjects and 38 had normal feet; right flatfoot was shown in 38 subjects and 35 had normal feet. Finally, 68 participants were involved in this investigation resulting in 34 patients with bilateral flatfoot and 34 with bilateral healthy normal feet.

The criteria for inclusion in the control group were: to be between 18 and 64 years old, healthy adults without a family history (FH) of significant health problems or a personal medical history of surgery or lower limb trauma, to have bilateral neutral feet and to have given written informed consent to participate in this project. Disregarded cases included: to be less than 18 or more than 65 years old, with non-neutral bilateral feet, autoimmune health problems, a personal medical history of surgery or lower limb trauma, or neurological disabilities, to refuse to sign the consent form or to be incapable of understanding the guidelines necessary to participate in the present study.

With respect to the criteria for inclusion in the group of cases, they were: to be 18 to 64 years old, healthy adults without a FH of relevant health disease and a personal medical record, bilateral flat feet, to have given written informed consent to participate in this project. Exclusion criteria included: use of medications, pregnancy or breastfeeding, a systemic disorder or being unable to participate or complete the study.

### 2.2. Procedure

Baseline measurements were recorded by a senior trained podiatrist in four phases. The first phase comprised an interviewed related with disease and clinical features, and overall health, demographic information such as age and sex, details included predictors (arthritis, depression, diabetes mellitus, musculoskeletal alterations, obesity, vascular disease or participation in daily sport activities).

Next, in a second phase, each participant then took off their socks and footwear. Afterward, the same senior podiatrist assessed and collected anthropometric values such as weight and height for the body mass index (BMI) to be analyzed from the weight (kg) and height (m), using Quetelet's equation: BMI $=$ weight / height$^2$ [18].

Then, in a third phase, the senior podiatrist examined the feet for the evaluation of alterations, deformities and global structural integrity, all through mobility, palpation and strength assessment of the feet using the Kendall test [19].

The following phase consisted in the diagnosis of the foot arch types (flat, normal and high) which were assessed with the navicular drop test (ND) in each foot. All participants stood in a relaxed, weight-bearing position. A mark was made by the podiatrist on the skin directly above the navicular bone, which is located on the inner side of the foot, just above the arch. Next, the person was then instructed to relax their foot while the examiner supported their lower leg and ankle to ensure a consistent starting position. The podiatrist measured the vertical distance between the starting mark and the lowest point of the navicular bone when the person's foot was in a relaxed position. The person was then instructed to rise onto their toes, allowing the arch to bear their full weight. Subsequently, the examiner measured the vertical position again between the starting mark and the lowest point of the navicular bone in the elevated position. The difference between the two measurements represents the ND. The test was done 3 times on each participant [20]. Finally, plantar pressures were evaluated using a specific portable pressure platform with resistive sensors (Neo-Plate, Herbitas. Spain) which is a validated non-invasive measurement method [21]. This procedure was conducted using the protocol by Becerro-de-Bengoa-Vallejo et al. for recording all measurements such as static motion analysis related with the: 1) average peak pressure, 2)surface area, 3)body weight on the legs and 4) foot arch types of each subject in this studyde Bengoa et al. [22].

### 2.3. Static plantar pressure analysis

A specific portable device with multiple resistive sensors and dual booster was used to measure the distribution of pressure on the feet while standing, after its automatic multistep calibration, as required for use by the maker, was executed prior to the start of the investigation. The pressure plate measured 40 x40 cm, with a flat surface thickness of eight millimeters; had a total weight of four kilograms and included 4096 resistive sensors. The device recorded pressure to the nearest 0.01 kPa (Kpa) in each sensor. Vertical force was measured with a frequency from 100 to 500 Hz. The pressure analysis system was connected using a specific cable to the computer and Neo-Plate, Windows version (Laboratorios Herbitas SL, Valencia, Spain) specialized software for data capture. The static pressure mapping systems were obtained for each foot variable as follows: (1) Surface area in cm$^2$, (2) forefoot surface area in cm$^2$, (3) heel surface area in cm$^2$, (4) percentage of body weight supported by the lower legs, (5) percentage of body weight on the forefoot, (6) percentage of body weight on the heel, (7) forefoot maximum peak pressure in Kpa) and (8) heel maximum peak pressure in Kpa, and are shown in Fig. 1.

