# Quantitative Analysis of Foot Plantar Pressure During Walking

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Statistical Analysis C
Data Interpretation D
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Source of support: Jagiellonian University project K/ZDS/006487

**Background:** There are many methods of dynamic analysis of foot loading, however, we still need a simple, easily applicable system for foot plantar pressure analysis. In this study we asked the question: "Can a new system for foot evaluation, the ITE System, provide a good quantitative dynamic foot pressure analysis? Can it be used in clinical practice?".

**Material/Methods:** Twenty healthy volunteers, 8 females and 12 males, aged 20 to 25 years old took part in this study. Normal static foot loading was tested using a typical pedobarographic platform, followed by a dynamic analysis using the foot-pressure ITE System. A new algorithm for data analysis (from 8 sensors) was proposed.

**Results:** The sum of all maximal values from sensors was 11.71 N mean, with relatively low standard deviation (SD) of 1.81. Loading of sensor 1 (heel) was the highest – on average 29.84%. Sensor 2 (medial midfoot) received the lowest loading – normal range for this segment would be 0–4%. The manner of loading heel/toes, dynamics of changes in loading during gait was quite diverse; when analyzing courses of changes on sensors, 4 gait patterns were observed.

**Conclusions:** Use of the ITE System creates a new possibility for dynamic foot evaluation, drawing from pedobarography and methods of gait analysis. The proposed data analysis algorithm is simple and can be applied in all cases. Normally, 30% of the sum of all pressures during stance phase falls on the rearfoot; 39% falls on forefoot.

**MeSH Keywords:** **Biomedical Engineering • Foot • Gait**

**Full-text PDF:** https://www.medscimonit.com/abstract/index/idArt/914915

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## Background

Bipedal gait is a convenient method of traveling for shorter distances [1]. Analysis of a patient's gait is an integral part of the orthopedic examination. The easiest and most commonly performed gait assessment is gait observation. This method has been used by doctors for centuries. However, with time, a need for a quantitative gait evaluation has evolved concerning the distinctive gait phases. When standing or walking, the only contact with the ground is through the feet. Therefore, the feet are the key element of gait, and their pathology may result in disturbance of ambulation.

Evaluation of foot loading may be based on static, postural, and dynamic analysis, including gait analysis [1–5]. Detailed research into foot kinetics has been developed using advancements in our knowledge about the human gait. This has resulted in more scientific approaches to the issue, particularly with the development of professional gait analysis laboratories [4–6]. At the beginning, of this new approach, unisegmental foot models were created. Foot orientation was defined as a vector from the center of mechanical axis of rotation of the ankle joint to the space between the second and third metatarsal bones. With the introduction of new equipment for gait analysis, the foot model has evolved with an increase in the number of sensors representing different segments of foot. Multi-segmental models have been developed using multiple sensors placed on the foot surface [7]. At the same time, new methods based on pedobarography were developed. The use of piezoelectric sensors by Schwartz, a novelty at that time, enabled the development of modern techniques in foot loading analysis [8–11]. Accuracy of measurements has improved, particularly with the introduction of a specialized software allowing automatization of the process.

At present, over 50 different devices are used for foot loading analysis [11]. Some systems require specialized laboratories, others require relatively expensive and delicate insoles with pressure sensors [12]. Thus, the need arose for a new system based on insoles and a simple interface that could be used during examination in the ordinary orthopedic or physiotherapeutic clinics.

The aim of this paper was to present a new system for foot evaluation and an analysis of its possible clinical uses.

## Material and Methods

The investigation was approved by the local bioethics committee KBET no. 122.6120.73.2015. Material consists of 20 healthy volunteers, 8 females and 12 males, aged 20 to 25 years old. No foot pathology was recorded in orthopedic examination,



**Figure 1.** Footpressure ITE System: a device fixed to the outer surface of a shoe that registers and transmits data.
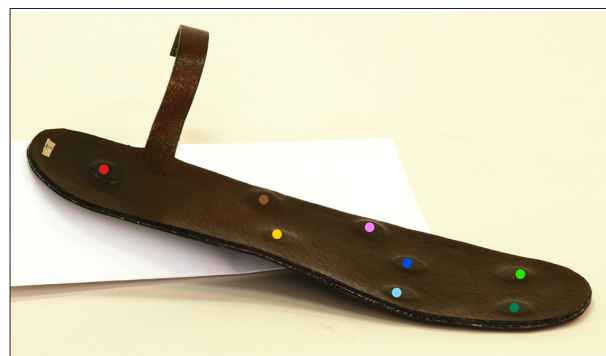


**Figure 2.** Footpressure ITE System: measuring insole with 8 piezoelectric sensors, distributed in foot regions defined by Blomgren and Lorkowski. Distribution of sensors: sensor 1 – red (heel), sensor 2 – yellow (medial midfoot), sensor 3 – dark blue (metatarsal), sensor 4 – dark green (great toe), sensor 5 – brown (lateral midfoot), sensor 6 – light blue (metatarsal 1), sensor 7 – (lateral metatarsal), sensor 8 – light green (small toes).

none of the participants had undergone surgical procedures at the foot area, and there were no reported fractures or sprains.

