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Normal pressure values and repeatability of the Emed® ST4 system

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Abstract

The aims of this study were to assess the repeatability of the Emed® ST4 system and identify the range of pressure values observed in the normal foot. Fifty-three healthy subjects, 17 females (32%) and 36 males (68%), were recruited. Measurements were performed on two occasions approximately 12 days apart. Peak pressure (PP), contact area (CA), contact time (CT), pressure–time integral (PTI), force–time integral (FTI) and instant of peak pressure (IPP) were recorded. The coefficient of repeatability (CR) was less than 16.9% for all 122 parameters considered. The highest areas of PP were found under the second and third metatarsal heads, with mean (S.D.) equal to 361 kPa (104) and 330 kPa (84), respectively, followed by the great toe 321 kPa (141) and heel 313 kPa (77). CA was highest under the heel at 35 cm^2 (5). The percentage CT was in the range 75–85% under the metatarsal heads, and 70% under the hallux. PTI was highest under metatarsal heads one to three and hallux. FTI was highest under the heel. Emed® ST4 system was found to be repeatable. The ranges of the parameters documented can be applied in orthopaedic clinics as part of the assessment of pathological conditions.

Keywords: Normal; Barefoot; Pressure; Emed® ST4; Repeatability

1. Introduction

The foot is one of the most ergonomically efficient structures of the body and can sustain the enormous pressures generated by dynamic activities. Abnormal levels of pressure can cause foot pathologies and various measuring devices are available in orthopaedic clinics to investigate these. The Emed® systems are among the most commonly used clinical tools for barefoot pressure measurement in humans worldwide. Kernozek et al. [1] used the Emed SD system to determine pre- and post-operative plantar loading characteristics of hallux valgus in Chevron Akin osteotomy. Huber and Dutoit [2] used foot pressure studies to objectively assess clubfeet post-operatively. Thometz et al. [3] found that radiographs used in conjunction with dynamic plantar pressure analysis provided a complete assessment of the corrected clubfoot. Abboud et al. [4] investigated the relationship between in-shoe pressure and the coordinated activity of five lower limb muscles in diabetic patients. They concluded that the foot reaches foot flat in a less ordered manner causing high plantar pressures.

As the application of foot pressure measurement systems widens, it becomes increasingly necessary to determine their repeatability and to establish a range of normal values for reference and comparison purposes. No previous publications have addressed the repeatability of the Emed® ST4 or higher resolution Novel systems, nor have ranges of values been identified for normal foot parameters during barefoot walking using the mid-gait method.

This study examined the repeatability of the Emed® ST4 system (model-ST4; Novel GmbH, Germany). Ranges for clinically important parameters in the normal foot are determined, which can be referred to by clinicians when investigating pathological cases.

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2. Materials and methods

Fifty-three healthy volunteers were recruited for the study. Subjects were excluded if they had experienced foot pain within the previous 6 months, had any previous foot surgery, presented with congenital or acquired foot deformities on clinical examination, or had any other disability that could affect their gait (e.g. flat feet, visual and/or hearing impairments, problems in the lower limb or spine, or any condition that necessitated the use of walking aids). Age, gender, height, weight, and foot size were also recorded. The local Research Ethics Committee approved the study and all subjects gave written 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 1.7 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; hence their data was not included in assessing the system's repeatability but were included for determining pressure ranges values. Of the 53 subjects, 17 (32%) were female and 36 (68%) were male.

Several different versions of the Emed® systems are available depending on specific requirements [5]. The Emed® ST4 system used in the current study incorporates the Nicol capacitance pressure mat platform, which is a force transducer matrix consisting of a 190 mm × 360 mm rubber mat with 2736 sensors at a resolution of 4 sensors/cm^2. An applied force alters the capacitance across two perpendicular strips, which the system senses and relays to a computer.

The Emed® ST4 platform was mounted in the centre of a flat 10 m walkway at ground level. The long path allowed measurements to be recorded during free movement and thus ensured that the effect of acceleration and deceleration at the start and end of each walk was minimised. The accuracy of the Emed® ST4 system is ±5%. This was regularly assessed on the day of data collection with the help of a simple test during which a static measurement was made with a subject standing on the Emed® platform on one leg. The force measured was closely equivalent to the body weight (±5%), which confirmed the accuracy of the system. Subjects were asked to walk at normal speed while four left and four right footsteps were recorded. After a brief pause, the process was repeated. The whole session was carried out again, approximately 2 weeks later.