Too, the foot arch types mapping systems were compared with the results of ND test that and are shown in Fig. 2 to contrast the same diagnosis of the bilateral flatfoot.

### 2.4. Sample size method

The specific method for calculating sample size was designed to analyze the probability of detecting a true effect or relationship between variables applying the G*Power program release 3.1.9.7, available for Windows version (Heinrich Heine University, Germany). To calculate

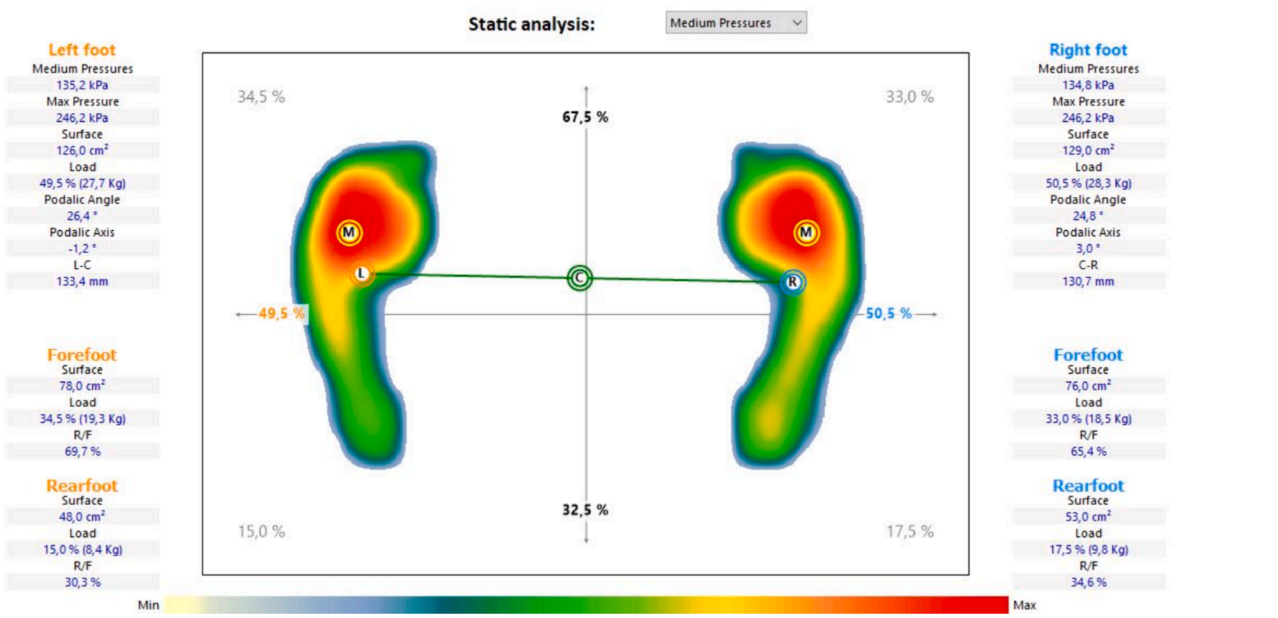


**Fig. 1.** Static analysis of plantar pressures maps using software Neo-Plate.

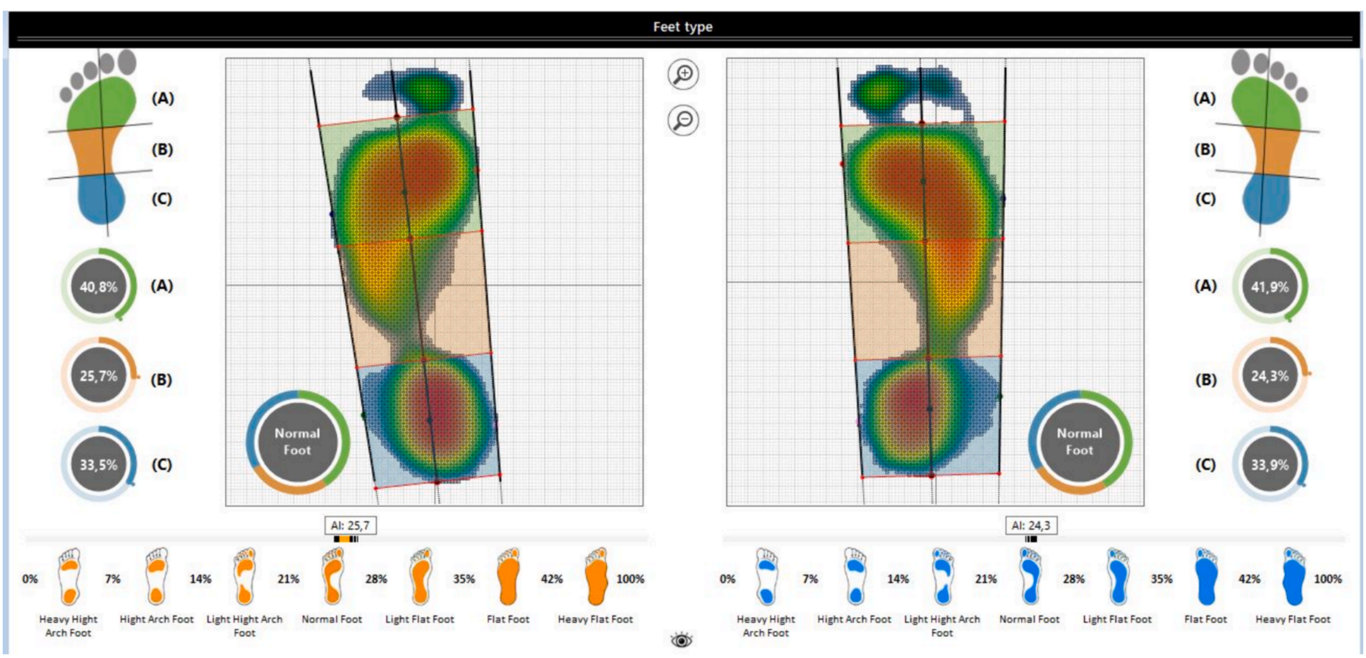


**Fig. 2.** Foot arch types analysis using software Neo-Plate.

the required sample size a two-tailed hypothesis, an effect size determined by d = 0.66, an error probability with a α = 7 %, power established by (1-β) = 80 % and a distribution ratio for two groups established by N2/N = 1 were computed. Consequently, the total sample size determined for this research was 68 participants (34 in each group).

### 2.5. Ethical principles and legal practice considerations

The analytical case-control study with file number PID2019-108009RB-I00 was checked and approved by the local Research Integrity Ethics Committee at the Universidade da Coruña (A Coruña, Spain) application data 20190017.

Each voluntary participant was given a document with all the information on taking part in this study and they had the opportunity to ask any question to a senior trained podiatrist. All the subjects also signed their consent in written form, participating voluntarily and freely in this novel research.

All procedures complied with the WMA Declaration of Helsinki, the Council of Europe Convention on Human Rights and Biomedicine, the UNESCO Universal Declaration on the Human Genome and Human Rights and those of the relevant national bodies and institutions were observed at all times, in their updated revisions.

### 2.6. Statistical analysis

A descriptive analysis was performed on the variables included in the study. The mean, standard deviation (SD), and maximum and minimum values were calculated for the quantitative variables, and qualitative variables were examined using percentages and absolute values. The chi square test was applied in continuous values and independent t-tests were used to determine significant differences. The Mann–Whitney *U* test was also applied where data were not normally distributed. Independent t-tests were used to determine significant differences. Statistical calculations were performed using the statistical package SPSS Statistics 27 (IBM) considering significant results with a P value $< 0.05$.