### Methodology

Normal static foot loading was tested using a pedobarographic platform with Tekscan pressure sensors. The results were analyzed using the MatScan Clinical 6.62 program.

For dynamic analysis, the Footpressure ITE System was used, which consists of measuring a shoe's insole with a device fixed to the outer surface of a shoe that registers and transmits data [13,14] (Figure 1). The insole measuring uses 8 piezoelectric sensors, distributed in foot regions as defined by Blomgren and Lorkowski (Figure 2) [9,10,15]. The insole thickness was approximately 4 mm and the measuring device weighs was approximately 75 g. The measuring device was connected to the
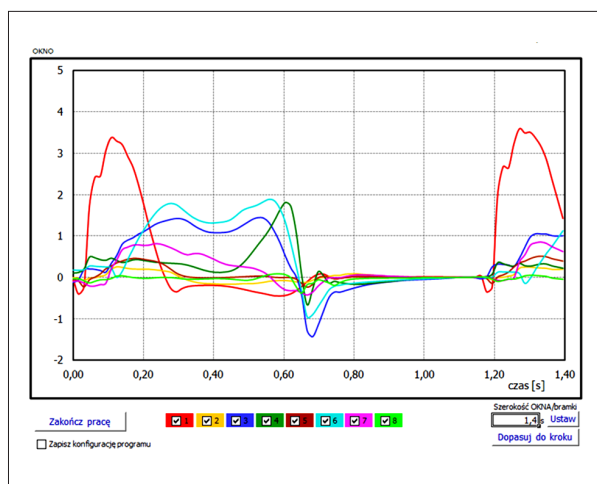
**Figure 3.** Heel loading used as a reference point in foot loading analysis with ITE System. The maximum values obtained from the sensor in so called mean stride.

computer wirelessly. The data was stored on a memory card. The device was protected by patent no P.402006.

The examination was conducted on a 20-meter long walkway with even surface; each participant walked the distance of the walkway a couple of times. Insoles were prepared in various sizes; the appropriate size was chosen by each volunteer. During testing, all participants used the same type of trainers. Data obtained (referring to the right foot) was then analyzed using code "Steps" ("Kroki") (written in Visual Basic for application language embedded within Excel spreadsheet).

The Jagiellonian University Ethics Committee(s) approved this study: No. 122.6120.73.2015.

Written informed consents were obtained before research was conducted.

## Results

Static pedobarographic measurements showed a difference in loading of the left and right foot that was no higher than 12% (range, 0–12%, mean 1.2%, SD 6.49). Seven participants loaded right foot over left, 13 loaded left foot over right. Pressure generated beneath the plantar surface of the foot was 190.6 N/cm$^2$ on average (range, 147.5–236.8 N/cm$^2$; SD 23.5). All feet had a normal longitudinal arch.

Dynamic measurements included: first the heel loading (sensor 1) was used as a reference point in the foot loading analysis with the ITE System, taking it as 100% [16]. The maximum values obtained from the sensor were evaluated in so called "mean stride" as described in the program (Figure 3). The typical

stride started from the heel strike (red peek) and ended with load under toes (mainly great toe, dark green peek). Records from sensor 2 (yellow) were minimal – with a proper longitudinal arch, this foot region would not typically be loaded. All the results obtained through the described algorithm are presented in Table 1 [16]. The data analysis revealed a considerable scattering of peak loading values for the heel strike. The measurement was applicable only to normal gait phases, and was unreliable for pes equinus or pes calcaneus. Thus, we saw the need for choosing an alternative reference point for the analysis of values received from other sensors. A new hypothesis was postulated that the sum of the maximal pressures on all sensors received in 1 stride (mean stride) should be the reference value used for further analysis. The authors made an assumption that the percentile distribution of maximal pressures should be invariable. The results achieved using this method are presented in Table 2. The sum of all maximal values from sensors was 11.71 N mean, with a relatively low SD of 1.81. Loading of sensor 1 was highest – on average 29.84%. For heel loading, a value of 20–40% should be regarded as a norm. Sensor 2 received the lowest loading – normal range for this segment would be 0–4%.

