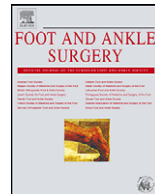




Contents lists available at [ScienceDirect](#)

Foot and Ankle Surgery

journal homepage: www.elsevier.com/locate/fas



Repeatability of the Pedar-X[®] in-shoe pressure measuring system

A.K. Ramanathan MCh(Orth), P. Kiran MCh(Orth), G.P. Arnold MSc, W. Wang PhD, R.J. Abboud PhD*

Institute of Motion Analysis & Research (IMAR), Department of Orthopaedic and Trauma Surgery, TORT Centre, Ninewells Hospital & Medical School, University of Dundee, Dundee DD1 9SY, UK

ARTICLE INFO

Article history:

Received 24 March 2009
Received in revised form 15 May 2009
Accepted 15 May 2009

Keywords:

Pedar-X[®]
Foot pressure
Biomechanical assessment
Repeatability
Coefficient of variation

ABSTRACT

Background: The Pedar-X[®] is one of the newer versions of in-shoe pressure measuring devices and the current study aimed to assess the repeatability of this device.

Methods: Twenty-seven healthy male volunteers were recruited and requested to walk on a 26-foot walkway wearing appropriate sized standardised off-the-shelf neutral running shoes (Donnay[®] International). The Pedar-X[®] insole was sandwiched between the foot and the shoe. Data were collected on two occasions, one week apart. Clinically relevant parameters studied were contact area, contact time in percentage roll over process, maximum force, pressure–time integral, force–time integral, peak pressure, mean force and mean area.

Results: Repeatability was analysed using the coefficient of variation. Of the 160 parameters considered, 93.1% revealed a coefficient of variation value of less than 25. Heel and the metatarsal head areas were the most repeatable.

Conclusion: The Pedar-X[®] in-shoe pressure measuring system is repeatable and as such can be used as a valuable tool in the assessment of in-shoe plantar pressure distribution.

© 2009 European Foot and Ankle Society. Published by Elsevier Ltd. All rights reserved.

1. Introduction

The foot is one of the most complex biomechanical structures in the human body. As quoted by Leonardo da Vinci in the 15th century, “the human foot is a masterpiece of engineering and a work of art”. The normal foot functions in an extremely efficient manner in carrying the torso and off loading the body’s weight to the ground while standing and walking. It also deals with the ground reaction forces (GRF) and takes up the cyclical load throughout the gait cycle as it is the only part of the normal human body that comes in contact with the ground during bipedal locomotion. It constantly adapts during walking, jogging, running and jumping demonstrating excellent maneuverability. A normal human walks approximately 3.5 million steps per year [1].

Various quantification equipment using different technologies are available for foot pressure analysis [2]. Many authors have previously used in-shoe pressure technology for evaluating the pressure distribution under the foot, which in turn is essential for accurate assessment of foot and gait pathologies [3–7]. The repeatability of earlier models of the Pedar[®] in-shoe system has been evaluated by Kernozek et al. [8] and Putti et al. [9].

Pedar-X[®] is a relatively new product among the in-shoe pressure measuring devices. As clinical decisions and treatment

strategies are planned based upon data from these invaluable systems, no more emphasis is needed for utilising highly dependable equipment. Repeatability is one of the elements which may define such dependability. This study was designed to assess the repeatability of the Pedar-X[®] in-shoe pressure measurement system.

2. Materials and methods

After obtaining the University Research Ethics Committee’s approval, the study was conducted by recruiting 27 healthy male volunteers. Participants with foot and ankle, knee, hip and spine pathologies, previous injuries and/or surgeries to the foot and ankle, limb length discrepancies and those with any clinical problems that could potentially affect their gait were excluded. On acquiring informed consent, anthropometric measurements including height, weight, shoe size and foot dimensions were recorded. The mean age, weight, height and body mass index (BMI) were 27.2 years (range 20–44 years), 75.7 kg (range 52.8–101.2 kg), 1.74 m (range 1.64–1.90 m) and 24.9 (range 19.39–31.45) respectively. Subjects were requested to walk at their natural self-selected speed along a 26-foot long walkway whilst wearing appropriate sized standardised neutral running shoes (Donnay[®] International) with the Pedar-X[®] insole sandwiched between the foot and the inside of the shoe. An average of three walks was obtained for each subject. A similar trial was repeated 1 week later.

* Corresponding author. Tel.: +44 0 1382 496276; fax: +44 0 1382 496200.
E-mail address: r.j.abboud@dundee.ac.uk (R.J. Abboud).

