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Research Article

Determination of the minimum number of steps for assessment of plantar pressure in gait of children, adults and older adults

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HIGHLIGHTS

• The first four measured steps were sufficient to obtain peak plantar pressure data with minimal variability
• This finding applies to children, adults, and older adults walking at their preferred gait speed
• The result was consistent across all assessments conducted on different days

ABBREVIATIONS

ANOVA	Analysis of variance
FF	Forefoot
MF	Midfoot
RF	Rearfoot
SD	Standard Deviation
WHO	World Health Organization

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BACKGROUND: Plantar pressure provides useful information for the study of locomotion. Such measure is often conducted based on average of different number of steps. Previous studies are not clear regarding the minimum number of observations to reduce group variability in determination of peak pressures, especially when comparing people in different age groups.
AIM: To determine the minimum number of steps required to determine peak pressure in different regions of the foot during the gait of people from different age groups.
METHODS: Children (n=12), adults (n=13) and older adults (n=12) underwent measurements of plantar pressure using a Matscan pressure mapping system for two days, while walking barefoot at their preferred gait speed. Peak pressure was determined for 10 steps in each of the days of assessment and analyzed considering foot regions of rearfoot, midfoot and forefoot. Peak pressure variability was determined considering data from two to ten steps.
RESULTS: Four steps measurements showed the lower variability in peak pressure in participants from different age groups. Although variability in rearfoot showed to be higher, the minimal number of steps we determined was useful to determine peak pressure across the different regions of the foot.
INTERPRETATION: The determination of peak pressure in assessment of gait in able bodied participants from different age groups can consider data recorded from four steps.

KEYWORDS: Child | Aging | Foot joints | Kinetics | Biomechanics

INTRODUCTION

Plantar pressure distribution during gait can be influenced by several factors, including joint range of motion, anatomical foot structure, sex, and body mass [1–3], which in addition to age are also factors that contribute increase measurement variability [4]. Peak plantar pressure increases from childhood to adulthood and older age, also with changes in the regions experiencing highest peak magnitudes. Children exhibit the highest pressures under the heel (rearfoot), while adolescents, adults, and older adults present the highest pressures in the metatarsal regions (forefoot) [5]. Adolescence is a critical period for plantar load modifications, as there are variations in pressure, peak force, and contact area compared to childhood phase [6]. The effect of aging on plantar pressure distribution during gait is modulated by sex, with older men showing higher mean pressure on the lateral metatarsals and midfoot, and older women exhibiting higher mean pressure on the medial metatarsals [7]. Anthropometric and functional variables (height, body mass, waist circumference, ankle muscle strength) explain a relevant portion of age-related changes [5].

There are many systems developed with different technologies to measure plantar pressure distribution such as sensor-equipped insoles inserted inside the shoes, and also sensor-equipped mats of varying sizes that allow greater freedom of movement for those being evaluated [3], but commonly used variables to quantify plantar pressure include mean pressure, contact area, and peak pressure [8]. In this regard, peak pressure is an important variable in the assessment, treatment, and prevention of plantar surface injuries [9], and it is also a relevant parameter for gait and foot health evaluation [5]. Repeated exposure to high peak pressures has been associated with the sites of skin lesion development [5,10,11]. During gait, certain joint conditions, such as osteoarthritis [12], transient conditions like plantar fasciitis [13], and even muscle fatigue [14] can increase plantar peak pressure [4]. Moreover, peak pressure measurement is considered the best variable for assessments performed with baropodometric systems, which are commonly used in clinical practice, due to the high reliability of data reported in previous studies [15].