Each stride can be divided into stance phase and swing phase [2]. Normal gait is more or less equal standing in turns on the right and the left foot. The time of each stride for a particular gait pace should be more or less equal, and in the test group it was a mean of 0.997 seconds (range, 0.9–1.160; ±0.067 seconds). Foot ground contact time it was a mean of 0.573 seconds (range, 0.480–0.7; ±0.053 seconds), i.e., a mean of 57.6% (range, 52–63%; ±3.3%). Stance phase slightly longer that swing phase is considered characteristic for an average pace of gait [2].

The manner of heel/toes loading and the dynamics of the changes in loading during the gait were quite diverse. Analyzing the range of changes through the sensors, a 4 gait patterns were observed.

Consequently, the participants were divided into 4 groups according to the type of gait [16].

Group 1 consisted of 5 females, with a distinct initial contact phase, according to Perry (sensor 1 measurement were 32%) and with a strong pre-swing phase. Foot ground contact time was 60% of the length of a stride, whereas forefoot loading was 46.9% of the stance phase (Tables 3, 4). The swing phase lasted 40%, on average.

Group 2 had 6 participants; the initial contact and pre-swing phase were distinct along with the mid-stance phase (Table 5). The overall time of stance phase was 62% of the stride length (32% of the sum of pressures on all sensors were

**Table 1.** Maximcal pressure [N] recorded from sensors for mean stride. Percent counted in reference to readings received from sensor no 1.

|  | Sensor 1 | Sensor 2 | Sensor 3 | Sensor 4 | Sensor 5 | Sensor 6 | Sensor 7 | Sensor 8 |
|---|---|---|---|---|---|---|---|---|
| Mean | 3.50 (100%) | 0.21 (6%) | 2.31 (7%) | 1.65 (49%) | 0.87 (27%) | 0.87 (27%) | 1.49 (44%) | 0.80 (24%) |
| SD | 0.89 | 0.10 | 0.94 | 0.69 | 0.43 | 0.36 | 0.71 | 0.75 |
| Minimum | 1.64 | 0.03 | 0.65 | 0.69 | 0.08 | 0.12 | 0.39 | 0.06 |
| Maximum | 5.92 | 0.46 | 3.86 | 3.14 | 1.76 | 1.68 | 3.51 | 2.53 |

**Table 2.** Maximal percentile pressure recorded on each sensor referred to the sum of all readings.

|  | Suma [N] | Sensor 1 | Sensor 2 | Sensor 3 | Sensor 4 | Sensor 5 | Sensor 6 | Sensor 7 | Sensor 8 |
|---|---|---|---|---|---|---|---|---|---|
| Mean | 11.71 | 29.84% | 1.86% | 19.44% | 14.03% | 7.48% | 7.55% | 12.48% | 7.32% |
| SD | 1.81 | 5.59% | 0.93% | 6.77% | 5.14% | 3.94% | 3.18% | 5.03% | 7.26% |
| Minimum | 8.22 | 19.95% | 0.20% | 6.92% | 5.61% | 0.73% | 0.97% | 4.11% | 0.43% |
| Maximum | 16.2 | 40.24% | 4.03% | 27.86% | 25.39% | 17.15% | 14.58% | 23.86% | 24.71% |

**Table 3.** Stance phase as the percentage of stride length and forefoot load as a part of stance phase.

|  | Grup 1 | Grup 2 | Grup 3 | Grup 4 |
|---|---|---|---|---|
| Stance phase/stride | 60.0% | 62.0% | 56.0% | 60.0% |
| Forefoot load/stance phase | 46.9% | 48.3% | 35.4% | 56.9% |

**Table 4.** Group 1. Maximal percentile pressure recorded on each sensor referred to the sum of all readings.

|  | Suma [N] | Sensor 1 | Sensor 2 | Sensor 3 | Sensor 4 | Sensor 5 | Sensor 6 | Sensor 7 | Sensor 8 |
|---|---|---|---|---|---|---|---|---|---|
| Mean | 10.56 | 32.1% | 2.2% | 10.5% | 18.5% | 4.3% | 8.1% | 5.9% | 18.4% |
| SD | 1.36 | 2.5% | 1.2% | 2.3% | 4.1% | 2.4% | 1.3% | 1.1% | 4.5% |
| Minimum | 9.39 | 29.7% | 0.6% | 6.9% | 14.0% | 0.7% | 6.6% | 4.1% | 10.5% |
| Maximum | 13.05 | 35.8% | 4.0% | 13.0% | 25.4% | 7.8% | 9.7% | 7.0% | 24.7% |

