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The Pedar® in-shoe system: Repeatability and normal pressure values

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Abstract

The Pedar® system is one of the most commonly used systems for in-shoe pressure measurement. Good repeatability is necessary to ensure the consistency of measurements on which clinical judgements are based. In addition, there is a need to establish a range of normal in-shoe pressure values, which will help to identify abnormalities. The aim of this study was to assess the repeatability of the Pedar® system and determine the pressure values in normal subjects. Fifty-three subjects, 17 females (32%) and 36 males (68%), were recruited and measurements were performed twice with an average gap of 12 days (range 1–32 days) using only one brand of standardised running shoes (Donnay® International). Peak pressure (PP), contact area (CA), contact time (CT), pressure-time integral (PTI), force-time integral (FTI) and instant of peak pressure (IPP) were calculated. The coefficient of repeatability (CR), expressed as a percentage of the mean, was no greater than 15.3% for all 122 parameters considered. The highest PP areas were under the great toe, with mean (S.D.) equal to 280.4 (83.0) kPa and heel 264.3 (44.1) kPa, followed by the first 248 (70.1) kPa, second 246.5 (48.3) kPa, and third 224.7 (50.4) kPa metatarsal heads. The CA was highest under the heel at 41.54 cm^2. The CT of the metatarsals was 77% to 87% of the total CT while that of the hallux was 75%. The PTI and FTI were highest under the heel. We concluded that the Pedar® system was repeatable. The normal pressure values identified can therefore be used to provide a reference range in clinical practice using this specific type of footwear.

Keywords: Normal; In-shoe; Foot; Pressure; Pedar®

1. Introduction

The average person takes 3–3.5 million steps per year [1] and it is therefore no surprise that a variety of foot problems can occur. The foot is the only anatomical structure that comes in contact with the ground during the gait cycle and also while standing. Hence, it has to withstand any impact generated as a result of the body weight and in turn the ground reaction force produced. A reduction in these forces is thought to be aided by the wearing of shoes, which in turn generates different forces at the foot-shoe insole interface depending on the shoe structure and the material used. Systems using various technologies are able to detect in-shoe pressure distribution [2]. One such system is the Pedar® system. Previous studies have used this system to evaluate disorders in gait and associated foot pathologies [3–5]. However, despite its widespread use, normal pressure values have not yet been published. Hence, the aims of this study were firstly to measure the repeatability of the system and then to identify the normal in-shoe pressure values in healthy adults using a standardised off the shelf neutral running shoe (Donnay® International, DM 04 00 R) covering UK sizes 3–11 (Fig. 1). The results will inform other Pedar® users of the normal range of in-shoe pressure values in healthy adults for the shoe brand used, which can be set as standards for comparison with pathological cases or the assessment of orthoses using this specific brand of sports shoe. The values determined can therefore be applied in subsequent studies.

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Fig. 1. Donnay® International (DM 00 04 00 R) shoes.

2. Materials and methods

Fifty-three volunteers aged between 18 and 65 years were recruited for the study. Subjects were excluded if they suffered from pain in their feet within the last 6 months, had any surgery on their feet at any time in their life, presented with congenital or acquired deformities of the feet on clinical examination or any other disability that might in some way affect their gait (e.g. flat feet, use of walking aids, visual and/or hearing impairments or any problems in the lower limb or spine that might affect normal gait). Age, gender, height, weight, foot size and size of shoes currently worn were recorded. The study was approved by the local Research Ethics Committee and all subjects gave their informed consent.

The mean age, weight and height of the group were 34.4 years (range 19–52 years), 74.2 kg (range 44–120 kg) and

