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Functional, impulse-based quantification of plantar pressure patterns in typical adult gait

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ABSTRACT

Background: Dynamic pedobarography is used to measure the change in plantar pressure distribution during gait. Clinical methods of pedobarographic analysis lack, however, a standardized, functional segmentation or require costly motion capture technology and expertise. Furthermore, while commonly used pedobarographic measures are mostly based on peak pressures, progressive foot deformities also depend on the duration the pressure is applied, which can be quantified via impulse measures.

Research Question: Our objectives were to: (1) develop a standardized method for functionally segmenting pedobarographic data during gait without the need for motion capture; (2) compute pedobarographic measures that are based on each segment's vertical impulse; and (3) obtain a normative set of such pedobarographic measures for non-disabled gait.

Methods: Pedobarographic data was collected during gait from sixty adults with normal feet. Using the maximum pressure map for each trial, an expert and novice rater independently identified the hallux, heel, medial forefoot, and lateral forefoot and computed nine normalized vertical impulse measures.

Results: From the computed impulse measures, the Heel-to-Forefoot Balance was 33.3 ± 5.5%, the Medial-Lateral Forefoot Balance (with hallux) 59.2 ± 8.0%, the Medial-Lateral Forefoot Balance (without hallux) 53.5 ± 7.7%, and the Hallux-to-Medial Forefoot Balance 21.0 ± 8.9% (mean ± standard deviation). The intra- and inter-rater reliability ranged between 0.93 and 1.00 and between 0.89 and 0.99, respectively (ICC(2,1)).

Significance: We developed a simple, stand-alone method for pedobarographic segmentation that is mechanistically linked to relevant anatomical regions of the foot. The normative impulse measures exhibited excellent reliability. This normative dataset is currently used in the clinical assessment of different foot deformities and gait impairments, and in the evaluation of treatment outcomes.

1. Introduction

Foot deformities are a frequent cause of pain, fatigue, and dysfunction [1,2]. Diagnosis and management of such deformities can be complex, and over-treatment can lead to unnecessary costs for patients and the health care system [3,4]. In this light, plantar foot pressure measurements provide useful information about foot posture and deformities, facilitating better diagnosis of functional problems [1]. For example, elevated plantar foot pressure has been associated with foot deformities and, in turn, calluses, decreased plantar tissue thickness, and limited joint mobility [1]. Although plantar pressure distributions are easier to assess under static conditions, i.e., when pressure patterns are mostly constant over time, dynamic plantar foot pressure measurements have been shown to be more valuable [2], especially as part of clinical gait assessments [2,5,6].

In this context, dynamic pedobarography is a relatively simple, reliable, and non-invasive technology used to measure the change in plantar pressure distribution throughout the gait cycle [7]. Pedobarography measures foot contact patterns, the plantar foot pressure distribution and magnitude, as well as the temporal progression of the

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foot's center of pressure [8–10]. These measurements and associated outcome measures allow the observation of foot pathology over time, the evaluation of treatment outcomes, and the development of novel clinical study protocols [11]. Past efforts have obtained pedobarographic measures that are based on dividing the foot's maximum pressure map into six equally sized regions [6,11]. The underlying method is robust and relatively easy to implement, but based on "arbitrary divisions of the foot" [12] that do not take the geometry and/or pressure distribution *within* different foot regions into account. To address this limitation, an anatomy-based segmentation method has been developed, tested, and validated that is informed by the actual anatomical structures of the foot [12–15]. While this method is superior in detecting foot deformities, particularly clubfoot [12], it relies on the integration of costly, three-dimensional motion capture technology to identify where each foot structure is located relative to the acquired pressure map during the stance phase of gait – and on clinicians being able to use the technology and identify the required anatomical landmarks of the foot. As a consequence, this method cannot be used in clinical centers that do not meet these requirements.

