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Test-retest reliability of multiscale fractal dimension measurements of plantar pressure maps during dynamic tasks

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ABSTRACT

The tools used to evaluate foot types are divergent since they adopt classic linear analyzes, based on anthropometric or image measurements, which do not dynamically contemplate the variability of foot shape. The use of newer techniques such as multiscale fractal dimension (MFD) may be a key to this type of problem. However, for these measures to be used safely and consistently, it is essential to evaluate their reliability. The aim of this study was to evaluate the test-retest reliability of MFD measurements of adult plantar pressure maps during gait, as well as the standard error of measurement (SEM), and minimal detectable change (MDC_{90}). Seventy-two subjects were included in the test-retest, with a one week interval. The plantar pressure maps were constructed using a pressure platform. The data were processed in a routine for extracting the MFD curve measurements (maximum and integral values). The Intraclass Correlation Coefficient results ($ICC_{3,k}$) were excellent for both measurements (maximum value 0.96, 95% confidence interval [0.93–0.97], and integral 0.95 [0.92–0.97]) with low SEM and MDC_{90} values below 10% of the mean. The application of MFD to the plantar pressure data generated by the pressure platform is reliable and could allow exploration of the complexity of foot shapes, enabling their classification.

1. Introduction

Common approaches for classifying foot type rely on the use of static evaluation methods (Razeghi and Batt, 2002; Neal et al., 2014). Although evaluation of foot is well recognized in the orthopedic literature, fully accepted standardized measures to determine foot types and an agreement on the "gold standard" method for this type of evaluation are lacking (Evans et al., 2003; Hillstrom et al. 2013), as confirmed in systematic reviews that verified the relationship of foot type with other factors and pointed out the differences between the methods (Buldt et al., 2018; Neal et al., 2014).

The use of new techniques that employ unconventional methods, such as the one derived from chaos theory – fractal dimension (FD), may be an alternative for this type of analysis, using traditional techniques. The FD has been widely used to characterize complexity of real and abstract objects, and employs fractional values to describe an object in terms of space occupation and self-similarity (Plotze et al., 2005).

To provide a better description of complexity of objects, the multiscale fractal dimension (MFD) has been proposed (Plotze et al., 2005). The shape variations express with respect to a given scale, named multiscale shape representation, and provide even more information about the objects, besides encoding such representations into "good signatures" (i.e., feature vectors) (Torres et al., 2004). The MFD uses several spatial scales to analyze the shape of two-dimensional objects, based on the progressive smoothing of the curvature of an object along its contour (dilatations) (Torres et al., 2004). Among its applications, the analysis of biological data is highlighted, for example, studies involving human movement such as gait analysis (Ducharme et al., 2018) and assessing the dynamics of human postural control (Doherty et al., 2014).

Thus, this study aimed to evaluate the test–retest reliability of MFD measurements of adult plantar pressure maps during gait, and to quantify the accuracy of the measurements and estimates.

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The hypothesis was that the dynamic foot images from MFD measurements would be reliable and could represent a future alternative to classify foot types.

2. Methods

Adult individuals (between 18 and 65 years old) of both sexes, and asymptomatic, were included. Exclusion criteria were: history of foot surgery or musculoskeletal injuries/deformities in the lower limbs and spine, surgery in the previous 6 months, and body mass index (BMI) above 30 kg/m^2.

This is a cross-sectional study following the Guidelines for Reporting Reliability and Agreement Studies (GRRAS) (Kottner et al., 2011), conducted at a Universidade Estadual de Londrina, Laboratory of Biomechanics and Clinical Epidemiology and previously approved by the Institutional Review Board (# 90238618.8.0000.5231). One-way fixed effects ANOVA was used to sample size estimation, with an effect size of 0.4, probability of an α error of 0.05 and 1 - β of 0.8 through the G*Power program 3.1.9.2 (Faul et al., 2007), with a total of 66 participants. However, 10% was added to compensate for possible losses and 72 participants were involved in the final study.

An initial assessment was performed of body mass (kg), height (m), BMI (kg/m^2), and for foot characterization: total foot length, truncated length (most posterior calcaneal part to the center of the first metatarsophalangeal joint), and medial longitudinal arch height at 50% of total foot length (Williams and McClay, 2000) as proposed by Mulligan and Cook (2013). The participants plantar pressure maps were collected to calculate the MFD. A pressure platform (BaroScan®) was used: 65 $\times$ 54 $\times$ 3 cm sensor platform; 50 $\times$ 50 cm active surface, and 10 mm thickness; 7.8125 $\times$ 7.8125 mm sensor surface; with 4096 sensors; 200 Hz acquisition frequency and resistive technology with 12-bit analog conversion, capable of capturing pressures from 0.05 (minimum) to 10 kgf/cm^2 (maximum).