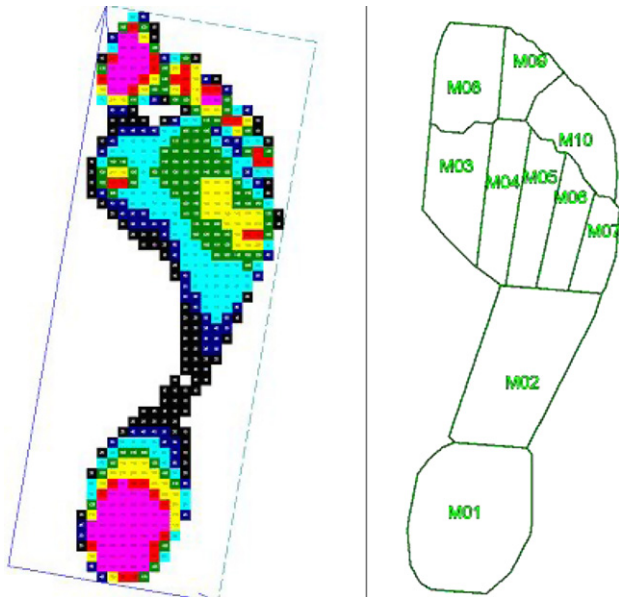


Fig. 1. Areas of the foot and the corresponding Pedar-X[®] masks.

The newer Pedar-X[®] system has various advantages over older versions in that it is a mobile system with three options for transferring data to a computer (cable, Bluetooth[®], or memory card). It also has a choice of two sampling frequencies (50 Hz or 100 Hz). It weighs only 360 g and the insoles which contain 99 embedded sensors, have a thickness of 1.9 mm. These insoles have a pressure range of 15–1200 kPa. The frequency chosen for this study was 50 Hz. Everyday, before and after data collection, the insoles were checked using the Trublu[®] calibrating system to ascertain that all sensors were functioning accurately.

Using “automask” software, the foot was divided into 10 areas: M1—heel, M2—mid foot, M3–M7—first to fifth metatarsal heads respectively, M8—hallux, M9—second toe and M10—three to five toes (Fig. 1). The most clinically relevant parameters studied were: contact area (CA) (cm²), contact time in percentage roll over process (CT%ROP), maximum force (MF) (N), pressure–time integral (PTI) (kPa s), force–time integral (FTI) (N s), peak pressure (PP) (kPa), mean force (MeF) (N), mean area (MeA) (cm²). Measurements from both feet were analysed separately for repeatability. These accounted for 160 evaluated parameters.

2.1. Statistical methods

Data were tested for outliers and summarised using descriptive statistics. The methods of Bland and Altman [10] were used to assess the repeatability. As suggested by Hopkins [11], the coefficient of variation (CV) was used to calculate repeatability. The CV expresses the typical error as a percentage of the mean and is defined as (SEM/mean) × 100, where SEM is the standard error of measurement and mean is the mean of the whole measurements (i.e. on both occasions). SEM is equal to Diff_{SD}/√2 where Diff_{SD} is the standard deviation of the differences between repeated measurements. The higher the CV value, the weaker the repeatability. The differences between the measurements over two occasions and the averages from the trials were calculated to test the repeatability.

3. Results

Corresponding areas of both feet showed near similar repeatability for most of the parameters (Tables 1 and 2).

Table 1 Mean, standard deviation (SD) and coefficient of variation (CV) for the various parameters under the areas of interest in the left foot.