Irrespective of whether motion capture and anatomical landmarks of the foot are utilized in the pedobarographic assessment of stance, there is also no consensus regarding the foot regions for which the pedobarographic measurements should be analyzed [5,6,14]. For example, some groups have divided the foot into five regions [6,11] – the heel, medial midfoot, lateral midfoot, medial forefoot, and lateral forefoot – to establish pedobarographic profiles for non-disabled children and young adults. At the same time, Giacomozzi et al. [12] and Stebbins et al. [14,15] divided the foot into the regions of medial heel, lateral heel, midfoot, medial forefoot, and lateral forefoot to assess the repeatability of pedobarographic measurements in non-disabled children. Within the adult population, studies have divided the foot into up to ten regions, including the medial and lateral heel/hindfoot, the medial and lateral midfoot, the medial, central, and lateral forefoot, the hallux, the second toe and the lateral toes [16,17]. These examples demonstrate that, although all studies targeted non-disabled individuals, plantar pressure maps are differently segmented to analyze the pedobarographic measurements. Since foot segmentation defines the foot regions that will give sufficient information about a specific foot area without losing critical information about global foot function, its standardization is, however, important for facilitating coherent interpretations and cross-center comparisons. A standardized segmentation of the foot that, at the same time, is reliable, functional, and not reliant on motion capture and anatomical landmarks needs yet to be established.

During gait, the foot needs to adapt to different load patterns without losing its functional integrity [5]. In this context, peak pressures have been one of the most common interest variables obtained via pedobarography [2,9]. They represent the largest pressure values recorded under localized areas of the plantar surface during gait and help clinicians to determine, for example, the effectiveness of foot orthoses in decreasing plantar pressure under a specific foot region [2,9]. Previous work has, however, suggested that progressive foot deformity is dependent not only on excessive pressure being applied to the foot, but also on the duration it is applied [2,5,9]. In other words, a high magnitude force with low duration may clinically not be as relevant as a medium magnitude force sustained over a long duration. Therefore, the vertical impulse of a foot region, i.e., the sum of the time-varying vertical force in that region multiplied by the time duration the force acts, is a useful outcome measure in clinical assessments of plantar pressure distributions during gait [9]. Despite its usefulness, a normative dataset on impulse-based outcome measures of pedobarographic measurements during gait as an important first step towards an impulse-based, functional quantification of pathologic plantar pressure distributions does not exist to date.

Based on the considerations above, the objectives of this study were threefold – to: (1) develop a standardized method for functionally segmenting pedobarographic data during gait without the need for motion capture; (2) compute pedobarographic measures that are derived from each segment's vertical impulse; and (3) obtain a normative set of such pedobarographic measures for non-disabled gait. The established dataset can serve as a benchmark for future clinical assessments and outcome evaluations in a range of foot deformities and gait impairments.

2. Methods

2.1. Study participants

60 non-disabled adults (30 female and 30 male; age: 35.8 ± 12.0 years; height: 171.1 ± 8.6 cm; weight: 72.2 ± 14.9 kg; mean ± standard deviation) with functionally normal feet and no history of foot pain or deformity, neuromuscular or musculoskeletal disease, or foot surgery participated in this study. All participants gave their written informed consent to participate in the study, whose experimental procedures were approved by the university's ethics review board (Study ID: Pro00042701).

2.2. Participant screening and experimental procedures

Screening of normal feet was conducted by a clinical expert of foot function based on a standardized physical examination and direct visual observation. Functionally normal feet were defined using the following parameters or features: (1) ankle dorsiflexion of at least 5 ° with the knee extended; (2) mild valgus hindfoot position in stance; (3) typical subtalar motion as demonstrated by achieving a varus hindfoot position, relative to the long axis of the tibia, with heel raise (Root's sign) [18]; (4) medial longitudinal arch visible in stance or reconstituted with heel raise; and (5) calcaneal bisector intersecting the toes at the second toe or between the second and third toes. In uncertain cases, a high-definition video recording was reviewed by a blinded, second clinical expert of foot function to reach a decision.

Participants were asked to walk, with bare feet, across the motion laboratory while passing over a pedobarography platform (emed-xl, Novel GmbH, Munich, Germany) that was inserted flush into the floor. Data collection for each participant and body side was continued until vertical plantar pressure values were collected for three clear footsteps atop the pedobarography platform, for a total of $3 \times 2 \times 60 = 360$ trials. Data were sampled at 100 Hz, with a resolution of four pressure measurements per square centimeter, and within a pressure range of 10 to 1275 kPa. After each successful trial, a graphical display of the foot's maximum pressure map was generated for visual analysis.