Plantar peak pressure data during gait are typically evaluated based on a limited number of steps, but there are differences among studies regarding the minimum number of steps needed to reduce measurement variability. Previous studies have used measurements from up to three steps [16], up to ten steps [17], or more than twelve steps [18] to determine plantar pressure during gait. Assessing a large number of steps (e.g., more than 10) in a single walking trial is often limited because clinical environments may not provide sufficient space, and measurements may be affected by acceleration and deceleration, whereas treadmill walking may reflect a different pattern than overground walking [19]. Furthermore, influence of task familiarization or even the repetition of protocols in different days of testing are not commonly addressed in the literature. High relative variability in some plantar pressure measurements has shown large values of the minimal detectable change, indicating that more than one step may be necessary to obtain accurate measurements [20]. Therefore, determining the minimum number of observations needed to minimize variability is important, especially for children [21] and older adults, since gait patterns in these populations are more variable [22].

In addition to the number of steps, it is necessary to consider that an assessment protocol can be influenced by the age of the participants [20]. Compared to younger adults, older adults have lower plantar sensitivity and shift pressure to more distal regions of the foot, such as the forefoot and medial foot, as a strategy to maintain balance [23]. Differences in preferred gait speed [24], impact absorption capacity of the soft tissues of the foot [25], and plantar sensitivity [26] across age groups can affect plantar pressure measurements if the same protocol is applied to participants of different ages.

Therefore, the question arises: what is the minimum number of steps required to determine peak pressure during gait across different age groups? In this study, we measured plantar peak pressure over up to 10 steps for each foot on two separate days of assessment. This was performed in children, adults, and older adults, with the aim of determining the number of steps that results in the lowest variability in peak plantar pressure for each region, and whether this minimum number of steps is consistent across two different testing days.

MATERIALS AND METHODS

Participants and Experimental Design

We considered individuals up to 12 years of age as children, those between 18 and 64 years as adults, and individuals aged 65 years or older as older adults. This classification is consistent with definitions commonly used by the World Health Organization (WHO), which recognizes 65 years as a conventional threshold for older adulthood due to its association with age-related physiological, functional, and health-related changes. These age ranges are also frequently employed in clinical and population-based research, facilitating comparability across studies. The sample was formed by convenience and included children (n = 12, 8 women and 4 men), adults (n = 13, 7 women, 6 men), and older adults (n = 12, 7 women, 5 men) who were able to walk independently and attended the scheduled assessment sessions participated in this study. They were all members of the local community and agreed to voluntarily participate in the study. All participants (or their legal guardians) provided a signed informed consent form. For the children, an assent form was also signed. This study was approved by the local institutional research ethics committee (IRB #062011). Participants with lower limb injuries in the past year or neuromuscular disorders affecting gait were excluded. Participant characteristics are presented in Table 1.

Participants were assessed while walking barefoot at their preferred speed along a 9-meter straight walkway. A pressure map system was placed at mid-distance of the walkway to record plantar pressure. They visited the assessment site on three separate days, spaced one week apart. The first day served as a familiarization session with the assessment protocol. On this day, participants signed consent and assent forms (when applicable), underwent body mass and height measurements, and completed the gait protocol. The gait protocol was repeated on the second and third visits, during which plantar pressure data were collected. All assessments were conducted at the same time of day to control for diurnal variations. Preferred walking speed was chosen to ensure participants demonstrated gait patterns as close as possible to their usual daily walking rhythm and were monitored using manual timing.

Table 1. Characterization of the participants included in the study. Data are presented as mean (standard deviation).

Variable	Children	Adults	Older adults
Age (years)	10 (2)	38 (7)	74 (4)
Body mass (kg)	44 (16)	71 (16)	70 (14)
Height (m)	1,43 (0,14)	1,65 (0,08)	1,59 (0,08)
Gait Speed (m/s)	1,21 (0,09)	1,56 (0,21)	0,89 (0,16)

*kg: kilograms; m: meters; m/s: meters per second.

