

Plantar pressure during gait: norm-referenced measurement for Brazilian healthy adults using the Footwork Pro[®] System

Pressão plantar durante a marcha: valores normativos para uso em brasileiros adultos saudáveis baseado no uso do sistema Footwork Pro[®]

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Abstract

Introduction: The measurement of plantar pressure is an important component in the evaluation of the locomotive system. However, the absence of norm-referenced measurement poses limitations to its use.

Objective: To verify the influence of gender on plantar pressure during gait in healthy adults and to propose norm-referenced measurement that may be used as a reference for monitoring. **Methods:** The study included 353 healthy participants (158 females and 195 males), aged between 20 and 64 years, and with a normal foot posture. Using a pressure platform, the peak plantar pressure and pressure-time integrals were measured in three areas of the foot: forefoot, midfoot, and hindfoot.

Results: Both indicators of plantar pressure showed no significant differences between genders ($p \leq 0.05$). Higher peak plantar pressure was found in the forefoot region, while a higher pressure-time integral was found in the hindfoot region. Percentile distribution values were made available for the data set of females and males. **Conclusion:** The available norm-referenced measurement may be used to identify pathological gait parameters, monitor the efficacy of therapeutic interventions, and detect individuals in need of referral for a more sophisticated and detailed evaluation.

Keywords: Foot. Gait analysis. Posture. Pressure. Reference values.

Resumo

Introdução: A medida da pressão plantar é um componente importante na avaliação do aparelho locomotor. No entanto a ausência de valores normativos traz limitações para o seu uso.

Objetivo: Verificar a influência de gênero sobre a pressão plantar durante a marcha de adultos saudáveis e propor valores normativos que possam ser empregados como referência em seu monitoramento. **Métodos:** Foram incluídos no estudo 353 participantes saudáveis (158 mulheres e 195 homens), com idade entre 20 e 64 anos e postura de pé normal. Por intermédio de plataforma de pressão foram realizadas medidas de pico de pressão plantar e integral pressão-tempo em três áreas do pé: antepé, mediopé e retropé. **Resultados:** Ambos os indicadores de pressão plantar não apresentaram diferenças significativas entre os gêneros ($p \leq 0,05$). Pico de pressão plantar mais elevado foi encontrado na região do antepé, enquanto maior integral pressão-tempo foi identificada na região do retropé. Valores de distribuição de percentis foram disponibilizados para o conjunto de dados de mulheres e homens. **Conclusão:** Os valores normativos disponibilizados podem ser utilizados a fim de identificar parâmetros patológicos da marcha, acompanhar a eficácia de intervenções terapêuticas e detectar indivíduos com necessidade de encaminhamento para avaliação mais sofisticada e detalhada.

Palavras-chave: Pés. Análise de marcha. Postura. Pressão. Valores de referência.

Introduction

The measurement of plantar pressure distribution during gait analysis is an essential biomechanical tool to identify normal and pathological patterns of human locomotion.¹ In this particular, it becomes relevant to analyze the foot function given its participation as a support point to dissipate and transfer reaction forces on the ground.² Measurement instruments capable of measuring the foot function through the plantar pressure use imaging technology, platforms, and sensory insoles.² In this case, pressure platform systems allow for the direct measurement of the vertical component of the ground reaction forces and the load distribution on the plantar surface with acceptable accuracy and reproducibility.^{3,4}

Although its clinical applicability is related to monitoring foot pathologies⁵ and evaluating the effectiveness of orthosis use,⁶ surgical interventions,⁷ and physical

rehabilitation,⁸ the value of plantar pressure analysis as a diagnostic and screening tool for possible health dysfunctions remains uncertain. The lack of uniformity of measurements, sensitivity among different instruments, masking forms of foot areas,⁹ and, mainly, scarce propositions of norm-referenced measurement constitute some of the barriers for its appropriate use in rehabilitation procedures.

To ensure the suitable proposition of norm-referenced measurement, it is necessary to investigate the influence of gender on plantar pressure. Previous studies have tried to identify possible differences between men and women in the distribution of plantar pressure during gait analysis; however, their findings have been inconsistent.¹⁰⁻¹² Thus, new studies are needed in order to clarify this gap in the literature.