The participant was instructed to walk barefoot on the platform at a self-selected cadence. Following previous studies, the two-step method was used during dynamic collection. Reliability studies indicated that the two-step method for collecting plantar pressure data provided values similar to those obtained by the midgait method (Bryant et al., 1999; Hafer et al., 2013; McPoil et al., 1999). This type of method presents parameters with less than 10% error when considering an average of five attempts, with consistent results for measurements of plantar pressures performed on the same platform (Bryant et al., 1999; Hafer et al., 2013; McPoil et al., 1999). In this study, five attempts as recommended in previous studies were used.

A routine was executed in Matlab® software to calculate variables related to MFD. A surface map was created of the accumulated pressures of the activated sensors along the cycle of each step (whole foot support phase) to draw a foot shape contour with a threshold of 0.05 kgf/cm^2 (minimum pressure) (Fig. 1).

This contour map was centered on a new resolution image of 1024 $\times$ 1024 pixels to determine the cost of this contour by the Euclidean distance transform. Each instance of the multiscale form is obtained by a cost map threshold at a given squared Euclidean distance value. Thus, the higher the threshold values, the more simplified the formats become; the smaller details are removed progressively as the thresholds increase (Fig. 2) (Torres et al., 2004).

The next step consisted of performing a histogram to identify the frequency for each cost value as a function of the dilatation radii. In total, 200 dilatation radii were used and those without associated costs were removed. Next, a set of points corresponding to the logarithm of the foot contour areas was created as a function of the logarithm of the dilatation radii and from this set of points, a 9th order polynomial curve was adjusted to calculate the multiscale fractal curve by the Minkowski–Bouligand (F_r) FD, defined according to the equation (Torres et al., 2004):

Fig. 1. Foot shape contour from the minimum pressures generated by the pressure platform.

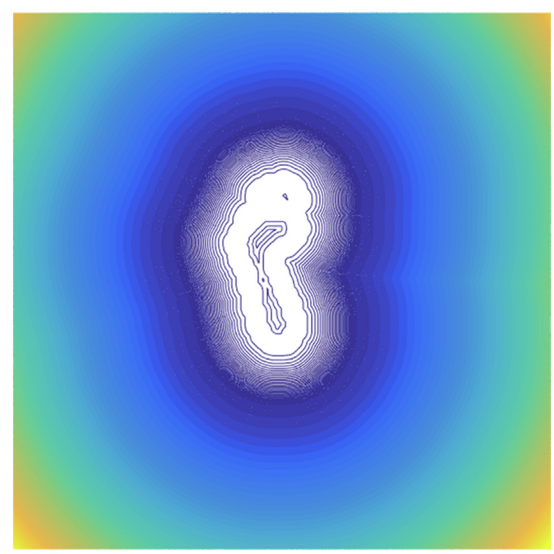

Fig. 2. Foot contour and multiscale contours (dilatations) obtained by the Euclidean distance transform.

$$F_r = 2 - \lim_{r \to 0} \frac{\log(A(r))}{\log(r)}$$

A: dilatation area; r: dilatation radii.

Multiscale fractal curve (Fig. 3) was generated and extracted the variables of maximum MFD value and the integral. These variables represent the complexity of the shape of the feet from pressure plantar maps. For the test–retest reliability statistical analysis, the mean of the 5 steps of the left foot (LF) was used.

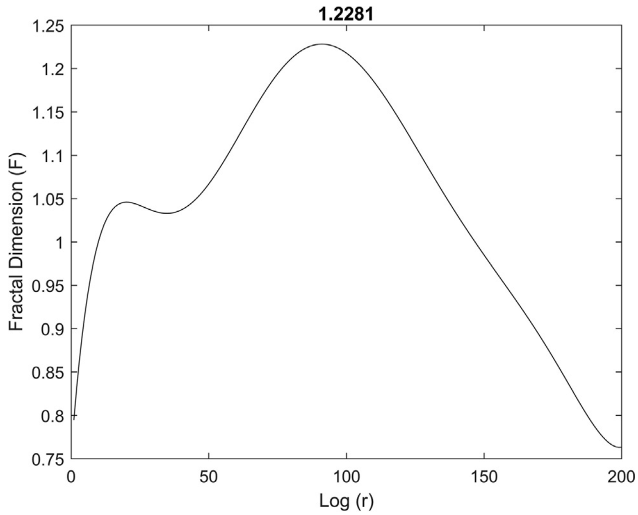

Fig. 3. Fractal curve generated from the logarithm of the areas as a function of the logarithm of the dilatation radii of the foot contour.