Pedar-X [®] mask areas	Left foot																							
	CA (cm ²)		MeF (N)		PP (kPa)		PTI (kPa s)		FTI (N s)		MF (N)		MeA (cm ²)		CT(%ROP)									
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD								
Heel	46.2	3.0	4.6	227.9	26.9	8.4	178.7	23.9	9.5	60.9	14.0	16.2	162.7	30.5	13.2	536.8	58.1	7.7	29.1	4.1	9.9	91.2	14.1	11.0
Mid foot	26.4	2.2	6.0	74.2	15.5	14.7	88.1	22.7	18.2	40.8	26.6	46.1	53.7	20.5	27.0	137.3	24.0	12.3	16.9	2.3	9.7	89.6	6.3	5.0
1st MT head	14.0	1.5	7.6	56.6	13.1	16.3	166.4	32.8	13.9	48.5	13.1	19.0	40.1	12.5	22.1	147.0	33.9	16.3	8.5	1.7	14.4	82.4	13.4	11.5
2nd MT head	14.0	1.1	5.5	62.2	12.8	14.5	161.6	33.6	14.7	47.5	13.1	19.6	44.0	12.8	20.6	156.1	32.4	14.7	9.5	1.6	12.1	83.9	11.0	9.3
3rd MT head	7.5	0.6	5.5	35.5	7.0	13.8	155.3	28.7	13.1	47.7	12.1	18.0	25.2	6.2	17.5	84.0	12.9	10.8	5.5	0.9	11.1	86.7	9.6	7.9
4th MT head	7.2	0.4	3.4	30.7	6.2	14.3	124.9	19.1	10.8	42.7	10.3	17.1	21.8	5.1	16.5	67.1	9.5	10.0	5.5	0.9	11.6	89.2	9.5	7.5
5th MT head	6.7	0.5	5.2	22.4	4.2	13.3	94.0	15.5	11.6	34.7	7.6	15.5	16.0	3.4	15.3	48.3	7.2	10.6	4.7	0.7	10.4	85.7	9.0	7.4
Hallux	8.6	1.3	11.0	30.5	9.2	21.4	173.7	44.6	18.2	41.8	13.2	22.3	21.3	7.4	24.6	100.4	27.2	19.2	4.4	1.1	18.0	71.7	17.9	17.6
2nd toe	8.1	1.9	16.3	15.5	3.8	17.4	91.5	22.1	17.1	22.1	5.2	16.7	10.7	2.9	19.1	51.5	11.0	15.2	3.4	0.9	17.8	59.8	14.4	17.0
3rd–5th toe	8.5	1.7	13.9	12.7	4.3	24.1	93.3	29.7	22.5	25.6	9.4	25.9	8.8	2.9	23.4	38.7	8.2	14.9	3.6	1.0	19.1	68.0	12.2	12.7

CA—contact area; MeF—mean force; PP—peak pressure; PTI—pressure–time integral; FTI—force–time integral; MF—maximum force; MeA—mean area; CT(%ROP)—contact time in percentage roll over process; MT—metatarsal;

Table 2
Mean, standard deviation (SD) and coefficient of variation (CV) for the various parameters under the areas of interest in the right foot.

	CA (cm ²)			MeF (N)			PP (kPa)			FTI (N s)			PTI (kPa s)			MF (N)			MeA (cm ²)			CT(%ROP)		
	Mean	SD	CV	Mean	SD	CV	Mean	SD	CV	Mean	SD	CV	Mean	SD	CV	Mean	SD	CV	Mean	SD	CV	Mean	SD	CV
Heel	46.2	2.9	4.5	220.0	35.2	11.3	173.8	21.6	8.8	156.7	30.6	13.8	517.1	66.0	9.0	28.8	4.4	10.7	89.5	10.1	8.0			
Mid foot	27.3	1.5	3.8	76.1	13.4	12.4	87.0	19.8	16.1	57.4	40.5	49.9	138.9	21.9	11.2	17.6	2.3	9.4	89.4	6.0	4.7			
1st MT head	14.0	1.3	6.6	57.3	14.4	17.8	163.9	40.3	17.4	40.6	11.8	20.6	148.1	29.7	14.2	8.7	1.6	12.8	81.1	11.7	10.2			
2nd MT head	14.4	0.9	4.6	60.5	11.8	13.8	158.6	32.2	14.4	42.9	10.7	17.7	154.3	26.2	12.0	9.6	1.6	12.1	82.1	9.1	7.8			
3rd MT head	7.3	0.5	4.8	33.6	7.4	15.5	147.2	22.3	10.7	23.9	6.7	19.7	80.0	13.2	11.6	5.3	0.8	10.7	84.6	7.5	6.2			
4th MT head	6.9	0.4	4.0	30.1	6.5	15.2	124.1	16.0	9.1	21.4	6.1	20.3	66.0	9.4	10.0	5.2	0.8	11.2	88.2	7.4	6.0			
5th MT head	7.3	0.8	7.2	23.2	6.9	21.2	107.6	24.8	16.3	16.6	5.6	24.1	50.5	11.7	16.3	5.1	0.9	12.2	87.2	8.6	7.0			
Hallux	8.2	1.3	11.2	33.8	12.3	25.8	189.9	42.9	16.0	23.9	9.5	28.2	105.7	23.4	15.6	4.5	1.1	17.4	72.6	13.4	13.1			
2nd toe	8.6	1.8	14.7	15.6	4.7	21.5	105.7	22.5	15.1	11.0	3.9	25.2	54.6	14.9	19.2	3.5	1.0	19.2	58.7	11.0	13.2			
3rd-5th toe	8.3	1.9	15.9	10.7	4.9	32.2	69.5	19.0	19.4	7.5	3.2	29.8	36.9	10.9	20.9	3.0	0.9	21.8	59.5	14.3	17.0			

CA—contact area; MeF—mean force; PP—peak pressure; PTI—pressure-time integral; FTI—force-time integral; MF—maximum force; MeA—mean area; CT(%ROP)—contact time in percentage roll over process; MT—metatarsal.