The foot was divided into 10 regions: heel, mid-foot, first, second, third, fourth and fifth metatarsal heads, hallux, second toe and third to fifth toes (Fig. 1). Of the 18 separate parameters recorded by the Emed® ST4 system, six of the most clinically relevant were selected for investigation: 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). Total contact time was also calculated. In total, 122 parameters were assessed: six parameters, under 10 masks, plus total contact time, measured separately for the left and right foot.

The data were not normalised for foot size and weight. The standard deviation reflects the within subject and between subject variations as well as trial to trial differences and variation in the Emed® system.

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 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 standard deviations of the between-day differences identified in the ANOVA were used to determine the coefficient of repeatability (CR) of each parameter [6]. This was expressed as a percentage of the mean by using the formula [(coefficient of repeatability)/mean] × 100, i.e. the lower the CR the stronger the repeatability. Repeatability was investigated for the left and right foot separately and the mean CR determined.

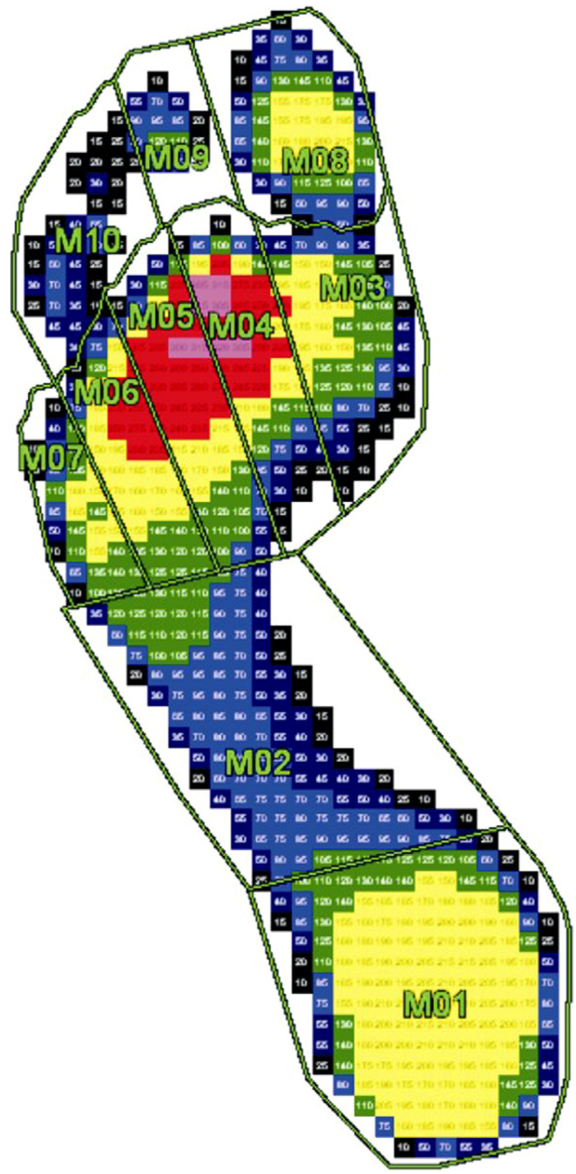

Fig. 1. Foot divided into 10 regions.

3. Results

The CR (expressed as a percentage of the mean) was less than 10% in 91% of the parameters (111 of 122). Measurements with a higher CR were recorded mainly

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)