Neo-Plate, Windows version specialized software was used to obtain the static pressure mapping systems that were generated for each foot with or without AF.

## 3. Results

### 3.1. Descriptive data

A total of 68 persons between 19 and 40 years old and a mean age ± SD of 24.54 ± 5.46 years finished all the investigation phases.

Table 1. This table presents the information related to the clinical and main sociodemographic characteristics of the study subjects. In particular, it shows that participants are at risk of being overweight (BMI = 25.10 ± 5.37 kg/m$^2$) with statistically relevant differences ($p < 0.005$). Descriptive socio-demographic characteristics of the participants, stratified by group, with or without bilateral AF are presented in Table 1.

### 3.2. Main outcome findings data

The main measurements are shown in Table 2. When we assessed static pressure mapping systems, we observed that mean peak pressures were higher in the left foot in the AF group than in the group without AF. There was also a difference ($p < 0.005$) between groups in total, left and right total areas, as well as in the left and right heel surface areas.

There were no statistically relevant differences ($p < 0.005$) among groups in the body weight supported between the lower left and right legs.

## 4. Discussion

The main purpose of this analytical case-control study was to evaluate the characteristics in foot morphology related to static plantar pressure distribution in adults with and without a bilateral condition following the procedure by Becerro de Bengoa Vallejo et al. [23] recording results for each foot variable such as surface area, forefoot surface area, heel surface area, percentage of body weight supported by the lower limbs, percentage of body weight on the forefoot, percentage of body weight on the heel, forefoot maximum peak pressure, heel maximum peak pressure and foot arch types of all the subjects who participated in this research.

**Table 1**
Main characteristics of all subjects with or without bilateral adult flatfoot.

| Characteristics | Total group (n = 68) Mean ± SD (Range) | Adults with bilateral flatfoot (n = 34) Mean ± SD (Range) | Healthy adults (n = 34) Mean ± SD (Range) | *P*-Value |
|---|---|---|---|---|
| Age (years) | 24.54 ± 5.46 (19–40) | 24.41 ± 4.72 (20–37) | 24.68 ± 6.18 (19–40) | 0.393† |
| Weight (kg) | 66.92 ± 13.70 (48–98) | 74.50 ± 13.36 (53–98) | 57.57 ± 12.60 (28–89) | **< 0.001**† |
| Height (cm) | 150.0 ± 7.22 (150–185) | 162.65 ± 7.33 (150–177) | 165.79 ± 6.85 (155–185) | 0.028† |
| BMI (kg/m$^2$) | 25.10 ± 5.37 (18.87–39.26) | 28.34 ± 5.72 (21.08–39.26) | 21.86 ± 2.06 (18.87–26.00) | **< 0.001**† |
| Sex, male/ female (%) | 8/68 (11.8/88.2) | 6/28 (17.6/82.4) | 2/32 (5.9/94.1) | 0.259 ‡ |
| Foot Size | 38.44 ± 2.01 (36–46) | 38.33 ± 1.98 (36–42) | 38.54 ± 2.07 (36–46) | 0.408† |

**Abbreviations:** Kg, Kilogram; Cm, Centimeter; % Percentage; SD, Standard Deviation; N, Number.
† Mann-Whitney *U* test was used.
‡ Fisher exact test was used. In all the analyses, $P < 0.05$ (with a 95 % confidence interval) was considered statistically significant.