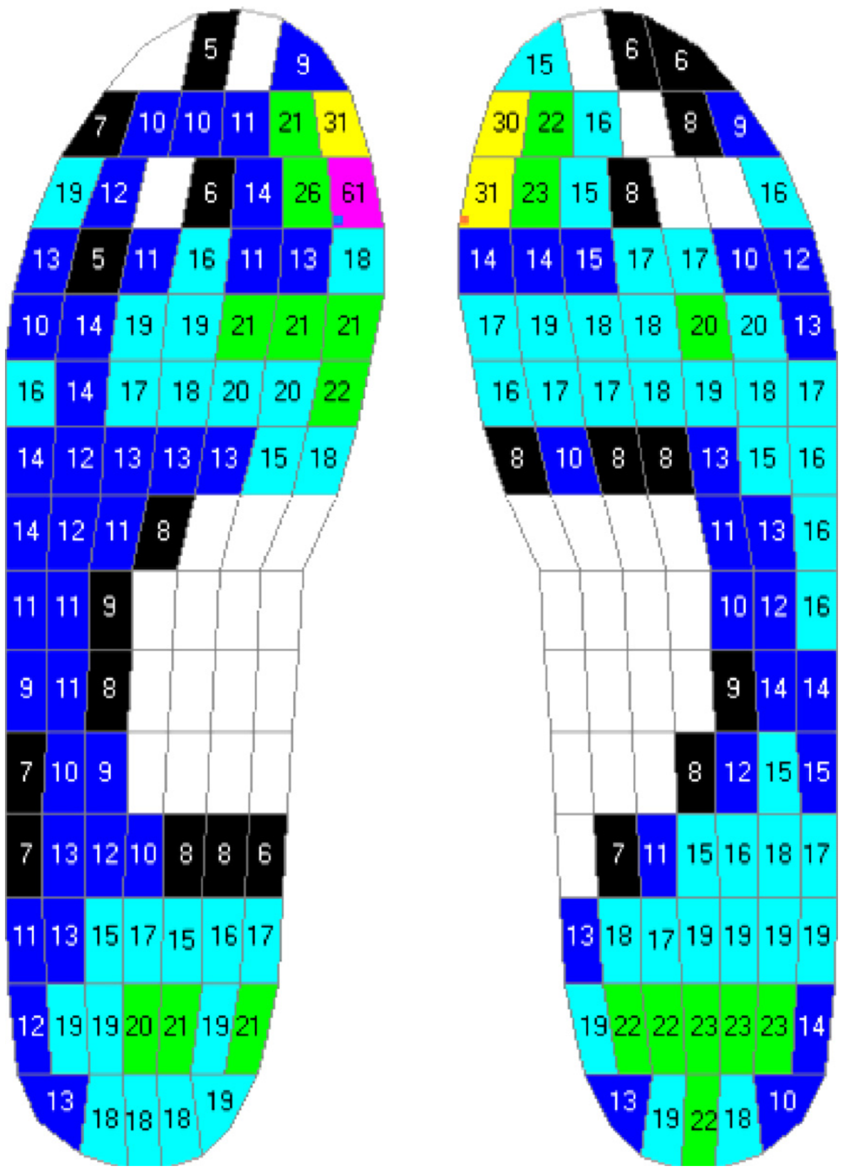

Fig. 2. Pedar insoles pressure output.

