Rev Bras Cineantropom Desempenho Hum

original article

https://doi.org/10.1590/1980-0037.2025v27e107658

Acute effects of 5 km, 10 km, and 15 km runs on plantar pressure and biomechanics in recreational runners

Efeitos agudos de corridas de 5 km, 10 km e 15 km sobre a pressão plantar e parâmetros biomecânicos em corredores amadores

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Received: June 26, 2025
Accepted: September 05, 2025

Abstract – This study aimed to investigate the acute effects of road running at different distances (5 km, 10 km, and 15 km) on plantar pressure and biomechanical parameters related to the Arch Index (AI) and the Center of Pressure Excursion Index (CPEI) in recreational runners. Thirty-one amateur runners were evaluated using static and dynamic baropodometry before and after training sessions. The analyses included measurements of plantar area, maximum and mean pressure, as well as changes in CPEI and AI. The 15 km run led to significant increases in static plantar area and dynamic pressure, indicating greater foot overload. In contrast, the 10 km run was associated with greater foot pronation, as evidenced by changes in CPEI. Additionally, sex and body mass index (BMI) influenced plantar pressure distribution, with men presenting higher dynamic pressure and BMI being related to increased plantar area. Different running distances induce distinct biomechanical changes, underscoring the importance of individualized assessment for safe training prescription and injury prevention strategies.

Key words: Biomechanics; Foot; Flat foot; Talipes cavus; Running.

Resumo – *Este estudo teve como objetivo investigar os efeitos agudos da corrida de rua em diferentes distâncias (5 km, 10 km e 15 km) sobre a pressão plantar e parâmetros biomecânicos relacionados ao Índice do Arco (IA) e ao Índice de Excursão do Centro de Pressão (IECP) em corredores amadores. Foram avaliados 31 corredores amadores por meio de baropodometria estática e dinâmica antes e após sessões de treino. As análises incluíram medidas da área plantar, pressão máxima e média, bem como alterações no IECP e IA. A corrida de 15 km gerou aumentos significativos na área plantar estática e na pressão dinâmica, indicando maior sobrecarga nos pés. Já a corrida de 10 km esteve associada a maior pronação do pé, evidenciada por alterações no IECP. Além disso, o sexo e o índice de massa corporal (IMC) influenciaram a distribuição da pressão plantar, com homens apresentando maior pressão dinâmica e o IMC relacionado a aumentos de área plantar. As diferentes distâncias de corrida provocam alterações biomecânicas distintas, ressaltando a importância de avaliar individualmente os praticantes para prescrição segura de treinos e estratégias de prevenção de lesões.*

Palavras-chave: *Biomecânica; Pé; Pé chato; Pé cavo; Corrida.*

How to cite this article
Britto ACT, Quadrado IC, Rodrigues VP, Coelho Junior JF, Noberto Junior M, Britto FAT, Carmo JC. Acute effects of 5 km, 10 km, and 15 km runs on plantar pressure and biomechanics in recreational runners. Rev Bras Cineantropom Desempenho Hum 2025, 27:e107658. DOI: https://doi.org/10.1590/1980-0037.2025v27e107658

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Scientific Editor
Diego Augusto Santos Silva

INTRODUCTION

Road running is one of the most popular sports practices worldwide, with millions of recreational participants seeking physical and mental health benefits[1,2]. However, this growing adherence is accompanied by a high incidence of injuries, affecting between 24% and 65% of runners. Over 90% of these injuries occur in the lower limbs, particularly the knee, ankle, foot, and leg[3,4].

Among the factors associated with the onset of these injuries are biomechanical alterations and inadequate plantar pressure distribution during running[5,6]. Running biomechanics directly influence the load on the plantar surface of the feet, which serve as the primary point of contact with the ground and are responsible for absorbing ground reaction forces[7,8]. Prolonged running sessions lasting more than 30 minutes have already been shown to induce changes in plantar pressure, such as medial and anterior shifts in force distribution[9,10], as well as specific overloads associated with muscle fatigue and foot strike patterns[11,12].

Technological advances, such as baropodometry, have made it possible to analyze plantar pressure distribution under static and dynamic conditions. This tool is valuable for investigating loading patterns that may predispose individuals to injury and for guiding preventive interventions, such as the selection of appropriate footwear or modifications to running technique[6,13,14].

Despite progress in the field, studies systematically evaluating the acute effects of running at different distances (5 km, 10 km, and 15 km) on biomechanical parameters such as the Arch Index (AI) and the Center of Pressure Excursion Index (CPEI) remain scarce. Furthermore, little is known about how individual variables such as sex and body mass index (BMI) influence these changes[6,15,16,17].