Plantar Pressure Assessment

A computerized pressure-sensitive mat (Matscan, Tekscan Inc., Boston, USA), measuring 60 × 60 cm, was used to record plantar pressure during gait. Data were sampled at 400 Hz for 10 steps per foot on each assessment day. The instrumented mat was placed in the middle of the 9-meter walkway, and participants were instructed to walk naturally, without focusing on stepping on the mat. At least twenty walking trials were performed, with each trial recording a single step on the mat. Step order in terms of which foot was being measured was not predetermined; participants were not instructed to lead with a specific foot. Data collection continued until 10 steps per foot were recorded. Data from the right foot were considered in the analysis.

Peak pressure was calculated as the highest pressure value detected by the active sensors [28] in the different foot regions: forefoot (FF), midfoot (MF) and rearfoot (RF). The foot regions were defined using software (Research Foot 6.64, Tekscan Inc., Boston, MA, USA) and anatomical aspects, determining that the RF comprised 31% of the foot length, the MF comprised 19% of the foot length, and the FF comprised 50% of the foot length [25]. Data were averaged for each foot region and normalized to the total foot pressure [29].

Determination of the Minimum Number of Steps

Previous studies have used different approaches to determine the minimum number of steps needed for plantar pressure assessment, often considering data from a single age group [21,30,31]. In this study, data from 10 consecutive steps per foot, collected on each testing day, were used to calculate individual variability for each participant. To avoid the influence of acceleration or deceleration, the initial and final steps of each trial were excluded, and only the intermediate steps were analyzed. The standard deviation was computed for incremental combinations of the first 2 through 9 steps (i.e., 2, 3, 4, …, 9 steps). To reduce the influence of random fluctuations in variability estimates, we defined the optimal number of steps as the minimum number of consecutive steps beyond which the inclusion of additional steps no longer resulted in a further reduction in the standard deviation.

Statistical Analysis

Shapiro-Wilk tests were used to verify the normality of data distribution. Mauchly's test was applied to assess sphericity. For each participant, day, and foot region, peak plantar pressure values from 10 consecutive steps were determined for the right foot. Within-participant variability was quantified by calculating the standard deviation (SD) of peak pressure for incremental combinations of the first n steps (n = 2–9 per participant), using the formula:

$$SD_n = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(x_i - \bar{x}_n)^2}$$

The optimal number of steps was defined as the smallest number of consecutive steps after which the inclusion of additional steps did not further reduce the SD, indicating stabilization of variability estimates. This criterion was applied individually to minimize the influence of random fluctuations in SD values. To compare groups, foot regions, and assessment days, a repeated measures analysis of variance (ANOVA) was conducted with the factors group (3), foot region (3), and day of assessment (2). Statistical analyses were performed using the commercial statistical software package SPSS version 20.0 (Chicago, IL, USA), with a significance level set at 0.05.

RESULTS

Peak plantar pressure data from the right foot are depicted in Figure 1, which considers the average data from the two days in which peak plantar pressure was measured.

The lowest standard deviation for peak pressure measurements was observed, on average, for the first four steps in the measurement session. Furthermore, when comparing the two assessment days, the minimum number of steps required did not differ between days. The minimum number of steps to determine peak pressure with the lowest group variability (Figure 2) was not influenced by group ($F = 1.206$; $P = 0.318$), foot region ($F = 0.006$; $P = 0.994$), or day of assessment ($F = 0.952$; $P = 0.350$). No interactions between factors were observed ($F = 0.455$; $P = 0.768$).