Overall, statistically significant differences in static plantar pressure characteristics were detected between the two groups. The most common distinctiveness between contact area was in relation to mean peak pressure which were higher in the left foot in the AF group than in the group without AF, which is comparable to previous findings reported in the investigation by Han et al. comparing static plantar pressure distribution between normal and flatfoot patients [24]. Besides, this is the first study that has found in the AF group variations in the surface areas in both feet and increased peak pressures in the right and left foot total area, as well in the left and right heel surface area. For this reason, this investigation showing which the main clinical implications that is relate with the diagnosing and managing of AF abnormal static pressure distributions for help physicians and podiatry services planning treatment and preventive care activities in the attempt to find a improve quality of life, wellbeing and increase satisfaction outcomes in the foot care in patients with this foot condition. This way, it is very important to evaluate and design different shoes or insoles for each foot in AF to control this condition at the onset of foot complications, gait alterations, thus improving the deambulation in the activities of the daily life, your autonomy and independence of this population.

Our main findings are in line with previous investigations on other illnesses such as diabetic foot, Parkinson's disease and in the arthritic population, indicating that the use of adequate shoes for surface area in each foot is not as evident as it might appear [25–27]. The fact that all the patients with AF in our investigation showed a difference in surface area between the right and left foot indicates that in some cases it is advisable to wear shoes of different designs and sizes to improve foot health and gait [28,29].

There are some limitations to this case-control study. First of all, the consecutive sampling bias should be researched and a simple random sampling technique could be more suitable for future studies. In second place, the complete plantar pressure portable measurement system, can simply identify and record vertical force at a frequency of 60 Hz; other forces and frequencies that may be important to the capturing and recording of the human movement of forces on the area of the foot, such as shearing stresses and dynamic plantar pressure distribution in the foot, were not studied. Furthermore, linked biomechanical movement pattern data, such as electromyography and kinematics were not recorded, so it is complicated to draw conclusions about the impact of foot pressures on total foot function. Lastly, all information recorded in this case-control study was taken with subjects unshod, and it is likely that shoe characteristics, such as general structure, cushioning, wear patterns, fit, and sole bending stiffness, may influence plantar pressures when wearing footwear.

Finally, our novel case-control study gives helpful knowledge to researchers and clinicians on a very common foot problem regarding the static plantar pressure distribution in an adult population. Moreover, it reveals the importance of constant research associated with AF and its evaluation to improve the analysis and outcome of foot health problems and the AF population's well-being and quality of life.

## 5. Conclusions

Adults with bilateral flatfoot showed differences in the surface areas in both feet and recorded higher levels in static plantar pressures with respect to the control group, a factor which can be associated with this common bilateral condition in adults.