In light of this, the present study aimed to investigate the acute changes in plantar pressure and in the AI and CPEI parameters in recreational runners following 5 km, 10 km, and 15 km runs. The study also examines how sex and BMI interact with these parameters, contributing to the development of personalized strategies for injury prevention and performance optimization in amateur runners.

METHODS

Sample

This cross-sectional study included 31 amateur road runners with a minimum of three months of regular training in the 5 km, 10 km, or 15 km distances. Inclusion criteria were: age over 18 years, no history of orthopedic surgery, and regular running practice. Exclusion criteria included antalgic gait, physical limitations resulting from lower extremity conditions, active medical treatment for lower limb injuries, wounds or diseases affecting the plantar region, history of significant trauma (such as fractures, surgeries, or burns), or recurrent injuries leading to asymmetric gait.

All participants signed an Informed Consent Form. The confidentiality of all information was ensured, and participants were free to withdraw from the study at any time. After testing, individual results were shared with each participant.

Equipment

Plantar pressure was assessed using a baropodometric platform, model S-Plate® (Medicapteurs, France), equipped with 1,600 resistive sensors, an active area of 400 mm x 400 mm, a sampling frequency of 100 Hz, and a sensitivity range of 0.4 N to 100 N.

Protocol

Data collection was conducted at the participants' usual training locations. Each participant underwent two evaluation phases: one before and one after running. The pre-run assessment was performed with participants barefoot, walking over the platform at a self-selected pace while visually focusing on a fixed point ahead to avoid looking at the platform. The second full step of the gait cycle was recorded; data collection was repeated if the step was not fully captured or if visible gait asymmetry was observed.

Post-run measurements were taken within 10 minutes of completing the training, under the same conditions as the initial assessment, including the approach length.

Measurements were conducted barefoot rather than using in-shoe sensor insoles for practical reasons and to ensure standardization among participants. Although insoles provide more specific measurements within the shoe, their applicability is limited by factors such as shoe type, comfort, and unstable positioning inside the footwear. Barefoot assessments are validated for investigating plantar loading patterns and are reliable for detecting changes under different test conditions.

Evaluation of the AI and CPEI indices

Arch index (AI)

Foot posture was assessed using the Arch Index (AI), calculated from the peak pressure image during relaxed bipodal stance. AI was defined as the ratio between the midfoot area and the total plantar footprint area (excluding the toes)[18]. Higher AI values indicate flatter feet. Participants were classified as having high-arched, normal, or flat feet based on sex-specific quintiles:

- Men: high-arched (0–0.171), normal (0.172–0.294), flat (0.295–0.491)
- Women: high-arched (0–0.157), normal (0.158–0.286), flat (0.287–0.486)

Center of pressure excursion index (CPEI)

Foot function was estimated using the Center of Pressure Excursion Index (CPEI), derived from plantar pressure images during dynamic gait. The CPEI quantifies the lateral deviation of the center of pressure in the anterior third of the step and is normalized by foot width at the trisecting line[19]. Pronated feet exhibit lower CPEI values, while supinated feet show higher values. Categorization followed sex-specific quintiles:

- Men: pronated (−25.3 to 10.2), normal (10.3 to 23.4), supinated (23.6 to 42.2)
- Women: pronated (−11.2 to 6.1), normal (6.2 to 19.2), supinated (19.3 to 37.9)

Statistical analysis

Data analysis was performed using the R statistical package version 4 (R Foundation for Statistical Computing, Vienna, Austria) and GraphPad Prism version 10.0 (GraphPad Software Inc., San Diego, USA). Initially, descriptive statistics were conducted using absolute and relative frequencies, means, and standard deviations (±SD). Fisher's exact test was employed to compare the distribution of categorical variables across time points and running distances.

Normality and homogeneity of the continuous variables were assessed using the Shapiro-Wilk and Bartlett tests. Depending on the results, paired Student's t-tests or Wilcoxon tests were used to evaluate changes in variables between pre- and post-training conditions. One-way ANOVA followed by Tukey's post-hoc test or the Kruskal-Wallis test followed by Dunn's post-hoc test was applied to compare measurements across different running distances in the post-training condition. Multivariable linear regression models were used to analyze the effects of training duration, BMI, and sex on continuous variables. For all analyses, a significance level of 5% ($P < 0.05$) was adopted.

RESULTS

A total of 31 participants were included in the present study, comprising 48.4% men and 51.6% women. Table 1 presents the distribution of anthropometric data within the sample. Notably, the mean BMI was 26.2 ± 2.7 kg/m^2 for men and 24.0 ± 2.8 kg/m^2 for women.