Emed® 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	313 (77)	3.6	34.5 (5.2)	0.8	393 (95)	2.5	73 (25)	3.4	105 (31)	3.3	99 (56)	13.6
Mid-foot	113 (37)	4.7	23.8 (9.8)	2.1	438 (98)	2.2	33 (15)	5.9	28 (23)	7.3	212 (82)	10.3
1 MT[b] head	277 (90)	7.7	13.6 (2.4)	1.6	562 (66)	1.7	87 (37)	7.1	52 (20)	5.4	531 (71)	1.9
2 MT head	361 (104)	2.9	10.5 (1.8)	2.0	576 (66)	1.4	107 (35)	3.1	54 (15)	2.7	563 (70)	1.7
3 MT head	330 (84)	3.6	11.5 (1.9)	1.5	589 (70)	1.3	104 (30)	3.6	57 (16)	4.9	551 (74)	1.3
4 MT head	233 (67)	4.5	9.5 (1.4)	1.7	577 (70)	1.3	80 (30)	4.3	35 (13)	5.9	504 (90)	1.9
5 MT head	151 (78)	9.9	5.9 (1.0)	2.7	528(77)	1.7	50 (30)	7.8	14 (7)	8.6	413 (120)	6.3
Hallux	321 (141)	6.2	10.4 (2.1)	1.5	478 (113)	3.5	81 (49)	8.4	26 (13)	7.3	559 (80)	1.8
Second toe	158 (73)	5.4	3.6 (1.1)	4.5	432 (100)	2.8	37 (24)	6.6	5 (3)	8.7	570 (71)	1.6
Third to fifth toes	111 (54)	9.9	7.3 (2.4)	4.8	457 (116)	4.6	29 (22)	12.7	6 (5)	15.4	575 (78)	2.3

[a] CR: expressed as a percentage of the mean.
[b] MT: metatarsal.

under the toes (7 of 11 parameters). These included PP under the left fifth metatarsal head, and under the third to fifth toes on the right side (CR 10.6% and 11.0%, respectively). The coefficients of repeatability for PTI measured under the third to fifth toes on both sides were 11.4% and 14.0%, respectively. FTI had CR values of 10.1% under the left second toe, and 13.8% and 16.9% under the third to fifth toes on the left and right sides, respectively. The CR values for IPP under the left and right heels were 13.4% and 13.9%, respectively, and for the left and right mid-foot were 10.5% and 10.2%, respectively. Coefficients of repeatability, mean and standard deviation for the left and rights side were comparable and combined values are presented in Table 1.

Measurements of parameters under the normal foot are also summarised in Table 1. Results are presented to three significant figures. The highest PP was found under the second metatarsal head (mean 361 kPa (104)), followed by the third metatarsal head (330 kPa (84)), the great toe (321 kPa (141)), the heel (313 kPa (77)) and the first metatarsal head (277 kPa (90)). Minimum and maximum values observed in the study are presented in Table 2.

The heel made the largest contact with the Emed® ST4 platform (34.5 cm^2 (5.2)) followed by the mid-foot region (23.8 cm^2 (9.8)), first metatarsal head (13.6 cm^2 (2.4)), third metatarsal head (11.5 cm^2 (1.9)) and then second metatarsal head (10.5 cm^2 (1.8)). The CA of the hallux was relatively small (10.4 cm^2 (2.1)).

The mean total contact time of the foot was 687 ms (80). The third metatarsal head was the longest in contact with the platform (589 ms (70)), closely followed by the fourth (577 ms (70)), the second (576 ms (66)) and the first metatarsal heads (562 ms (66)). When expressed as a percentage of the total contact time, the third metatarsal head had the longest contact period with the ground (85.7%) and the heel had the shortest (57%). The first four metatarsal heads were in contact for more than 80% of the total time.

PTI was highest in the second metatarsal head (107 kPa s (35)) followed by the third and first metatarsal heads (104 kPa s (30) and 87 kPa s (37), respectively). The mid-foot and third to fifth toes had the lowest PTI. The highest FTI was under the heel and the mean (105 N s (31)) was approximately twice that under the third metatarsal head (57 N s (16)). FTI was low in the second and third to fifth toes (5 N s (3) and 6 N s (5), respectively).

Observed values of IPP depicted the normal progression of peak pressure from the heel to the mid-foot, then to the lateral border of the forefoot from the fifth to the first metatarsal heads, and finally from the hallux to the fifth toe. This corresponds to the heel strike, foot flat and toe-off phases of the gait cycle.