In the clinical context, the most commonly used plantar pressure indicators are the peak pressure¹³ and the pressure-time integral.¹⁴ Both indicators reflect the extent of the load on the foot during the support phase of the gait analysis. In this particular, the peak plantar pressure represents the highest pressure value recorded on the contact surface, while the pressure-time integral describes the cumulative effect of pressure as a function of time on a given plantar area;¹⁴ therefore, it considers the load propagation time and might be a more appropriate indicator of tissue stress.¹⁵

Despite the relevance of both indicators for several health conditions,^{16,17} little is known about the distribution pattern of the plantar pressure in healthy individuals, which hinders proper clinical decision making regarding potential referrals for further evaluation, detection of the effects of interventions, and directing the formulation of conducts focused on individual needs.

Some studies have linked plantar pressure overload with musculoskeletal pain and diabetic ulcerations.¹⁶ However, the plantar pressure threshold between pathological and healthy conditions remains uncertain in the literature. In this sense, studies aiming to propose norm-referenced measurement are scarce and involve restricted age^{18,19} or populations from different geographic origins.²⁰

In fact, the cultural habits of specific population groups may influence the anthropometric characteristics of the feet,²¹ which, in turn, determine their function.²² Thus, this study aims to provide normative values for the peak plantar pressure and the pressure-time integral based on a representative sample of healthy Brazilian adults.

Methods

The Research Ethics Committee of the Universidade Estadual de Londrina approved the study protocol under number 3.171.583. After being informed of the nature, objectives, and methodological procedures, all participants signed the Informed Consent Form.

Data were collected between January and August 2019. Adult participants of both genders, apparently healthy, aged between 20 and 64 years, and with normal standing posture were recruited. The sample consisted of residents in Londrina, Paraná, Brazil, who voluntarily accepted the invitation to participate in the study, disseminated through social communication, electronic media, and personal contact in universities, companies, public leisure spaces, and fitness centers. The following exclusion criteria were adopted: (a) impaired gait; (b) temporary or permanent injury of any segment of the lower limbs; (c) body mass index ≥ 40 kg/m²; (d) diagnosis of orthopedic, neurological, cardiorespiratory, and vestibular pathologies; and (e) participants with pronated or supinated foot posture.

Procedures

Before the data collection, the participants filled out a structured questionnaire to gather demographic data and determine their current health status. Bodyweight and height measurements were taken to calculate the body mass index (quotient between the measure of body weight in kilograms and height in squared meters - kg/m²) and identify the foot posture index.²³

The foot posture index consisted of six criteria for the postural positioning of the foot, with the individual in orthostatic. Through observation, the researcher assigned a score from -2 to +2 to each of the criteria, thus ranging the total sum from -12 to +12. The foot posture was then classified as highly pronated (score from 10 to 12), pronated (score from 6 to 9), neutral (score from 0 to 5), supinated (score from -1 to -4), and highly supinated (score from -5 to -12).²³ The foot posture index demonstrated acceptable reproducibility for both the final score and the single scores.²⁴

Plantar pressure measurements

The plantar pressure measurements were performed during gait analysis using the FootWork Pro® system (AM

Cube, France). The equipment has an active surface of 49 x 49 cm, 4 mm thickness, 4096 calibrated capacitive sensors, a 7.62 x 7.62 mm sensor, a frequency of 200 Hz, and a 120N/cm² maximum pressure per sensor. This equipment has shown satisfactory accuracy, precision, and reproducibility for plantar pressure measurements.³ According to the manufacturer's specifications, the required participants' information was entered into the electronic system, and the equipment was calibrated for each measurement.

We used a three-step gait initiation protocol,²⁵ which showed a satisfactory agreement with the midgait protocol as to the measurement of the dynamic indicators of plantar pressure.²⁶ The participants were first familiarized with the protocol by performing numerous trials until they understood the steps involved in the evaluation.² Next, the appropriate starting position for successful executions of the procedure was marked on the floor. Finally, the participants remained barefoot and were instructed to walk at a self-selected pace maintaining a habitual gait pattern.