2.3. Experimental data processing

2.3.1. Foot segmentation and vertical impulse calculation

Using the Automask software package (Novel GmbH) and the foot's maximum pressure map for each trial's stance phase, two raters independently identified four anatomical foot regions in the following order (Fig. 1, *M01* to *M04*): the hallux, heel, medial forefoot, and lateral forefoot. A detailed description of the foot segmentation procedure is provided in Supplement S1. The vertical impulse of each of the four segments of the foot was then obtained in two steps: First, the time-varying force profile for a given segment was calculated by multiplying the segment's overall pressure by its area for each point in time of the stance phase (i.e., each sample). Second, the vertical impulse for a given segment was computed by taking the integral of the force profile obtained above. To assess the intra- and inter-rater reliability of segmenting each trial's maximum pressure map and calculating vertical impulses, the maximum pressure maps of all 60 participants were segmented at different times and by two individuals. For the intra-rater reliability, an expert who has performed these segmentations for more than seven years segmented the maximum pressure map at two separate

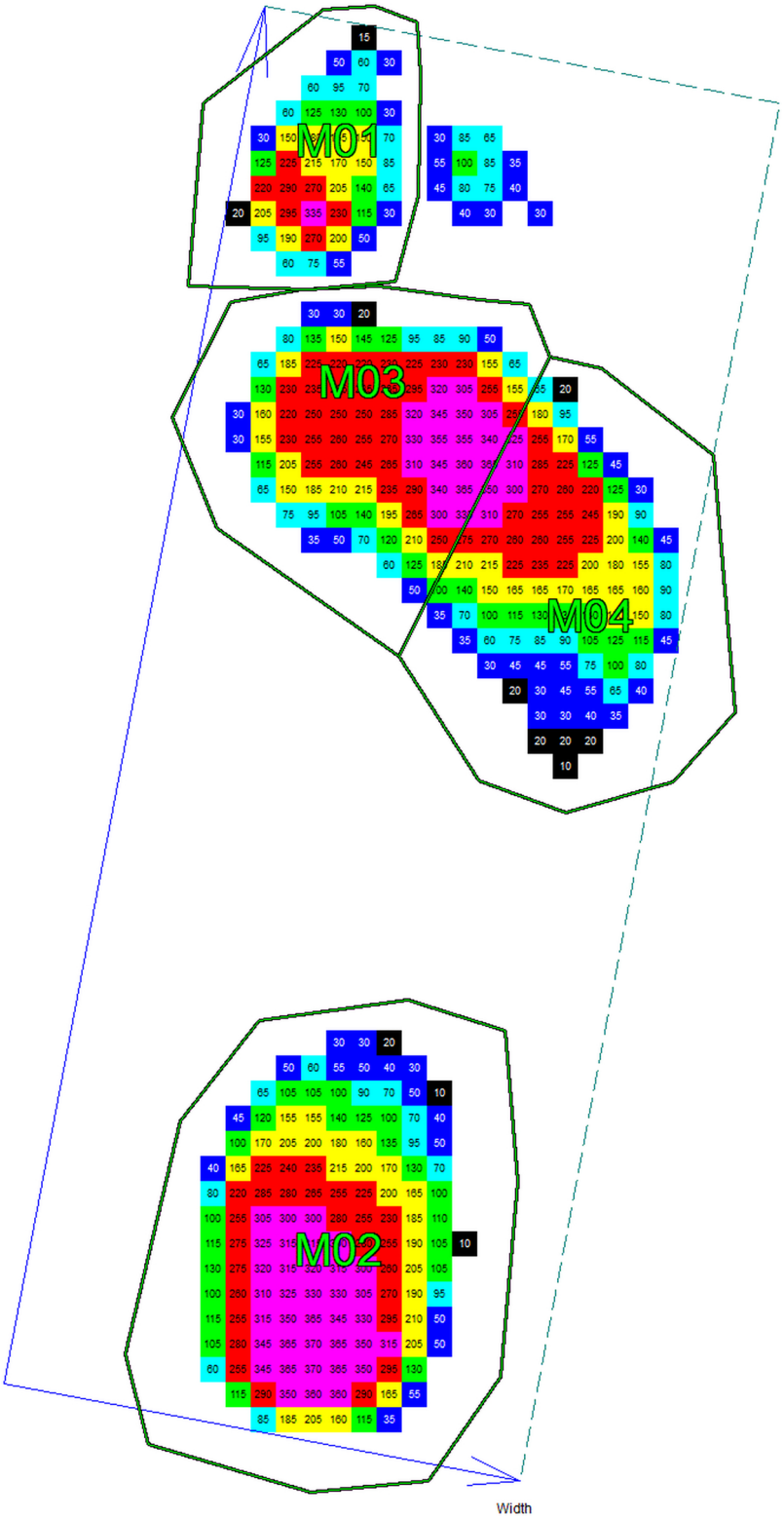

Fig. 1. A typical example of a foot's maximum pressure map for a single gait cycle (stance phase). Using the visual information on pressure data and foot geometry, a rater identifies and segments four foot regions in the following order: (1) the hallux (*M01*); (2) the heel (*M02*); (3) the medial forefoot (*M03*); and (4) the lateral forefoot (*M04*). See Supplement S1 for details on the foot segmentation procedure.

times approximately six months apart. For the inter-rater reliability, a novice rater, trained via the segmentation procedure provided in Supplement S1, performed the segmentations for the same dataset. Following segmentation, both raters independently extracted the vertical impulse values for all foot regions and calculated normalized impulse values and impulse ratios as described below (*normalized impulse measures*).

2.3.2. Calculation of normalized impulse measures

To account for differences in participant characteristics (especially