Table 1. Distribution of Anthropometric Data by Sex in the Evaluated Sample.

Variables	Total		Men		Women	
			(n=15; 48,4%)		(n=16; 51,6%)	
	Mean	±SD	Mean	± SD	Mean	± SD
Weight (kg)	71.0	±13.1	79.1	±10.6	63.5	±10.5
Height (m)	1.68	±0.09	1.73	±0.07	1.62	±0.07
BMI (kg/m2)	25.1	±2.9	26.2	±2.7	24.0	±2.8

Note. SD = standard deviation; BMI = body mass index.

Table 2 presents the assessment of the Arch Index (AI) and Center of Pressure Excursion Index (CPEI) before and after training across the different running distances. Statistically significant differences were observed in the post-run assessment of the 10 km group (P = 0.008), in which a higher frequency of pronated excursion was noted among the participants after the run. Significant differences were also found when comparing the 5 km and 10 km groups in the post-run period (P = 0.036), with a higher frequency of pronated position observed in the 5 km group than in the 10 km group.

Table 3 presents the analysis of variables related to plantar pressure and area. Statistically significant differences were observed only in the 15 km group when comparing pre- and post-run measurements. A statistically significant increase was found in the static bipodal area after the run (pre-run = 78.7 ±15.4 cm^2; post-run = 85.8 ±18.9 cm^2; P = 0.031), as well as in the dynamic area of the right foot (pre-run = 56.5 ±13.9 cm^2; post-run = 62.2 ±10.7 cm^2; P = 0.024).

Table 4 presents the effect of different training durations on plantar area and pressure, considering adjustments for sex and BMI. This analysis revealed that BMI was a factor associated with an increase in static bipedal area (Coef. = 0.511; P = 0.001) and an increase in left dynamic pressure (Coef. = 0.595; P = 0.005). Male participants exhibited higher values of right dynamic pressure (Coef. = 0.803; P = 0.036).

In the analysis of plantar pressure and area by quadrant (Table 5), quadrant III showed a significant increase in area (P = 0.005) and plantar pressure (P = 0.007) after the 15 km training.

Table 2. Comparative analysis of arch index and center of pressure excursion at pre- and post-training time points and across different running distances.

Variables	Pre- vs. Post-training Comparison at Same Distance									Post-training Comparison Between Distances	
	5 km			10 km			15 km				
	Pre	Post	P-value	Pre	Post	P-value	Pre	Post	P-value	5 km versus 10 km	5 km versus 15 km
	%	%		%	%		%	%		P-value	P-value
Arch Index			0.414			1.000			0.527	0.558	0.564
Flat	0%	0%		0%	0%		11.1%	16.7%			
Normal	42.9%	28.6%		40.0%	60.0%		61.%	38.9%			
High Arch	57.1%	71.4%		60.0%	40.0%		27.8%	44.4%			
Center of Pressure Excursion (Left Foot)			0.266			0.524			0.466	0.212	0.621
Normal	14.3%	42.9%		20.0%	0%		22.2%	38.9%			
Supinated	0%	14.3%		40.0%	20.0%		61.1%	38.9%			
Pronated	85.7%	42.9%		40.0%	80.0%		16.7%	22.2%			
Center of Pressure Excursion (Right Foot)			0.767			0.008*			0.835	0.036*	0.567
Normal	57.1%	28.6%		0	100%		33.3%	22.2%			
Supinated	14.3%	14.3%		60.0%	0%		27.8%	33.3%			
Pronated	28.6%	57.1%		40.0%	0%		38.9%	44.4%			

Note. *Statistically significant differences ($P < 0.05$).

Table 3. Comparative analysis of plantar pressure and contact area variables at pre- and post-training time points across different running distances.