We accomplished three trials for the right foot, which is sufficient to ensure the reliability of the plantar pressure.²⁷ In case the participant presented any of the rejection criteria, he would repeat the procedure until obtaining the required number of steps. The rejection criteria were: (a) attempt in which the foot did not fully contact the platform, (b) intentional abnormalities in gait observed by the investigator, (c) change in gait rhythm to adjust the steps before the contact with the platform, (d) imbalance during gait, and (e) failure to complete the sequence of steps after contact with the equipment.

The plantar pressure was measured using the AutoMask function of the FootWork Pro 2.9.1 software in three plantar regions: hindfoot (0-30% of the total foot length), midfoot (30-60% of the total foot length), and forefoot (60-100% of the total foot length).²⁸ Once the plantar regions were determined, when necessary, manual adjustments were performed by the investigator to ensure the quality of the measurements. We calculated the following indicators: the peak plantar pressure (PPP, Kpa), the highest pressure value obtained in each region of the foot, and the pressure-time integral (PTI, Kpa-s), obtained by calculating the area over the peak plantar pressure curve during the support phase of the gait analysis, expressed as a percentage of the total cycle time.

Statistical treatment

We tested the data for normality using the Kolmogorov-Smirnov test. Upon confirmation of the normality requirement for data distribution, we calculated the mean and standard deviation values.

We used the Student's t-test on independent samples to detect statistical differences between genders in the measurements of the dynamic plantar pressure. Norm-referenced measurement of the peak plantar pressure and the pressure-time integral were

presented by the relative position of the data through the distribution of the 5th, 10th, 25th, 50th, 75th, 90th, and 95th percentiles.

Data were analyzed using SPSS for Windows version 25 software (SPSS, Inc., Chicago, IL).

Results

Table 1 shows the data regarding the anthropometric characteristics of the participants.

Table 1 - Characteristics of the participants

	Female (n = 158)	Male (n = 195)	t-Test	p
Age (years)	36,09 ± 12,77	37,07 ± 11,71	0,737	ns
Hight (cm)	163,61 ± 6,81	176,54 ± 7,71	16,702	< 0,001
Bodyweight (kg)	66,64 ± 13,00	83,00 ± 13,54	11,539	< 0,001
Body mass index (kg/m ²)	24,88 ± 4,58	26,67 ± 3,68	3,973	0,001

Note: values are mean ± standard deviation. ns = not significant.

Table 2 displays the data of the peak plantar pressure and pressure-time integral according to gender. Notably, the three masks did not show statistically significant differences between gender for the peak plantar pressure and time-pressure integral. As for the peak plantar pressure, both genders showed higher values in the forefoot mask and expressively lower values in the midfoot mask. As for the pressure-time integral,

however, the hindfoot mask showed higher values, while the midfoot and forefoot masks showed less expressive differences.

As no statistically significant differences have been found between the two genders, Table 3 provides norm-referenced measurement for both females and males through the distribution percentiles of the peak plantar pressure and the pressure-time integral.

Table 2 - Comparison of dynamic plantar pressure indicators according to gender

	Female	Male	t-Test	p
Plantar Pressure Peak (Kpa)				
Forefoot	408,24 ± 44,11	409,03 ± 45,04	0,167	ns
Midfoot	129,98 ± 103,79	122,94 ± 89,14	0,675	ns
Hindfoot	355,15 ± 49,03	358,63 ± 49,33	0,663	ns
Pressure-time Integral (Kpa/s)				
Forefoot	38,46 ± 6,58	37,66 ± 6,10	1,175	ns
Midfoot	26,70 ± 10,96	26,21 ± 10,93	0,420	ns
Hindfoot	58,06 ± 14,85	59,17 ± 14,78	0,700	ns

Note: values are mean ± standard deviation. ns = not significant.