3.1. Contact area

In descending order, on the left foot, the system showed high repeatability under the 4th metatarsal head, heel, 5th, 2nd and 3rd metatarsal heads while on the right, high repeatability was shown under the mid foot, 4th metatarsal head, heel, 2nd and 3rd metatarsal heads. The highest repeatability was under the left 4th metatarsal head (CV 3.4) while the left 2nd toe region (CV 16.3) was the least repeatable.

3.2. Mean force

The heel, 5th, 3rd, 4th and 2nd metatarsal head areas of the left foot and the heel, mid foot, 2nd, 4th and 3rd metatarsal head areas of the right foot showed high repeatability, in descending order. The highest repeatable area was the left heel (CV 8.4) while the least repeatable was the right 3rd to 5th toe region (CV 32.2).

3.3. Peak pressure

In descending order, high repeatability was noted under the heel, 4th, 5th, 3rd and 1st metatarsal head areas of the left foot and heel, 4th, 3rd and 2nd metatarsal heads of the right foot. The right heel (CV 8.8) was the most repeatable area and the left 3rd to 5th toe region (CV 22.5) was the least repeatable.

3.4. Pressure-time integral

With PTI, the Pedar-X[®] showed high repeatability under the 5th metatarsal head, heel, 2nd toe, 4th and 3rd metatarsal heads of the left foot and heel, 3rd, 2nd and 4th metatarsal heads of the right foot, in descending order. The highest repeatability was noticed under the right heel (CV 14.3) while the least repeatability was found under the right mid foot area (CV 82). CV value for this parameter under the right mid foot region was the highest and was the only value greater than 50 in this study.

3.5. Force-time integral

In descending order, the system revealed high repeatability under the heel, 5th, 4th and 3rd metatarsal heads and 2nd toe on the left and heel, 2nd, 3rd and 4th metatarsal head regions on the right. The left heel (CV 13.2) was the most repeatable area while the right mid foot (CV 49.9) was the least repeatable.

3.6. Maximum force

The heel, 4th, 5th and 3rd metatarsal head regions and the mid foot of the left and the heel, 4th metatarsal head, mid foot and 3rd metatarsal head of the right were the highly repeatable areas, in descending order. Highly repeatable region was the left heel (CV 7.7) while the least repeatable was the right 3rd to 5th toe area (CV 20.9).

3.7. Mean area

Pertaining to the MeA, the Pedar X[®] showed high repeatability under the mid foot, heel, 5th, 3rd and 4th metatarsal heads of the left foot and mid foot, heel, 3rd and 4th metatarsal heads of the right, in descending order. The highest repeatability was demonstrated by the right mid foot (CV 9.4) and the least repeatability by the right 3rd to 5th toe region (CV 21.8).

3.8. Contact time in percentage roll over process

In descending order, high repeatability was demonstrated under the mid foot, 5th, 4th, 3rd and 2nd metatarsal heads on the

left and mid foot, 4th, 3rd and 5th metatarsal head regions on the right. The right mid foot (CV 4.7) was the most repeatable while the left hallux (CV 17.6), the least.

4. Discussion

Dynamic pedobarography is a constantly expanding field with new devices being designed and employed for various clinical applications. The repeatability of the earlier Pedar[®] in-shoe systems were evaluated [8,9]. During the normal gait process, the heel initiates the ground contact of the foot and progressively the load is spread across the various areas of the foot, among which the metatarsal heads' region is one of the most important. The Pedar-X[®] system showed a similar repeatability pattern for most of the foot areas considering the various parameters evaluated. When comparing the values of both feet (right and left), the majority of parameters showed similar repeatability for various foot regions.

The results of the current study are consistent with that of Putti et al. [9]. Both studies reveal that the 2nd toe and 3rd to 5th toe areas show comparatively less repeatability. This shows that the values under these areas need to be considered with caution. More emphasis needs to be given to these regions while designing pressure measuring insoles.