body weight), the impulses were normalized by dividing the impulse for a given foot region by the total impulse of the foot, yielding five normalized impulse measures: (1) %Hallux; (2) %Heel; (3) %Medial Forefoot; (4) %Lateral Forefoot; and (5) %Unaccounted (impulse portion of remaining foot areas). To evaluate overall foot balance, functionally relevant ratios of the medial to lateral and anterior to posterior impulses occurring across the foot were also calculated: (6) Heel-to-Forefoot Balance: the heel vertical impulse divided by the sum of the heel, forefoot, and hallux impulses. Values range from 0% (completely on forefoot) to 100% (completely on heel); (7) Medial-Lateral Forefoot Balance (with hallux): the sum of the medial forefoot and hallux impulses divided by the sum of the forefoot and hallux impulses. Values range from 0% (completely lateral) to 100% (completely medial); (8) Medial-Lateral Forefoot Balance (without hallux): the medial forefoot impulse divided by the sum of the forefoot impulses. Values range from 0% (completely lateral) to 100% (completely medial); and (9) Hallux-to-Medial Forefoot Balance: the hallux impulse divided by the sum of the hallux and medial forefoot impulses. Values range from 0% (completely on medial forefoot) to 100% (completely on hallux).

2.4. Experimental data analysis

All dependent variables obeyed a normal distribution, as tested by the Kolmogorov-Smirnov test and Q−Q plots [19]. Since left and right feet should be considered dependent [20], we randomly selected either right or left foot data for further analysis. In addition, since the variance between the three footsteps per body side was found to be negligible (analysis of variance, with $p > 0.796$ for all measures), the average of three footsteps per body side was used to obtain, for each of the nine normalized impulse measures, group-ensemble means and standard deviations. Both intra- and inter-rater reliability were analyzed using the intra-class correlation coefficient, ICC(2,1), assessing the agreement in values within the same rater and across two independent raters, respectively. Correlation coefficients were graded according to Fleiss [21], with less than 0.4 indicating poor, 0.4 to 0.75 indicating fair to good, and greater than 0.75 indicating excellent reliability. Data analyses were performed using IBM SPSS Statistics (version 24.0, IBM Corporation, Armonk, New York, USA).