Variables	5 km			10 km			15 km		
	Pre-training	Post-training	P-value	Pre-training	Post-training	P-value	Pre-training	Post-training	P-value
	Mean (±SD)	Mean (±SD)		Mean (±SD)	Mean (±SD)		Mean (±SD)	Mean (±SD)	
Static maximum pressure (g/cm2)	1998.3 (336.6)	1866.8 (265.9)	0.309	2316.6 (316.7)	2286.4 (361.2)	0.917	2170.3 (383.7)	1969.7 (333.2)	0.070
Static mean pressure (g/cm2)	781.6 (105.1)	725.3 (38.4)	0.077	914.8 (120.5)	864.2 (83.4)	0.544	867.1 (107)	798.1 (101.3)	0.053
Bipedal static area (cm2)	104.4 (22.7)	111.3 (19.8)	0.086	76.2 (12.9)	80.4 (14.2)	0.594	78.7 (15.4)	85.8 (18.9)	0.031*
Dynamic pressure – left (g/cm2)	3700.9 (933.5)	4060.4 (1121.3)	0.252	3823.6 (917.8)	4041.6 (780)	0.706	3887.2 (1016.6)	3857.6 (1603.3)	0.906
Dynamic pressure – right (g/cm2)	3625.9 (982.9)	3316.9 (390.3)	0.360	3489 (507.3)	3584.4 (954.9)	0.823	3199.9 (1071.4)	3274.3 (1347.7)	0.759
Dynamic area – left (cm2)	88.5 (23.3)	89.3 (22.5)	0.849	73.8 (20.3)	80 (21.3)	0.259	76.1 (16.4)	74.1 (12.3)	0.492
Dynamic area – right (cm2)	84.4 (13.4)	86.6 (16.4)	0.554	61.6 (19.7)	67 (23.1)	0.229	56.5 (13.9)	62.2 (10.7)	0.024*

Note. *±SD = standard deviation. *Statistically significant differences ($P < 0.05$).

Table 4. Multivariate regression models analyzing the effect of BMI, sex, and training distance on plantar pressure and contact area variables.

Dependent Variables	Regression Factors			
	BMI	Homens/mulheres	10 km/ 5km	15 km/ 5 km
	Std. Coef. (P-value)	Std. Coef. (P-value)	Std. Coef. (P-value)	Std. Coef. (P-value)
Static maximum pressure (g/cm2)	-0.014 (0.948)	0.261 (0.504)	1.197 (0.049*)	0.303 (0.516)
Static mean pressure (g/cm2)	-0.023 (0.912)	0.138 (0.715)	1.421 (0.018*)	0.746 (0.106)
Bipedal static area (cm2)	0.511 (0.001*)	0.413 (0.115)	-1.109 (0.007*)	-0.657 (0.039*)
Dynamic pressure – left (g/cm2)	0.595 (0.005*)	0.097 (0.783)	0.088 (0.867)	0.576 (0.177)
Dynamic pressure – right (g/cm2)	0.201 (0.330)	0.803 (0.036*)	0.452 (0.416)	0.362 (0.411)
Dynamic area – left (cm2)	0.290 (0.162)	0.355 (0.336)	-0.357 (0.517)	0.562 (0.204)
Dynamic area – right (cm2)	0.001 (0.992)	0.593 (0.072)	-1.170 (0.021*)	-1.352 (0.001*)

Note. *BMI = Body Mass Index. Std. Coef. = Standardized regression coefficient. Bold indicates statistically significant coefficient ($P < 0.05$).

Table 5. Comparative analysis of plantar pressure and area variables by quadrant at pre- and post-training times and across different distances.

Variables	5 km			10 km			15 km		
	Pre	Post	P Value	Pre	Post	P Value	Pre	Post	P Value
	Mean (±SD)	Mean (±SD)		Mean (±SD)	Mean (±SD)		Mean (±SD)	Mean (±SD)	
Area									
Quadrant I	12.38 (9.26)	12.38 (10.25)	1.000	5.80 (7.53)	10.00 (7.52)	0.058	6.33 (7.09	10.44 (9.41)	0.107
Quadrant II	38.75 (9.04)	40.38 (10.93)	0.456	30.60 (6.02)	31.2 (7.66)	0.862	31.61 (6.45	30.28 (6.20)	0.473
Quadrant III	16.38 (9.75)	18.63 (9.05)	0.606	9.80 (5.93)	11.60 (7.23)	0.726	9.39 (7.54	16.61 (9.17)	0.005*
Quadrant IV	36.88 (9.95)	39.88 (11.93)	0.552	30.00 (5.29)	27.60 (6.54)	0.145	30.78 (8.02	28.5 (7.55)	0.090
Pressure									
Quadrant I	6.75 (5.2)	7.13 (6.51)	0.791	4.00 (5.05)	7.00 (6.08)	0.174	4.33 (6.31	8.06 (8.37)	0.130
Quadrant II	44.63 (9.78)	44.75 (8.36)	0.954	49.40 (6.27)	48.40 (5.37)	0.473	48.89 (7.75	42.67 (9.74)	0.075
Quadrant III	11.63 (8.12)	11.75 (7.55)	0.969	7.00 (4.12)	8.40 (6.07)	0.633	7.17 (6.72	14.06 (8.56)	0.007*
Quadrant IV	37 (3.7)	36.25 (7.89)	0.821	39.60 (5.41)	36.00 (5.39)	0.358	39.5 (9.15	35.33 (12.39)	0.213