The same trained assessor evaluated the gait on the pressure platform. For the retest, participants were asked to approximately 7 days after the first collection (Terwee et al., 2007). Data analysis considered the mean of the five LF collections compared between the days.

Data are presented as mean ($\bar{x}$), standard deviation (SD), and 95% confidence interval (95% CI), and median and quartiles (25–75%). Test–retest reliability was assessed by calculating the Intraclass Coefficient Correlation ($ICC_{3,k}$) two-way mixed model, with 95% CI (Weir, 2005). The results were interpreted according to Fleiss et al. (2003). The Standard Error of Measurement (SEM) was calculated (SEM = SD $\times \sqrt{1 - CCI}$), where the SD is derived from the mean square of the residuals and the minimal detectable change with 90% CI (MDC_{90}) (MDC_{90} = [*z score* (for CI 90%)] $\times$ SEM $\times \sqrt{2}$; where the *z* score was associated with a 90% CI is 1.64) (King, 2011). The change that exceeded the measurement error for the test results was expected to be less than 10% of the test means.

3. Results

Seventy-two participants were included in the results. Table 1 presents the characteristics of the sample. The results for the maximum value of the MFD curve and the integral of the plantar pression maps for the first and second tests are presented in Table 2. No differences were observed, as demonstrated by the 95% CI overlap. Table 3 presents the results for the ICC [95% CI], SEM, and MDC_{90} between measures. Both measurements (maximum value of the MFD curve and integral) presented excellent reliability according to the classification proposed by Fleiss et al. (2003). Regarding the minimum difference to be considered "real," or MDC_{90} with 95% CI, the values did not exceed 10% of the mean for any of the studied variables.

4. Discussion

In this study, we observed that the maximum and integral fractal curve measurements demonstrated excellent reliability, with low measures of absolute consistency (SEM) and MDC_{90} values that did not exceed 10% of the mean (Cardoso et al., 2019). Studies reporting on the reliability of associated measures of the pressure platforms have related high reliability, as proposed by Vette et al. (2019) and Hafer et al. (2013).

Excellent reliability was also presented in studies of FD measurements of biomechanical data such as center of pressure displacement (CoP) where the authors evaluated the reliability of traditional and fractal CoP measurements and demonstrated that although traditional measurements are widely used to evaluate CoP, their reliability was questionable Doyle et al. (2005). Our FD measurements presented higher reliability (ICC between 0.75 and 0.90).

The same can be expected from the MFD measurements of plantar pression maps of individuals during gait for classifying foot type in future studies. This approach is performed by analyzing the complexity of the shape of the feet represented by maximum value and the integral of the MFD curve. It has clinical application since it is derived from dynamic measurements of plantar pressures during the gait support phase (plantar arch deformation), which provides the best starting point for a functional classification system for different types of feet (Razeghi and Batt, 2002);

Table 1
Characteristics of the sample in relation to sex.

	Female		Male	
	$\bar{x}$ (SD) [CI 95%]	Md (25–75%) [CI 95%]	$\bar{x}$ (SD) [CI 95%]	Md (25–75%) [CI 95%]
Age (years)	25.06 (7.46) [22.92; 27.20]	22 (20–28.50) [21; 25.82]	26.48 (8.08) [22.98; 29.97]	22 (20.25–31.75) [21; 30.65]
Body Mass (kg)	62.84 (11.62) [59.50; 66.17]	62 (54.75–70.50) [58; 65]	84.43 (14.42) [78.20; 90.67]	80 (72–97) [72.34; 92.60]
Height (m)	1.65 (0.07) [1.63; 1.67]	1.68 (1.60–1.70) [1.63; 1.68]	1.80 (0.08) [1.76; 1.84]	1.79 (1.75–1.87) [1.75; 1.83]
BMI (kg/cm^2)	22.79 (3.36) [21.82; 23.76]	22.38 (20.45–24.99) [21.82; 23.76]	25.86 (3.06) [25.54; 27.18]	27.05 (23.01–27.94) [23.23; 27.75]
LF Total Length (cm)	24.31 (1.43) [23.89; 24.72]	24.20 (23.37–25.10) [23.80; 24.48]	26.97 (1.74) [26.21; 27.72]	26,70 (26,05–27.50) [26.30; 27.32]
LF Truncated Length (cm)	17.80 (1.12) [17.47; 18.12]	17.60 (17–18.52) [17.30; 18.20]	19,83 (1.37) [19.23; 20.42]	19.50 (19–20.37) [19;20]
HD 50% TOL LF (cm)	6.25 (0.58) [6.08; 6.42]	6.4 (6–6.65) [6.10; 6.50]	6.90 (0.56) [6.66; 7.15]	7 (6,55–7.10) [6.70; 7.10]
n (%)	49 (68.05)		23 (31.95)	