3. Results

Study participants required a total of 6–15 passes across the motion laboratory to generate six clear footsteps (three per foot) atop the pedobarography platform. In Fig. 2, a single participant's force time series for the hallux, heel, medial forefoot, and lateral forefoot can be seen. Presented are the mean force profiles (solid lines) and the ± 1 standard deviation bands (shaded areas) for three steps with the left foot based on the expert rater segmentations. Shortly after heel strike, the force exerted on the heel rapidly rises to an overall maximum value. At that maximum, both the medial and lateral forefoot have already made contact with the ground and experience comparable force profiles, with the lateral forefoot one slightly preceding that of the medial forefoot. Approximately halfway through the stance phase, the force magnitudes of the heel, medial forefoot, and lateral forefoot are similar, suggesting a balanced load distribution across these regions. At this point in time, the force exerted on the hallux slowly increases, while decreasing to zero just slightly after the forefoot loses contact. Note that, for each anatomical foot region, the area under the respective force profile captures the region's vertical impulse (units of *N·s*).

Table 1 lists, for the data presented in Fig. 2, the vertical impulse measures for the three different steps as well as respective means and standard deviations across the steps. Shown are the raw vertical impulse values (top of Table 1), the normalized vertical impulse values (middle of Table 1), and the vertical impulse ratios evaluating overall foot balance (bottom of Table 1). It can be seen that, in agreement with Fig. 2, the heel generates the largest impulse, but that the combination

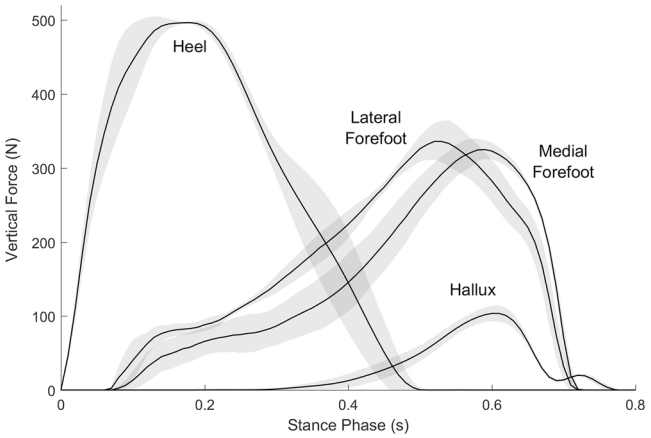

Fig. 2. A single participant's force time series for the four anatomical foot regions: hallux, heel, medial forefoot, and lateral forefoot. Presented are the mean force profiles (solid lines) and the ± 1 standard deviation bands (shaded areas) for three steps with the left foot. For each anatomical foot region, the area under respective force profile captures the region's vertical impulse (units of *N·s*).

Table 1
Example of raw vertical impulse values (*N·s*), normalized vertical impulse values (%), and functionally relevant vertical impulse ratios (%). Shown are left foot data from one participant placing three clear footsteps atop the pedobarography platform during gait (SD: standard deviation across three steps).

Raw vertical impulse values (*N·s*)				
	Step 1	**Step 2**	**Step 3**	**Mean (SD)**
Hallux	15.8	18.6	21.5	18.6 (2.3)
Heel	162.4	140.5	133.5	145.5 (12.3)
Medial Forefoot	87.3	105.4	105.7	99.5 (8.6)
Lateral Forefoot	117.8	123.0	109.7	116.8 (5.5)
Unaccounted	15.9	16.1	15.7	15.9 (0.2)
Total	399.2	403.6	386.1	396.3 (7.4)
Normalized vertical impulse values (%)				
	Step 1	**Step 2**	**Step 3**	**Mean (SD)**
%Hallux	3.9	4.6	5.6	4.7 (0.7)
%Heel	40.7	34.8	34.6	36.7 (2.8)
%Medial Forefoot	21.9	26.1	27.4	25.1 (2.3)
%Lateral Forefoot	29.5	30.5	28.4	29.5 (0.9)
%Unaccounted	4.0	4.0	4.0	4.0 (0.0)
Total	100	100	100	100 (0.0)
Vertical impulse ratios (%)				
	Step 1	**Step 2**	**Step 3**	**Mean (SD)**
Heel-to-Forefoot Balance	42.4	36.2	36.0	38.2 (3.6)
Medial-Lateral Forefoot Balance (with hallux)	46.7	50.2	53.7	50.2 (2.9)
Medial-Lateral Forefoot Balance (without hallux)	42.6	46.2	49.1	46.0 (2.7)
Hallux-to-Medial Forefoot Balance	15.3	15.0	16.9	15.7 (1.0)

of medial and lateral forefoot exceeds that value. In addition, the foot is well balanced medio-laterally (with and without hallux), which again agrees with Fig. 2.