Note. ±dp = desvio-padrão, *Diferenças estatisticamente significantes (P <0,05)

DISCUSSION

No significant intra-group or inter-group differences in AI were found at any point in the study. Increased impulses and a medial and anterior shift in the CPEI trajectory curve were observed post-run, consistent with the findings of Bercovitz et al.[10], and have been associated with injuries, particularly to the lower extremity of one foot, as reported by Van Gent et al.[20]. The post-run change in CPEI may reflect valgus alignment at the ankle joint, stemming from post-exercise imbalance between the medial and lateral calf muscles[21]. Previous studies have indicated that abnormal foot structure or biomechanics may increase the risk of overuse injuries[22]. Factors such as pre-run arch height, running distance, and runner level may explain differences in the outcomes.

Excessive pronation during the initial stance phase of foot contact is influenced by repetitive movement from running and the high magnitude of impact forces[23]. In his studies, Fukano reported post-run changes in foot arch and dorsal height, both of which decreased throughout the week and took more than a week to return to pre-run profiles. These changes have been associated with increased plantar loads in the medial region of the foot[24]. It can be inferred that single or multiple functional deteriorations—such as microtrauma, muscle fatigue, and/or creep due to repetitive loading of the soft tissues supporting the arch[25]—resulted from the run. However, the present study did not identify the specific cause.

Contrary to the findings of study[26], no significant differences were observed in plantar pressure distribution between the two feet before and after running, which may be related to individual habits and substantial inter-individual variability. This may reflect the influence of leg dominance, resulting in differences in lower limb kinematics and kinetics between sides. However, this is speculative, as leg dominance was not recorded in this study. A more plausible explanation is the limited sample size.

Post-training evaluation after a 10 km run, compared to 5 km, showed higher values of maximum static pressure (Coef. = 1.197; $P = 0.049$) and average static pressure (Coef. = 1.421; $P = 0.018$), and lower values of static bipedal area (Coef. = -1.109; $P = 0.007$) and right dynamic area (Coef. = -1.170; $P = 0.021$). A similar finding was reported in study(10), which observed increased post-run peak pressure values across the total foot area. The 15 km training, compared to 5 km, resulted in lower values of static bipedal area (Coef. = -0.657; $P = 0.039$) and right dynamic area (Coef. = -1.352; $P = 0.001$). Nagel et al.[27] reported a reduction in the total contact area of the foot and a significant increase in peak pressure, which contrasts with the present findings, where a larger area in quadrant III facilitated increased pressure distribution.

This study has some limitations that should be considered when interpreting the findings. The relatively small sample size may have reduced the statistical power for detecting subtle effects, a limitation also noted in studies with amateur runners[6,18]. Another important aspect is that plantar pressure was assessed only under barefoot conditions. Although this method is validated, it does not capture the role of footwear, which has a recognized influence on plantar load distribution and injury risk[11,14]. In addition, factors such as running surface, training experience, and leg dominance were not controlled, despite evidence of their impact on plantar biomechanics[22,23]. Finally, because the design was short-term, the study focused only on acute effects, without addressing recovery dynamics or long-term adaptations, which have been highlighted in longitudinal investigations[24,25].

CONCLUSION

Running induced biomechanical changes in foot support patterns, with a tendency toward pronation after exercise, particularly following longer training sessions. These alterations varied according to plantar structure, suggesting that different foot types respond differently to the mechanical stress of running. Training distance influenced the distribution of plantar load, which may be related to variability in injury patterns among individuals.

These findings highlight the importance of considering individual biomechanical characteristics when prescribing training and preventing injuries in novice runners. Future studies should investigate the recovery time required for plantar posture following exercise, as well as the role of footwear in modulating these adaptive responses.

COMPLIANCE WITH ETHICAL STANDARDS

Funding

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors. This study was funded by the authors.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author, upon reasonable request.

Ethical approval

Ethical approval was obtained from the local Human Research Ethics Committee –Federal University of Maranhão and the protocol (no. 6.619.255) was written in accordance with the standards set by the Declaration of Helsinki.

Conflict of interest statement

The authors have no conflict of interests to declare.

Author Contributions

Conceived and designed the experiments: Britto ACT, Quadrado IC, Carmo JC; Performed the experiments: Britto ACT, Quadrado IC, Britto FAT; Analyzed the data: Britto ACT, Rodrigues VP; Contributed reagents/materials/analysis tools: Britto ACT, Quadrado IC, Rodrigues VP, Coelho Junior JF, Noberto Junior M, Carmo JC; Wrote the paper: ritto ACT, Quadrado IC, Britto FAT.

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