$\bar{x}$: mean; SD: standard deviation; 95% CI: 95% confidence interval; Md = median; HD: height of the dorsum; TOL: total foot length; and LF: left foot.

Table 2
Maximum value and the integral of the MFD curve of the plantar pression maps during gait in the first and second evaluation (LF).

	1st evaluation		2nd evaluation	
	$\bar{x}$ (SD) [CI 95%]	Md (25–75%) [CI 95%]	$\bar{x}$ (SD) [CI 95%]	Md (25–75%) [CI 95%]
Maximun value	1.210 (0.04) [1.20;1.219]	1.216 (1.196–1.238) [1.207;1.229]	1.211 (0.04) [1.201;1.222]	1.220 (1.198;1.242) [1.208; 1.232]
Integral	2.547 (0.08) [2.528;2.566]	2.563 (2.531–2.597) [2.550; 2. 580]	2.55 (0.09) [2.529;2.571]	2.566 (2.522–2.611) [2.555; 2.587]

MFD = multiscale fractal dimension; LF = left foot; $\bar{x}$ = mean; SD = standard deviation; CI = 95% confidence interval; and Md = median.

Table 3
ICC, SEM, and MDC results between the test–retest measurements of maximum value and the integral of the MFD curve of the plantar pression maps during gait (LF).

	ICC [CI 95%]	SEM	MDC_{90} [CI 95%]
Maximum value	0.96 [0.93; 0.97]	0.002	0.005 [0.002; 0.008]
Integral	0.95 [0.92; 0.97]	0.002	0.006 [0.003; 0.008]

ICC = Intraclass Correlation Coefficient; SEM = standard error of measurement; MDC_{90} = minimal detectable change with 90% confidence interval; MFD = multi-scale fractal dimension; LF = left foot; and CI = 95% confidence interval.

the plantar pressure reflects the height of the medial longitudinal arch (Swedler et al., 2010). In addition, it presents the possibility of an objective evaluation, with low operational management that can be implemented in pressure platform software already available on the market.

The area of dynamic systems theory can provide a number of tools for biological data analysis. FD is one of these techniques and provides an indication of the complexity of a shape (Doyle et al., 2005). The dimension of a fractal curve is a number that characterizes the way in which the length measurement between two points increases as the scale decreases (Falconer, 2003). By applying a multiscale transformation to the fractal curve, it is possible to extract a curve-related spatial scale function and not just a numerical value as in the traditional FD. This superior performance of the MFD in relation to the traditional FD is due to the fact that an object is represented not only by a number but by a function that represents its different degrees of fractality for the different scales observed (Backes and Bruno, 2009). Thus, the maximum and integral value data of the MFD curve and the plantar pression maps can represent a viable alternative for classifying foot types since these data showed excellent reliability and accuracy using a pressure platform that allows investigation of the interaction between foot posture and lower limb biomechanical function (Buldt et al., 2018) providing dynamic, instantaneous, noninvasive, affordable measurements used in both basic and clinical research (Giacomozzi et al., 2014).

Although the MFD data present excellent reliability, it is important to point out that these values were collected only for healthy individuals. In addition, studies are needed involving a significant sample so that cut-off values can be defined and used to classify foot types.

5. Conclusion

The reliability of the MFD measurements of plantar pression maps of adult individuals during gait was considered excellent. The accuracy of the measurements (SEM) and estimates of MDC_{90} could contribute to the design of future studies so that these measures can be used as an evaluation tool for both research and clinical practice.

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.

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