4. Discussion

Foot pressure data can be collected using different techniques, including the one-step, two-step, and the mid-gait methods [7–9]. While the two-step procedure reduces both the number of steps and the time taken, and has been

Table 2
Range for the peak pressure (PP) in the 10 regions of the foot

Emed® masks	Range (kPa)	
	Minimum	Maximum
Heel	155	580
Mid-foot	22.5	230
1 MT[a] head	72.5	615
2 MT head	97.5	695
3 MT head	95	615
4 MT head	110	503
5 MT head	30	473
Hallux	37.5	713
Second toe	17.5	593
Third to fifth toes	12.5	368

[a] Metatarsal.

shown to be reliable when compared with the mid-gait method [8], the mid-gait method was used in the current study as it is more representative of normal gait. Van der Leeden et al. [10] found that a minimum of three measurements were sufficient to obtain a consistent average. Four measurements were taken in the current study.

The first aim of this study was to assess the repeatability of the Emed® ST4 system using the coefficient of repeatability. It was considered unlikely that there would be any major changes in the pressure characteristics of the feet during the two sessions (mean 11.8 days). In addition, the only differences between mask assignments occur due to gait variation. Repeated analysis of the data will result in the same mask assignment. Any differences could therefore be attributed to gait variation rather than measurement error [11]. Hughes et al. [12] reported a good level of reliability of the Emed®-F system, with a measurement error of less than 5%.

From the 122 parameters assessed in the current study, the highest CR was 16.9%, observed in FTI under the third to fifth toes on the right side. The majority of the parameters (111 of 122, 91%) had a CR less than 10%. Taking into consideration the fact that no two foot steps in a normal subject are identical due to sway during gait [11], the highest CR achieved is therefore clinically acceptable, which suggests that the Emed® ST4 system is repeatable.

The second aim was to establish ranges for PP, CA, CT, PTI, FTI and IPP under the normal foot. Values for PP, mean pressure and PTI under the normal foot have been established by the two-step method for a group of 30 healthy subjects using the Emed® SF system [13]. The corresponding figures for the mid-gait approach have not been documented. Ranges determined in this study were derived from measurements of 53 healthy volunteers.

The highest PP values were found under the second and third metatarsal heads, the great toe and heel. These findings are in agreement with Bryant et al. [13] and Hughes et al. [12]. While Bennet and Duplock [14] and Shorten et al. [15] grouped the central forefoot into one area, Bryant et al. [13] identified five metatarsal regions. The highest PP in the latter study was in the hallux followed by the second and third metatarsals and the heel. Shorten et al. [15] and Bryant et al. [13] used the Emed® SF system whereas Bennet and Duplock [14] used the Musgrave Footprint device. Observed differences in the values of PP could be attributed mainly to different sensors, their sizes, layout and calibration [5]. In addition the subjects, equipment, test conditions and methods may have an impact too [12].

Reference values for CA, CT, FTI and IPP under the normal foot have not been reported previously in the literature. In this study, CA was highest under the heel, which acts as the first contact area to absorb the force and redistribute the pressure. In contrast, the smaller contact areas under the metatarsal heads and the hallux lead to higher pressures.

In agreement with other studies [12], CT was highest under the metatarsal heads followed by the hallux. The metatarsal heads were found to bear weight for 75–85% of the total foot contact time, while the figure for the hallux was 70%. These findings are similar to those reported by Hutton and Dhanendran [16].

In the current study, PTI was highest in the second, third, first metatarsal heads and the hallux, supporting the findings of Bryant et al. [13]. Both PTI and FTI provide information about the load distribution over time. This is thought to be important in the pathogenesis of skin lesions [17].

FTI was highest under the heel, where it was twice as high as in the metatarsal heads. This is in contrast to PTI, which is lower under the heel than the metatarsal heads. This is due to the increased contact area of the heel.

IPP demonstrates the time at which peak pressure occurs. The pattern and the individual values are important while considering the centre of pressure progression.

Clinically, peak pressure is the most relied upon parameter. The range of pressures identified in this project should only be considered when using the Emed® ST4 system. The findings of this study reinforce those reported by other authors: the highest regions of pressure are under the second and third metatarsal heads, the great toe and the heel.

In conclusion, the Emed® ST4 foot pressure system was found to be repeatable. Ranges of values of the six investigated parameters in normal feet have been analysed and can be used as part of the assessment of foot pathologies.

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Conflict of interest

All authors have no financial and personal relationships with other people or organisations that could inappropriately influence (bias) their work.

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