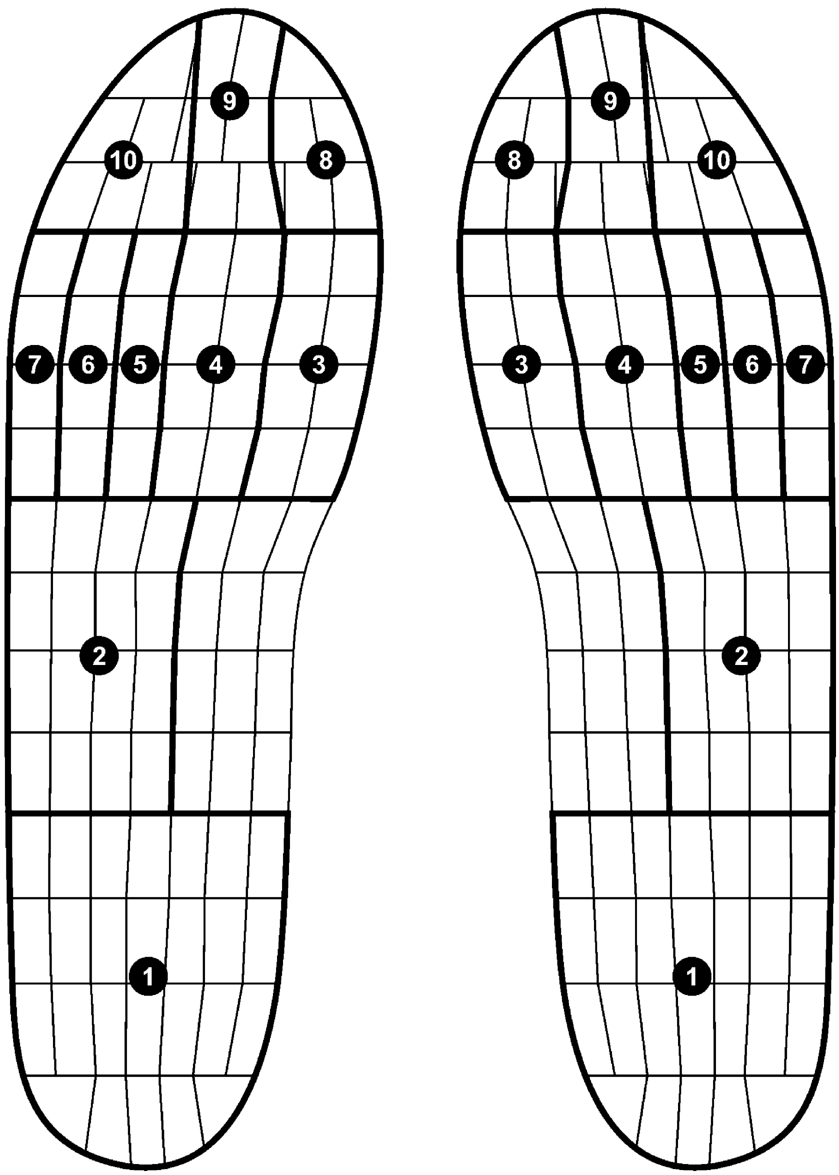

Fig. 3. The 10 regions of the left and right insoles.

1.70 m (range 1.51–1.85 m), respectively. The mean number of days between repeated data collections for the same individual was 11.8 days (range 1–32 days). Two volunteers were unable to attend a second session. Of the 53 subjects, 17 (32%) were female and 36 (68%) were male.

The Pedar® in-shoe system has insoles comprising 99 capacitive sensors (Fig. 2). The insoles were calibrated up to 500 kPa using the trublu® calibration device according to the manufacturer's manual. In addition, the insoles were assessed on a daily basis before the start of data collection and after completion of data collection to check the accuracy of the individual sensors using the trublu® calibration device. The Pedar® insoles were inserted into the particular Donnay® model of shoe and connected to the Pedar® box. Eight steps were collected per straight line walk and eight walks were collected per session on the same walkway using a frequency set at 50 Hz. The same was repeated during the second session.

The foot was divided into 10 regions: heel, mid foot, first, second, third, fourth and fifth metatarsal, hallux, second toe and toes 3–5 (Fig. 3). The software for the Pedar® system calculates information on 18 parameters. Evaluation was carried out on six of the most clinically relevant parameters: peak pressure (PP) kPa, contact area (CA) cm^2, contact time (CT) ms, pressure-time integral (PTI) kPa s, force-time integral (FTI) N s and instant of peak pressure (IPP) ms. The total contact time was calculated also. Measurements taken from the left and right foot were analysed separately for repeatability. In total, 122 parameters were assessed.

Table 1
Mean, standard deviation (S.D.) and coefficient of repeatability (CR) for the peak pressure (PP), contact area (CA), contact time (CT), pressure-time integral (PTI), force-time integral (FTI) and instant of peak pressure (IPP) for the 10 regions of the foot, left and right sides combined