The group-ensemble normalized impulse measures (means and standard deviations) are provided in Table 2. Shown are the normalized vertical impulse values (top of Table 2) and the functionally relevant vertical impulse ratios (bottom of Table 2). In agreement with the exemplary data in Table 1, the heel generates the largest impulse for a single anatomical region; however, the forefoot exceeds that magnitude when combining medial and lateral forefoot. As a consequence, the Heel-to-Forefoot Balance is approximately 33%. In addition, impulses are fairly balanced across medial and lateral sides, with the medial side making a slightly larger contribution to the overall foot impulse (with and without hallux). To demonstrate the clinical utility of the

Table 2
Group-ensemble, normative means and standard deviations of the normalized vertical impulse values (%) and functionally relevant vertical impulse ratios (%).

	Mean	Standard Deviation
Normalized vertical impulse values (%)		
%Hallux	7.9	3.5
%Heel	30.8	5.5
%Medial Forefoot	28.8	5.4
%Lateral Forefoot	25.1	5.1
%Unaccounted	7.4	3.9
Vertical impulse ratios (%)		
Heel-to-Forefoot Balance	33.3	5.5
Medial-Lateral Forefoot Balance (with hallux)	59.2	8.0
Medial-Lateral Forefoot Balance (without hallux)	53.5	7.7
Hallux-to-Medial Forefoot Balance	21.0	8.9

developed segmentation method and of the established normative dataset on vertical impulse measures, Supplement S2 presents and characterizes the foot segmentations and vertical impulse measures for two examples of hindfoot varus.

The intra- and inter-rater reliability analyses of the normalized vertical impulse measures for the same rater (expert) and the two independent raters (expert and novice), respectively, are presented in Table 3. It can be seen that the ICC(2,1) analysis revealed excellent intra- and inter-rater reliability (larger than 0.75 [21]). While the intra-rater reliability within the expert rater ranged from 0.93 for Medial-Lateral Forefoot Balance (without hallux) to 1.00 for %Hallux (mean ± standard deviation: 0.97 ± 0.02), the inter-rater reliability between the expert and novice raters ranged from 0.89 for Medial-Lateral Forefoot Balance (without hallux) to 0.99 for %Hallux (mean ± standard deviation: 0.94 ± 0.03). Of note, all 95% confidence intervals were within the excellent reliability category as the lower limit did not present values below 0.83.

4. Discussion

The present study set out to fill a significant gap in methods for analyzing pedobarographic data of the foot during gait. First, we have developed a pressure segmentation method that, while driven by functional regions of the foot, does not require motion capture and associated expertise. Second, we have proposed a set of normalized outcome measures that are based on the vertical impulse of the identified foot regions and, as such, take the duration a certain force acts on a foot region into account. Finally, using the proposed method, we provide a normative dataset of the normalized impulse measures that can serve as a benchmark for clinical assessment (*see Supplement S2*) and outcome evaluation of foot deformities and gait impairments.

Applying a functional method for identifying foot regions in pedobarographic gait analyses has advantages over more generic techniques [6,11] in that the method specifically targets each individual's foot. For example, a markedly supinated foot may not have any contact at the medial structures, which, unless known, could cause an approach with equally sized regions [6,11] to mislabel the segments (*see Supplement S2*). While a more sophisticated, foot-specific technique for foot segmentation exists [13–15] that additionally exhibits validity and clinical relevance [12], it requires the use of motion capture technology. Such technology, however, is costly and not available in many rehabilitation centers that perform pedobarographic analyses. In addition, it requires clinicians to be trained in its use and have expertise in identifying anatomical landmarks of the foot that are tracked during gait. While the method developed by our team requires training in pressure map segmentation, we have demonstrated that a novice rater can quickly obtain the required knowledge in a short period of time (approximately 20 min) using the provided segmentation guidelines (*see Supplement S1*). In fact, the intra- and inter-rater reliability analyses revealed that, for all nine impulse measures, the agreement within the expert rater as well as between the expert and novice raters was excellent (Table 3). The implications of these results are twofold: First, raters can consistently identify foot regions based only on a footprint (i.e., maximum pressure map) and the knowledge that the foot is a typically developed adult foot. Second, an individual previously unfamiliar with pedobarography and its analysis can quickly learn to apply our segmentation method and obtain outcome measures that are of the same quality as those from an expert with more than 7 years of experience. As such, an efficient technique has been developed that is function-based, reliable, and easy to implement as not reliant on motion capture technology and associated expertise. Nevertheless, the previously proposed, anatomy-based method developed and validated by Giacomozzi et al. [12,13] and Stebbins et al. [14,15] remains of high scientific value in the research domain – and in clinical centers with adequate motion capture infrastructure and expertise.