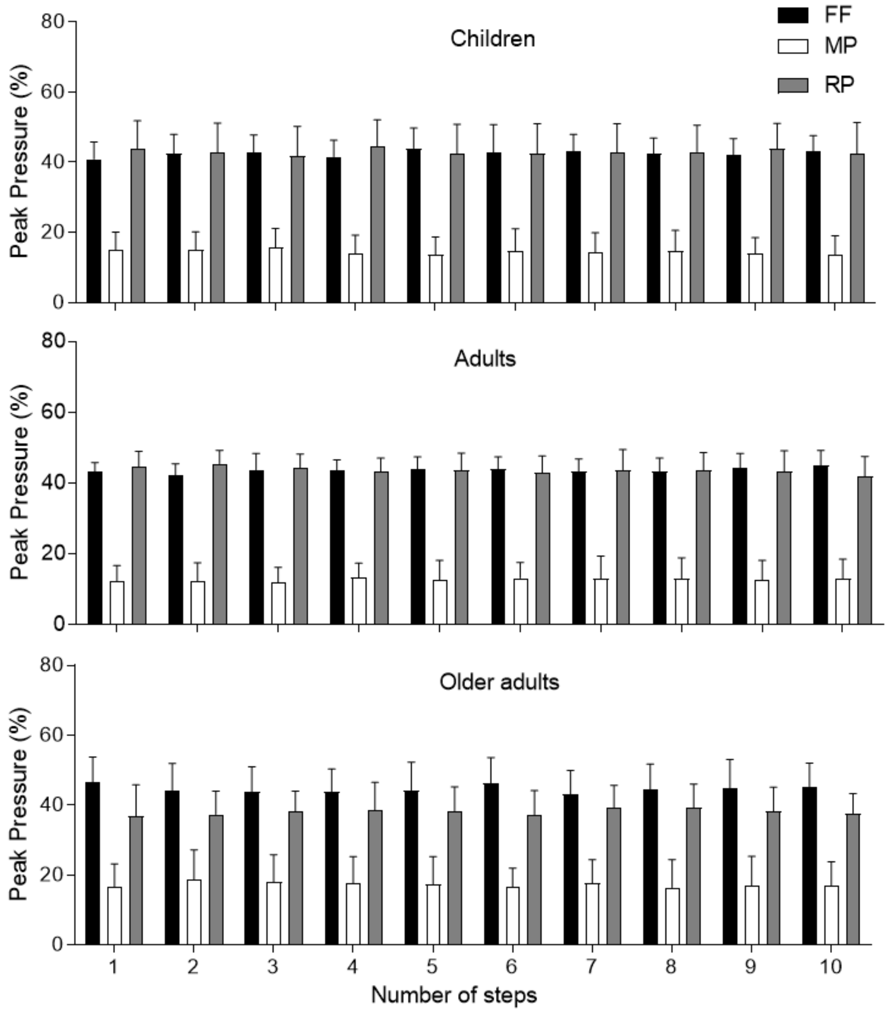

Figure 1. Mean and standard deviation data of peak plantar pressure in the right foot for the different groups and different steps. Data are merged considering the two days of testing.

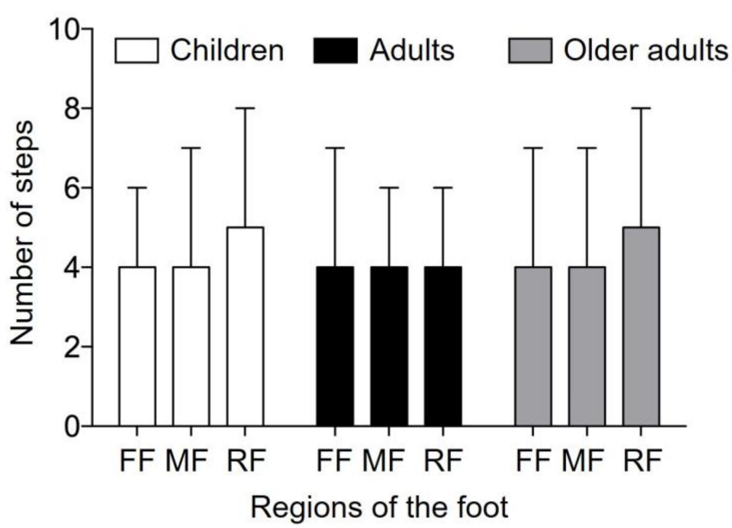

Figure 2. Mean and standard deviation of the number of steps found in each of the groups to elicit the lower standard deviation in peak pressure for the forefoot (FF), midfoot (MF) and rearfoot (RF).