Pedar® masks	PP (kPa)		CA (cm^2)		CT (ms)		PTI (kPa s)		FTI (N s)		IPP (ms)	
	Mean (S.D.)	CR[a]	Mean (S.D.)	CR	Mean (S.D.)	CR	Mean (S.D.)	CR	Mean (S.D.)	CR	Mean (S.D.)	CR
Heel	264.3 (44.1)	2.4	41.54 (6.4)	1.2	470.1 (103.9)	3.6	64.58 (12.7)	3.5	145.03 (37.2)	3.9	78.92 (28.5)	8.0
Mid foot	109.0 (38.5)	5.4	21.58 (6.3)	2.5	511.3 (116.8)	4.2	39.18 (17.5)	5.7	43.08 (27.9)	5.5	250.0 (108)	9.8
1 MT[b] Head	248.0 (70.1)	3.9	12.29 (2.3)	2.7	498.9 (84.1)	4.4	65.43 (22.3)	4.8	48.05 (19.1)	4.9	502.8 (55.8)	2.8
2 MT Head	246.5 (48.3)	2.6	12.67 (2.0)	2.1	523.6 (73.7)	3.3	65.52 (16.3)	3.8	52.19 (16.2)	4.8	496.8 (55.5)	2.9
3 MT Head	224.7 (50.4)	2.9	6.79 (1.0)	1.2	549.3 (68.9)	3.6	62.96 (16.3)	4.0	28.97 (10.1)	4.4	487.7 (57.4)	2.8
4 MT Head	161.0 (49.7)	4.6	6.26 (1.1)	2.8	557.0 (76.8)	3.2	49.29 (17.1)	5.5	20.08 (8.8)	5.2	469.1 (62.5)	2.8
5 MT Head	141.6 (58.4)	7.7	6.23 (1.3)	3.0	543.9 (98.2)	2.8	46.53 (20.4)	7.6	18.93 (9.6)	7.1	445.2 (74.4)	3.5
Hallux	280.4 (83.0)	5.5	7.86 (1.4)	3.0	487.2 (112.3)	3.3	60.29 (20.6)	7.6	24.83 (10.7)	7.9	534.3 (60.1)	2.7
Second toe	138.9 (55.3)	10.5	7.72 (1.8)	4.5	394.5 (110.8)	4.3	28.93 (13.3)	13.6	9.89 (5.1)	14.7	530.4 (61.8)	3.1
3–5 Toe	121.3 (45.5)	8.7	7.48 (2.3)	6.0	429.2 (110.5)	6.7	29.52 (12.9)	9.7	9.19 (5.4)	10.8	523.1 (62.4)	2.9

[a] CR – Expressed as a percentage of the mean.
[b] MT = Metatarsal.

3. Statistical methods

Data were explored for outliers and distribution. Normality was investigated using the Shapiro-Wilks test. Plausibly Normal data were summarized using the mean and standard deviation, presented in the format mean (standard deviation). Repeated measures analysis of variance (ANOVA) was used to investigate the variability of pressures measured in walks conducted on the same day and on different days. The usual checks for violations of the assumptions underlying the ANOVA procedure were carried out. The Huynh-Feldt correction was applied for non-sphericity. The Bonferroni correction for multiple comparisons was applied when means were compared post hoc. The significance level used was 5% and the confidence level was 95%. The standard deviations of the between-walk differences were used to determine the coefficient of repeatability of each system [6]. The coefficient of repeatability (CR) was expressed as a percentage of the mean using the formula ‘‘(coefficient of repeatability/mean) $\times$ 100’’. A reference range for normal pressures was calculated as ‘‘mean $\pm$ 1.96 $\times$ standard deviation’’.

4. Results

Pressure values were plausibly normally distributed (the value of the Shapiro-Wilks statistic was not significant in each case).

The mean was calculated for the different foot regions on Days 1 and 2 for right and left foot separately. The CR (expressed as a percentage of the mean) was less than 10% in 93.4% of the parameters (114 of 122) and more than 10% in PP left second toe (11.9%), PTI left second toe (14.2%), PTI right second toe (12.9%), PTI right toes 3–5 (10.7%), FTI left second toe (15.3%), FTI right second toe (14.0%), FTI right toes 3–5 (12.8%) and IPP left mid foot (10.6%). Since there were no significant between-side differences in mean or standard deviation, the CRs were combined for right and left and are presented in Table 1.

The highest pressure was found under the hallux (280.4 (83.0) kPa), followed closely by pressure under the heel (264.3 (44.1) kPa). The first, second and third metatarsal heads bore pressures of 248 (70.1) kPa, 246.5 (48.3) kPa and 224.7 (50.4) kPa, respectively. The normal peak pressure values are depicted in Table 1. Reference ranges are presented in Table 2.