One limitation of the present work is that having a clinician or gait analysist segment the foot's pressure map contains an element of subjectivity. It should be noted, however, that this is true for many assessment tools that are currently viewed as best clinical practice. Examples are the *Berg Balance Scale* that is the gold standard in assessing balance proficiency in different populations [22,23]; or the *Action Research Arm Test* that is a clinical standard for evaluating upper limb function [24]. Another limitation is that the functional segmentation

Table 3
Intra- and inter-rater reliability of the normalized vertical impulse values (%) and functionally relevant vertical impulse ratios (%). The intra-rater reliability compares the vertical impulse measures for segmentations when performed by the expert rater twice: the first time shortly after experimental data collection, and the second time approximately six months later. The inter-rater reliability compares the vertical impulse measures for segmentations from the expert rater to those from a novice rater. Intra- and inter-rater reliability were quantified via the intra-class correlation coefficient, ICC(2,1).

	Intra-rater		Inter-rater	
	ICC	95% confidence interval	ICC	95% confidence interval
Normalized vertical impulse values (%)				
%Hallux	1.00	1.00–1.00	0.99	0.98–0.99
%Heel	0.99	0.99–0.99	0.98	0.97–0.99
%Medial Forefoot	0.96	0.93–0.97	0.93	0.88–0.95
%Lateral Forefoot	0.95	0.92–0.97	0.93	0.88–0.95
%Unaccounted	0.99	0.98–0.99	0.94	0.90–0.96
Vertical impulse ratios (%)				
Heel-to-Forefoot Ratio	0.99	0.99 –0.99	0.98	0.97–0.99
Medial-Lateral Forefoot Balance (with hallux)	0.95	0.92–0.97	0.92	0.87–0.95
Medial-Lateral Forefoot Balance (without hallux)	0.93	0.89–0.96	0.89	0.83–0.93
Hallux-to-Medial Forefoot Ratio	0.99	0.99–0.99	0.98	0.98–0.99
Mean (Standard Deviation)	**0.97 (0.02)**	**0.95 (0.04)–0.98 (0.01)**	**0.94 (0.03)**	**0.91 (0.05)–0.96 (0.02)**

method and normalized impulse measures have not been fully validated clinically. To address this, we have started to collect a normative dataset of normalized impulse measures in non-disabled children that is stratified by age. Next, a clinical study will be performed to evaluate the capability of the proposed method in detecting various foot deformities in both children and adults (e.g., due to cerebral palsy). However, the data presented in Supplement S2 suggest that the established norms can facilitate the clinical assessment of pathologic feet. A final limitation is that our segmentation only targets the hallux, heel, medial forefoot, and lateral forefoot. This decision was made as these regions have been shown to give sufficient information about a specific foot area without losing critical information about global foot function [9]. However, our method should be extended to conform with the regions described by Giacomozzi et al. [12] and Stebbins et al. [14,15], i.e., by splitting our heel region into medial and lateral components and by including medial and lateral midfoot segments. Using these additions, future work could focus on a quantitative comparison between the proposed technique and the one described by Giacomozzi et al. [12] and Stebbins et al. [14,15].

Conflict of interest

There are no conflicts of interest for the authors of this study.

Ethical approval

The study was approved by the Health Research Ethics Board (HREB) of the University of Alberta, Edmonton, Alberta, Canada (HREB Study ID Number: Pro00042701).

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.gaitpost.2018.09.029.

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