Murphy et al. [12] found that the contact area and plantar pressure parameters in the mid foot region revealed excellent reliability. In the current study, the mid foot region revealed variable repeatability for different parameters as it was the highest repeatable area for MeA and CT%ROP while it was the least repeatable region for PTI and FTI. The study by Putti et al. [9] also showed that the mid foot region was one of the few areas which was less repeatable for a particular parameter considered (instant of peak pressure).

Accounting for both feet in the current study, there is a total of 160 parameters. Of these, 93.1% revealed a CV of less than 25, 6.3% had a CV between 25 and 50, 0.6% had a CV of more than 50 with no CV value being more than 100. Considering the normal variations present during walking [2] and pressure variations in each step [13], these values of repeatability are acceptable.

The current study showed that all parameters are repeatable. From the outcome data highlighted in this study on CA, MeF, PP, PTI, FTI, MF, MeA and CT%ROP, it can be acknowledged that the findings support the application of Pedar-X[®] in-shoe pressure capturing system as a dependable clinical investigation modality. Such applications include: pre-operative assessment of foot deformity, objectively assessing the success of corrective foot surgery, assessment of rheumatoid and diabetic foot disorders, and evaluating the pressure distribution under the feet in various common foot pathologies. However, foot pressure measurements can only supplement a good clinical judgement. The most important contribution of pedobarography would be in providing objective data and supplementing the clinicians' clinical assess-

ment, thereby aiding them in deciding the treatment option which would give the best clinical outcome.

5. Conclusion

This study concludes that the Pedar-X[®] system is repeatable. The studied parameters followed a pattern of almost identical repeatability in both feet. The system showed a motif of greater number of parameters with higher repeatability under the heel and the metatarsal head regions. The mid foot and hallux showed a moderate degree of repeatability. The accuracy of the system would improve if the repeatability under the comparatively less repeatable areas was also addressed.

Conflict of interest statement

The authors have no personal, professional or financial affiliations with other people or organisations that may be perceived to have biased the presentation.

Acknowledgements

The authors would like to thank Mr I. Christie for his technical assistance. The study was internally funded by the Institute of Motion Analysis & Research.

References

- [1] Tudor-Locke C, Bassett Jr DR. How many steps/day are enough? Preliminary pedometer indices for public health. *Sports Med* 2004;34(1):1–8.
- [2] Abboud RJ, Rowley DI. Foot pressure measurement. In: Helal B, Rowley DI, Cracchiolo III A, Myerson MS, editors. *Surgery of Disorders of the Foot and Ankle*. Martin Dunitz Limited; 1996. ISBN 1-85317-212-X.123–38.
- [3] Grampp J, Willson J, Kernozek T. The plantar loading variations to uphill and downhill gradients during treadmill walking. *Foot Ankle Int* 2000;21(3):227–31.
- [4] Hsiao H, Guan J, Weatherly M. Accuracy and precision of two in-shoe pressure measurement systems. *Ergonomics* 2002;45(8):537–55.
- [5] Mao DW, Li JX, Hong Y. The duration and plantar pressure distribution during one-leg stance in Tai Chi exercise. *Clin Biomech* 2006;21(6):640–5.
- [6] Hurkmans HLP, Bussmann JBJ, Benda E, Verhaar JAN, Stam HJ. Accuracy and repeatability of the Pedar[®] Mobile system in long-term vertical force measurements. *Gait Posture* 2006;23(1):118–25.
- [7] Carl HD, Pfander D, Swoboda B. Assessment of plantar pressure in forefoot relief shoes of different designs. *Foot Ankle Int* 2006;27(2):117–20.
- [8] Kernozek TW, LaMott EE, Dancisak MJ. Reliability of an in-shoe pressure measurement system during treadmill walking. *Foot Ankle Int* 1996;17(4):204–9.
- [9] Putti AB, Arnold GP, Cochrane L, Abboud RJ. The Pedar in-shoe system: repeatability and normal pressure values. *Gait Posture* 2007;25(3):401–5.
- [10] Bland JM, Altman DG. Statistical methods for assessing agreement between two methods of clinical measurement. *Lancet* 1986;1(8476):307–10.
- [11] Hopkins WG. Measures of reliability in sports medicine and science. *Sports Med* 2000;30(1):1–15.
- [12] Murphy DF, Beynonn BD, Michelson JD, Vacek PM. Efficacy of plantar loading parameters during gait in terms of reliability, variability, effect of gender and relationship between contact area and plantar pressure. *Foot Ankle Int* 2005;26(2):171–9.
- [13] Akhlaghi F, Daw J, Pepper M, Potter MJ. Inshoe step-to-step pressure variations. *Foot* 1994;4:62–8.