Table 3 - Norm-referenced measurement for peak plantar pressure and pressure-time integral

	Forefoot	Midfoot	Hindfoot
Peak Plantar Pressure (Kpa)			
Mean	408,68	126,09	357,07
Standard deviation	44,57	95,90	49,16
Percentile 5	334,10	10,00	271,35
Percentile 10	352,00	17,00	289,20
Percentile 25	382,50	35,00	324,75
Percentile 50	409,00	120,00	359,50
Percentile 75	437,25	187,00	389,00
Percentile 90	465,50	257,00	418,00
Percentile 95	475,65	295,60	441,65
Pressure-time Integral (Kpa/s)			
Mean	38,02	26,43	58,67
Standard deviation	6,32	10,93	14,80
Percentile 5	28,00	12,00	34,00
Percentile 10	29,50	14,00	39,40
Percentile 25	34,50	18,00	49,00
Percentile 50	38,00	24,00	58,00
Percentile 75	42,00	32,00	69,00
Percentile 90	46,00	42,00	80,00
Percentile 95	48,65	48,00	84,30

Discussion

To our understanding, the current study advanced previously conducted efforts that sought to establish norm-referenced measurement for plantar pressure indicators during gait analysis.¹⁸⁻²⁰ Though some studies have reported normative data, they were obtained through in-shoes baropodometry systems or extensive platforms, rendering their use in small-space environments infeasible. Moreover, it is worth noting that these studies were limited to specific ages and did not take the influence of foot posture into account. Furthermore, the lack of standardization of the measurement units, as well as different algorithms for calculating the variables, may result in inappropriate interpretations of the plantar pressure measurements.

In this study, no statistical differences were found between men and women in the plantar pressure data, contradicting previous findings.^{11,29} However, one should note that these earlier studies investigated children and the elderly. Differences in the foot structure may explain the differences observed between genders. However, especially for adults, it is expected that the

musculoskeletal maturity of the gait system may play a similar role in both genders.

Like a similar study,³⁰ higher plantar pressure peaks were observed in the forefoot region. Although the selected sample consisted of healthy adults with normal standing posture, the literature has highlighted that elevated plantar pressures in this specific area contribute to a high prevalence of painful processes.³¹

Usually, pressure-time integral data are presented together with the peak plantar pressure. However, this has been under debate due to the similar behavior of their variables.³² Eventual differences point to a lack of control over gait speed, impacting the pressure-time integral more prominently than the plantar peak pressure. From the perspective of laboratory studies that allow controlling intervening variables, there may be no need to cover both indicators. However, it is noteworthy that the gait velocity pattern in daily life activities is not constant, highlighting the need to understand the pressure-time integral in different daily activities, such as standing and walking on various surfaces.

The current study showed no differences in both plantar pressure indicators by gender, which supports an earlier paper that showed a strong linear dependence between peak plantar pressure and the pressure-time integral in healthy subjects.³³ Therefore, the discriminatory feature of the latter cannot be ascertained. We suggest, however, further studies, especially with outcomes related to pathological conditions, to verify this discriminatory capacity, as well as the relevance of its association to the plantar peak pressure.

One of the main contributions of the current study was to provide norm-referenced measurement for the most commonly used plantar pressure indicators in clinical practice. It is also relevant to point out that the participants were healthy and had a normal standing posture, thus ensuring a valuable contribution to establishing expected profiles of plantar pressure, allowing for early tracking of individuals with a propensity to musculoskeletal disorders in the feet and for guiding the evolution of rehabilitation interventions. Another pertinent aspect is the simple, reliable, and practical methodology to obtain plantar pressure data in a clinical environment.

The study is not without potential limitations. First, the non-performance of random sampling techniques, sample size calculation, and self-report of health status may have resulted in a methodological bias. Besides, the Footwork Pro® plantar pressure measurement system lacks evidence regarding the conformity of its plantar pressure values with those produced by other devices, which may make eventual comparisons infeasible. Finally, potential confounding variables such as ankle range of motion, muscle strength, and plantar sensitivity were not controlled. We believe, however, that these variables were not affected due to the inclusion criteria of the participants.

Conclusion

This study sought to fill a gap in the literature regarding the availability of normative plantar pressure values during gait analysis in healthy adults. We first analyzed eventual differences in plantar pressure between male and female subjects and, based on the similarity identified, processed the data of both genders together to propose the norm-referenced measurement.

Clinicians and researchers can use the suggested norm-referenced measurement to compare pathological parameters of gait analysis based on data from apparently healthy individuals, measure the efficacy of therapeutic interventions, and detect individuals in need of referral for more sophisticated and detailed assessment.

Authors' contribution

FRPGR was responsible for the study design, data interpretation, and manuscript writing. DPG was responsible for the study design, data analysis and interpretation, and manuscript review. Both authors approved the final version.

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