**Table 5.** Group 2. Maximal percentile pressure recorded on each sensor referred to the sum of all readings.

|  | Suma [N] | Sensor 1 | Sensor 2 | Sensor 3 | Sensor 4 | Sensor 5 | Sensor 6 | Sensor 7 | Sensor 8 |
|---|---|---|---|---|---|---|---|---|---|
| Mean | 11.43 | 32.0% | 2.0% | 22.6% | 11.1% | 8.5% | 6.2% | 13.1% | 4.6% |
| SD | 1.05 | 2.0% | 0.5% | 4.2% | 3.8% | 3.5% | 3.8% | 2.2% | 2.4% |
| Minimum | 9.91 | 29.8% | 1.1% | 15.0% | 5.6% | 4.5% | 1.0% | 10.3% | 0.9% |
| Maximum | 12.84 | 35.7% | 2.7% | 27.3% | 15.9% | 14.3% | 13.8% | 16.9% | 7.5% |

measurements from sensor 1), whereas forefoot loading time (forefoot rocker + toe rocker according to Perry) was 48.3% of the stance's phase. The swing phase averaged 38%.

Group 3 had 6 participants with a pre-swing phase stronger than initial contact phase (measurements from sensor 1 was 22.8%) (Table 6). For this group, the foot ground contact was 56%, swing phase 44%, and forefoot loading only 35.4% of the stance's phase.

**Table 6.** Group 3. Maximal percentile pressure recorded on each sensor referred to the sum of all readings.

|  | Suma [N] | Sensor 1 | Sensor 2 | Sensor 3 | Sensor 4 | Sensor 5 | Sensor 6 | Sensor 7 | Sensor 8 |
|---|---|---|---|---|---|---|---|---|---|
| Mean | 12.23 | 22.8% | 1.5% | 25.2% | 14.3% | 9.8% | 8.8% | 15.1% | 2.4% |
| SD | 2.12 | 1.7% | 0.1% | 2.0% | 4.4% | 4.0% | 3.2% | 3.0% | 1.5% |
| Minimum | 8.22 | 20.0% | 1.2% | 22.4% | 8.9% | 5.3% | 5.7% | 11.3% | 0.4% |
| Maximum | 14.89 | 25.0% | 1.7% | 27.9% | 21.1% | 17.2% | 14.6% | 20.4% | 4.8% |

**Table 7.** Group 4. Maximal percentile pressure recorded on each sensor referred to the sum of all readings.

|  | Suma [N] | Sensor 1 | Sensor 2 | Sensor 3 | Sensor 4 | Sensor 5 | Sensor 6 | Sensor 7 | Sensor 8 |
|---|---|---|---|---|---|---|---|---|---|
| Mean | 13.84 | 38.9% | 1.8% | 14.9% | 10.7% | 5.3% | 6.6% | 19.1% | 2.7% |
| SD | 0.88 | 1.3% | 1.6% | 1.8% | 4.7% | 0.8% | 2.3% | 4.8% | 0.1% |
| Minimum | 12.96 | 28.3% | 0.2% | 13.0% | 6.0% | 4.6% | 3.2% | 14.3% | 2.6% |
| Maximum | 16.2 | 40.2% | 3.5% | 20.1% | 15.4% | 7.3% | 8.9% | 23.9% | 5.9% |

Group 4 had 3 male participants, with a distinct initial contact phase followed by a rather weak pre-swing when compared to Group 1 (sensors under toes – no 4 and no 8 showed 10.7% and 2.7% respectively) (Table 7). Foot ground contact for this group was 60%, swing phase 40%, and forefoot loading was as extensive as 66.9% of the stance phase.

## Discussion

Gait analysis is an important element of a comprehensive orthopedic evaluation of patients with foot pathology. Abnormal foot biomechanics leads to limping, pathological plantar loading, and foot pain. Disturbances in other areas of the lower limbs often are representation in the gait and the way feet are set on the ground. Therefore, a dynamic evaluation of foot operation is very important, and is usually performed during an orthopedic examination using visual gait analysis.