**Table 2**
Main outcome measurements of static plantar pressures in all subjects with or without bilateral AF.

| Characteristics | Total group (n = 68) Mean ± SD (95 %CI) | Adults with bilateral flatfoot (n = 34) Mean ± SD (95 %CI) | Healthy adults (n = 34) Mean ± SD (95 %CI) | *P*-Value | Effect size Coheńs *d* |
|---|---|---|---|---|---|
| Left foot medium peak pressure (Kpa) | 138.20 ± 9.74 (135.84 – 140.55) | 141.85 ± 9.17 (138.65 – 145.05) | 134.54 ± 9.01 (131.40 – 137.69) | **< 0.001**† | 0.804 |
| Left maximum peak pressure (Kpa) | 242.65 ± 6.86 (240.99 – 244.31) | 244.74 ± 1.95 (244.06 – 245.42) | 240.56 ± 9.11 (237.38 – 243.74) | 0.399† | 0.635 |
| Left surface area ($cm^2$) | 132.26 ± 18.88 (127.69 – 136.83) | 138.68 ± 14.74 (133.54 – 143.82) | 125.85 ± 20.53 (118.68 – 133.02) | **< 0.001**† | 0.718 |
| Body weight on the lowerleft limb (%) | 48.85 ± 3.11 (48.10 – 49.61) | 49.29 ± 2.86 (48.29 – 50.29) | 48.41 ± 3.33 (47.29 – 49.57) | 0.564† | 0.284 |
| Left forefoot surface area ($cm^2$) | 69.44 ± 8.73 (67.33 – 71.55) | 71.47 ± 6.50 (69.20–73.74) | 67.41 ± 10.19 (63.85–70.97) | 0.012† | 0.476 |
| Body weight on the left forefoot (%) | 26.45 ± 2.99 (25.73 – 27.18) | 26.37 ± 3.40 (25.18 – 27.56) | 26.55 ± 2.56 (25.64 – 27.43) | 0.338† | 0.060 |
| Left heel surface area ($cm^2$) | 62.82 ± 12.39 (59.83 – 65.82) | 67.21 ± 11.42 (63.22 – 71.19) | 58.44 ± 11.90 (54.29 – 62.59) | **0.003**† | 0.2244 |
| Body weight on the left heel (%) | 22.40 ± 2.92 (21.69 – 23.11) | 22.91 ± 3.38 (21.73 – 27.09) | 21.88 ± 2.32 (21.08 – 22.70) | 0.038† | 0.356 |
| Right foot medium peak pressure (Kpa) | 142.49 ± 6.11 (141.00 – 143.96) | 143.10 ± 6.70 (141.66 – 146.33) | 140.97 ± 5.11 (139.19 – 142.76) | 0.072† | 0.356 |
| Right maximum peak pressure (Kpa) | 245.13 ± 4.57 (244.02 – 246.23) | 244.17 ± 6.26 (241.98 – 246.35) | 246.09 ± 1.15 (245.69 – 246.32) | 0.025† | 0.427 |
| Right surface area ($cm^2$) | 134.06 ± 16.83 (129.99 – 138.13) | 140.35 ± 10.71 (136.61 – 144.09) | 127.76 ± 19.46 (120.97 – 134.56) | **< 0.001**† | 0.802 |
| Body weight on the lowerright limb (%) | 51.15 ± 3.11 (50.39 – 51.90) | 50.71 ± 2.86 (49.71 – 51.71) | 51.59 ± 3.31 (50.43 – 52.75) | 0.564† | 0.284 |
| Right forefoot surface area ($cm^2$) | 69.05 ± 9.66 (66.72–71.40) | 71.33 ± 5.78 (69.31 – 73.34) | 66.79 ± 12.06 (62.58 – 71.00) | 0.071* | 0.480 |
| Body weight on the right forefoot (%) | 27.22 ± 3.55 (26.36 – 28.08) | 26.26 ± 3.86 (24.91 – 27.61) | 28.18 ± 2.97 (27.14 – 29.21) | 0.034† | 0.558 |
| Right heel surface area ($cm^2$) | 65.00 ± 10.40 (62.48 – 67.51) | 69.03 ± 8.68 (66.00 – 72.06) | 60.97 ± 10.51 (57.30 – 64.60) | **< 0.001**† | 0.836 |
| Body weight on the right heel (%) | 23.95 ± 3.34 (23.13 – 24.46) | 24.46 ± 3.61 (23.20 – 25.72) | 23.44 ± 3.01 (22.38 – 24.49) | 0.157† | 0.307 |

**Abbreviations:** Kpa, kilopascals; Kg, Kilogram; Cm, Centimeter; % Percentage; SD, Standard Deviation; N, Number.
† Mann-Whitney *U* test was used. In all the analyses, $P < 0.05$ (with a 95 % confidence interval) was considered statistically significant.

## CRediT authorship contribution statement

**Luis Padrón Cabrera:** Writing – review & editing, Writing – original draft, Visualization, Supervision, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Daniel López López:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Ricardo Becerro de Bengoa Vallejo:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Investigation, Formal analysis, Conceptualization. **Marta Losa-Iglesias:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Investigation, Formal analysis, Conceptualization. **Juan Gómez Salgado:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Investigation, Formal analysis, Conceptualization. **Javier Bayod López:** Writing – review & editing, Writing – original draft, Visualization, Supervision, Methodology, Investigation, Formal analysis, Conceptualization.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Data availability

Data will be made available on request.

## Acknowledgement

Funding for open access charge: Universidade da Coruña/CISUG.

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