The heel had the largest contact area within the insoles (41.54 (6.4) cm^2). This was followed by the midfoot (21.58 (6.3) cm^2), second (12.67 (2.0) cm^2) and then the first metatarsal region (12.29 (2.3) cm^2). The contact area gradually reduced from the first to the fifth metatarsal head regions. The contact area of the hallux was small at 7.86 (1.4) cm^2. The fourth, third and the fifth metatarsals were the regions showing longest contact time. With the exception of the second toe, the contact times of the various regions in the foot were comparable in the range of 450–550 ms.

The highest pressure-time integral values were, in decreasing order, in the regions of the second, first metatarsal head, heel, third metatarsal head region and hallux. Means of these values were in the range of 60–65 kPa s. The force-time integral was highest under the heel (145.03 (37.2) N s). This figure was three times higher than

Table 2
Reference range for the Peak Pressure (PP) in the 10 regions of the foot

Pedar	Reference range (kPa)	
	Lower bound	Upper bound
Heel	177.9	350.7
Mid foot	33.54	184.5
1 MT[a] Head	110.6	385.4
2 MT Head	151.8	341.2
3 MT Head	125.9	323.5
4 MT Head	63.59	258.4
5 MT Head	27.1	256.1
Hallux	117.7	443.1
Second toe	30.51	247.3
3–5 Toe	32.12	210.5

[a] Metatarsal

that under the second and first metatarsal heads and the mid-foot regions, which were the next highest. IPP depicted the progression of peak pressure in various areas of the foot. In this study, we found the normal progression of the pressure from the heel to the midfoot, then to the lateral border of the forefoot from the fifth to the first metatarsal region, and next from the fifth toe to the Hallux. This coincides with the natural progress of the foot through the gait cycle: heel strike, foot flat and toe off.

5. Discussion

The coefficients of repeatability of the Pedar® system were determined and reference ranges of normal foot pressure values of the Pedar® in-shoe system were identified for the Donnay® running shoes utilised. Kernozek et al. [7] tested the Pedar® system on a treadmill and reported excellent reliability. However, the protocol was not sufficiently robust to draw firm inferences. Murphy et al. [8] demonstrated excellent reliability in the midfoot region for the parameters of contact area and plantar pressure. However, the number of subjects used and the parameters assessed were few.

From the 122 parameters assessed in our study, the highest CR was 15.3%. The majority of the parameters (114/122, 93.4%) had a CR less than 10%. Taking into consideration that no two foot steps in a ''normal'' subject are identical due to sway during gait [9], the highest CR achieved is therefore clinically acceptable, which in turn renders the Pedar® system repeatable.

The normal in-shoe pressure values were measured. The highest PP in the shoe was in the region of the hallux, followed by pressures in the heel and the first, second and third metatarsal regions. Higher pressure in the hallux may be due to the pressure exerted during toe off when the whole body weight passes through it. Such pressures in the hallux could be highly deforming when wearing tight shoes with a narrow toe box. It may be the reason for the high incidence of hallux valgus in the shod population. The largest CA was in the heel region followed by the midfoot. The CA of the hallux was only 8 cm^2, approximately.

The CT was longest in the metatarsal regions. The metatarsal heads bear weight for 77% to 87% of the total foot CT, while the hallux accounts for 75%. The PTI was highest in the heel, first, second, third metatarsal region and in the great toe. This corresponds with the findings of Kernozek et al. [7]. The FTI was three times as high in the heel as compared to the other regions of the foot.

The means and standard deviations observed in this study have been used to define reference ranges for normal pressures for the specific shoes used in this study. These ranges can then be used in clinics while examining patients with foot problems, to help identify cases with borderline problems, and to compare and contrast pressures in high risk feet (e.g. the diabetic foot) using these specific sports shoes. Other brands and models can be utilised after determining their respective specific reference ranges. Reference ranges can make it easier for inexperienced users to understand subtle deviations from the norm. However, care should be exercised in using the reference ranges, and the whole clinical picture must be taken into account when making clinical judgements.

Current studies in our Institute are evaluating a range of other running shoe brands for normal pressures and reference ranges. Common reference ranges across the various brands would be highly beneficial. Alternatively, a database of shoes and their reference ranges could be established.

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