More advanced methods include the static and dynamic pedobarographics, performed sometimes along with other techniques of gait analysis [11,17]. The data received for the analysis from multiple sensors and grouped into pressure areas can be analyzed by specialized laboratories [18–20]. Some researchers question the value of these techniques in certain foot pathologies evaluations, while others perceive them as a vital diagnostic tool [11,21,22].

Evaluation of foot dynamics using the ITE System is considered precise, and at the same time, a simple method. It is possible to perform the evaluation in everyday conditions – the patient can be asked to go for a walk with a special insole while the data is collected [14]. Gait analysis using the ITE System

provides data about foot loading during ambulation. Gait speed, the length of a stride – both are obvious and simple measurements – however, since they vary between individuals, they can be used only for an individual patient's evaluation, for example, before and after rehabilitation. According to Perry, the first rocker is an important element of gait [3]. In the present study, according to our measurements, the heel pressure contributed 30% of all pressures recorded on the sensors during stance phase. This value depends not only on normal muscle work, but also on the range of extension in ankle joint [23]. There is a correlation between the foot posture and manner of ambulation when measured with gait analysis methods and the evaluation of angle at the heel contact, peak angle, time to peak angle, and the ankle range of motion [24].

During the next stage of stance phase the foot is completely loaded, however, the action begins with the ankle rocker – different muscles affect foot and calf at this time, and the magnitude of pressure on the sensors at this time depends also on the shape of longitudinal arch [6,24].

In our study material, there were 2 sensors in the midfoot area (sensor 2 medially, and sensor 5 laterally, and there were 3 sensors in metatarsal area (sensors 3, sensor 6, and sensor 7 from the head of first metatarsal bone to the fifth metatarsal). The readings from sensor 2 were practically negligible with a mean of 2% (range, 0.2% to 4%); whereas from sensor 5, they averaged 7.5% (range, 0.7% to 17%). In the normal foot, the loading of the medial part of the foot arch does not usually occur; however, while in a shoe, the readings from the insole can be detected (as in our sensor 2). Loading of the lateral side of the foot is usually relatively brief, as the stance phase is brief and, as for the gait kinematics, a forefoot rocker

begins, followed by the toe rocker which, possibly, may explain the low values of data from sensor 5. Sensors 6, sensor 3, and sensor 7 were active during the mid-stance phase and, together with sensors 4 and senor 8, during the end of stance phase, forefoot, and toe rocker. Percentile loading values recorded beneath the heads of metatarsal bones range from 7.5% to 19%, which gave a total of 39% of all recorded pressures.

Finally, the readings from the sensor underneath the hallux showed a mean of 14%, and from the toes 7%. The anterior part of the foot propels the next step, and concentric contraction of the posterior muscle group along with normal foot anatomy allows for this to occur properly.

The magnitude of the pressures recorded from particular sensors of pedobarographic devices can vary depending, for example, on the type of device, weight of the individual, and their sex. An absolute value of measurements is meaningful only when compared to the results obtained from the same person, for example, before and after treatment. Very often, the evaluation of the results is primarily qualitative. The quantitative evaluation is certainly relevant for podoscope examination, or its elements within pedobarographic examination, such as the length and width of the foot and the angle of hallux valgus, Clarke angle, Ky index, and Wejsflog index [25]. There are strict norms describing a range of motion in the joints of the lower limb during ambulation, however, in the evaluation of the magnitude of pressures in particular areas of a foot, the qualitative descriptions are often used instead of uniform quantitative norms [26].

Pediatric foot is another problem – difficulties in examination in the laboratory environment and difficulties in data analysis have been dealt with either by using models specially adjusted for children – bi-segmental (rearfoot and forefoot) with triplane analysis of these segments' positioning, or with the evaluation of the center of pressure progression (COPP) graph [27,28]. Pedobarography, rather as static examination, is an important tool in diagnosing and monitoring treatment of flat foot, especially in obese children [11,29]. The dynamic pedobarography examination in children, however, shows discrepancies [25]. It appears, that the ITE System examination, being easy to perform outside the gait laboratory, could be an alternative method of evaluation. However, there were some limitations to this study. The sample was small, only 20 volunteers. Other limitations included using only records for 1 foot, and only 1 type of shoe. Further research in a pediatric population is needed.

## Conclusions

Use of the ITE System creates a new possibility of dynamic foot evaluation, drawing from pedobarography and methods of gait analysis. Proposed data analysis algorithm is simple and can be applied in all cases. Normally, 30% of the sum of all pressures during the stance phase falls on a rearfoot; 39% falls on a forefoot.

### Conflict of interests

None.

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