DISCUSSION

The present findings indicate that a small number of gait cycles are sufficient to obtain stable plantar peak pressure measurements in healthy individuals. Specifically, the consistency observed when using the first four steps measured suggests that peak plantar pressure variability is minimized early in the walking sequence, regardless of age group or assessment day. This stability may reflect rapid adaptation of gait mechanics to the testing environment, supporting the feasibility of shorter data collection protocols in both research and clinical settings using a pressure map system of limited size.

When compared with previous studies, our results align with evidence showing reduced variability in the initial steps of plantar pressure assessment for two different assessment days for children, adults, and older adults. A previous study on plantar pressure and specific footwear reported that 12 steps were necessary to obtain reliable and valid plantar pressure data in patients with diabetes [18]. Another study testing different assessment protocols concluded that plantar pressure variability is lower in the first three steps [1,31]. These differences highlight the influence of population characteristics on plantar pressure reliability and underscore the need for population-specific protocols.

The minimum number of four steps was observed across different foot regions. However, we noted that a previous investigation found slightly higher variability in the rearfoot for children and older adults. Notably, children exhibited higher mean peak pressure in the rearfoot [32]. This pattern may result from gait characteristics in these age groups, as children have less dense heel tissue, which is more compliant to impact and absorbs peak pressure differently [33]. In contrast, strong positive correlations between age and plantar tissue stiffness suggest that older adults have stiffer plantar tissue [34], which may impair impact absorption during walking [35]. Although the RF region in children and older groups showed slightly higher variability, our analysis indicates that four steps are generally sufficient to capture stable plantar pressure patterns, as additional steps provide minimal further reduction in variability and do not substantially affect the overall conclusions. It is possible that small variations in foot landing strategy between participants may account for this variation.

Our results do not allow conclusions about parameters such as mean pressure or contact area. However, peak pressure is often considered the most appropriate parameter for ensuring reliable plantar pressure assessment [14,15]. This was one of the reasons we focused solely on peak pressure analysis. Moreover, peak pressure measurements tend to be more variable in older adults [22], suggesting that four steps may also suffice for mean pressure analysis. Peak pressure is extensively investigated as an indicator of plantar trauma and is associated with the sites of rupture and skin lesions [10,11]. Therefore, it is important to note that older adults require special attention when determining peak pressure, as it appears to be the most variable plantar pressure measure influenced by aging [4,22].

Our study has limitations. We have included a limited number of participants who walked at their preferred speed. Although this choice was made to increase ecological validity, higher walking speeds result in greater plantar pressure, which may affect the minimum number of steps required to determine peak pressure values. In the same manner, a proper sample size might also have some effect on the results. Several peer-reviewed studies investigating comparable biomechanical and gait-related outcomes have employed sample sizes similar to, or smaller than, that used in the present study. For example, research focusing on detailed biomechanical or gait analyses, where data collection is intensive and highly controlled, has reported meaningful and representative findings with comparable participant numbers [4,18,27].

Footwear can also influence peak pressure magnitude. We assessed participants barefoot to eliminate footwear effects; therefore, the minimum number of steps for assessing peak pressure while wearing shoes may differ. Plantar pressure measurements on the ground provide valuable information for clinical evaluation and diagnostic testing in medicine and rehabilitation [36]. Remote plantar pressure monitoring and specific protocols are still under development, and devices that allow continuous plantar pressure monitoring in real-world environments are in early stages. Further research is needed to establish clear guidelines for the number of steps and measurement frequency [37] and also consider the application of these findings to participants with clinical conditions related to loss of tactile sensitivity.

CONCLUSION

Plantar peak pressure can be reliably determined by using, on average, four steps for children, adults, and older adults walking at their preferred gait speed. This result was consistent across assessments conducted on different days and may help build testing protocols that might be useful to quickly screen participants and help in clinical decisions for measurements using pressure mat systems.

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