Plantar pressure sensors indicate females to have a significantly higher peak pressure on the hallux, toes, forefoot, and inside of the foot compared to males.

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Abstract

**Background:** Gender-related differences of plantar pressure distribution during activities should be thoroughly inspected as it can help establish treatment and prevention strategies for foot and ankle problems. In-shoe measurement systems are preferable without space and activity restrictions; however, previously reported systems are still heavy and bulky and induce unnatural movement. Therefore, a slim and light plantar pressure sensor was newly developed to detect the effect of gender difference on plantar pressure during standing and walking.

**Methods:** One-hundred healthy adult volunteers (50 females and 50 males) were recruited. Ten plantar pressure sensors were implanted in a 1-mm thick insole, with a total weight of 29 g. Plantar pressure was recorded with 200 Hz during 3 seconds of standing and while walking 10 steps. The maximum loads during standing and walking were analyzed in each sensor, and the results were compared between different areas of the foot in the antero-posterior direction and the medio-lateral direction and between different time points. The movement of the center of pressure (COP) during walking was also evaluated. Results were compared between genders by converting body weight to 50 kg.

**Results:** The movement of COP was constant for both genders. In all cases, the maximum load was observed on the inside of the foot. Females had a significantly higher peak pressure on the hallux, toes, forefoot, and inside of the foot compared to males while standing and walking (P < .01).

**Conclusions:** A newly introduced in-shoe plantar pressure sensor demonstrated a typical loading transition pattern of the foot. Furthermore, higher plantar pressure in the forefoot was detected in healthy females as compared to males during standing and walking activities.

**Introduction**

Analysis of the loading condition of the sole during walking and running is vital to improve footwear design[1], sports performance analysis and injury prevention[2], balance control[3], and for diagnosing diseases[4]. Various foot pressure evaluation devices have been developed, and the currently available systems are categorized into the plantar platform system and the in-shoe system. At present, over 50 different devices are used for foot loading analysis[7]. Some systems require
specialized laboratories, whereas others require relatively expensive and delicate insoles with pressure sensors[8]. The in-shoe system is preferable over the plantar platform system because of its portability, simplicity, and applicability on various shoe types[5], and subjects can perform natural movement during the experiment without the restriction of space and activity [6]. However, existing in-shoe systems are heavy and bulky, and induce unnatural movement, urging the need of a light and slim in-shoe type sensor.

Skeletal structure and muscular strength differ between females and males. However, the effect of gender on plantar pressure during activities remains undetermined. Putti et al. did not find any gender-based differences in plantar pressure while walking eight steps on the same walkway[9]; however, higher toe peak pressure was identified more often in females than in males during early adolescence[10]. To examine the effect of gender difference on plantar pressure, testing activities should be performed in positions as natural as possible, without any obstruction from the measurement.

Therefore, a slim plantar pressure sensor was newly developed to measure plantar pressure of healthy adults during unrestricted activities. The purpose of this study was to evaluate pressure distribution on the sole during gait and stance using the newly developed in-shoe measurement system and compare the results between genders.

Materials And Methods

Subjects

One hundred healthy adult volunteers (50 females and 50 males) were included in the study. Demographic data are shown in Table 1. In total, 200 feet were analyzed. Subjects were excluded if they had experienced foot pain within the previous 6 months, had previously undergone foot surgery, or had presented with congenital or acquired foot deformities on clinical examination. Demographics including age, gender, height, weight, and foot size were recorded. The study protocol was approved by the Institutional Review Board of our institution and written informed consent was obtained from all subjects before their enrollment.

Measurement devices
The newly developed plantar pressure sensor (University of Fukui Graduate School of Engineering, Japan) has 10 sensors of 1 mm thickness and 12 g weight. They are connected to a measuring unit that has 200 Hz of sampling rate and is 17 g in weight (Figure 1). Three sensors were placed on the toes, four on the forefoot, two on the midfoot, and one on the hindfoot. Four sizes (23 to 28 cm) of sports shoes and corresponding sizes of plantar pressure sensors were prepared to provide the best fit shoes for each subject.

**Measurement and analysis**

Each subject rested for 3 seconds after wearing the device, after which plantar pressure was measured while standing. Next, subjects were instructed to walk at least 10 steps at a comfortable speed while the plantar pressure was recorded (Figure 2). The maximum loading while walking was measured in the hallux (the sensor a), and the movement of the maximum loading point while walking was analyzed by evaluating in different areas of antero-posterior (AP) direction and medio-lateral (ML) direction (Figure 3). The hallux was measured individually, considering that there might be a difference in the hallux between females and males because hallux valgus was more common in females. When compared based on gender, the weight was converted to 50 kg equivalent and calculated (Excel 2016, Microsoft and COP graph creator, University of Fukui Graduate School of Engineering, Japan). The movement of COP during walking was analyzed in the AP and ML directions. When compared based on gender, the sensor was converted to 25.5 cm equivalent and calculated.

**Statistical Analysis**

A two-sample t-test was used for a gender-based comparison of the data (Excel 2016, Microsoft). For all analyses, statistical significance was set at \( P < .05 \). All data were reported as the mean ± SD.

**Results**

Females had a significantly higher peak pressure on the hallux, toes, forefoot, and inside of the foot compared to that of males during standing (Table 2. All; \( p < .01 \)). Similar to the results during standing, a significantly higher peak pressure was observed on the hallux, toes, forefoot, and inside of the foot in females than males during walking (Table 2, All; \( p < .01 \)). In all cases, greater loading was applied to inside of the foot in the middle of the stance phase than outside. COP movements were
similar across subjects such that they translated from the hindfoot through the middle of the midfoot, and finally toward the base of the first toe (Figure 4). There were no significant differences between genders (Table 3, All; \( p > .05 \)).

**Discussion**

The most important finding of this study was that females applied a significantly higher peak pressure on the hallux, toes, forefoot, and inside of the foot while both standing and walking than males. Females have a higher pelvic tilt and a center of gravity anterior to males[11], which can result in higher plantar pressure at the toes and forefoot. The movement of knee-in while walking was likely to occur in females because of weaker gluteus medius strength compared to males[12]. Thus, the peak pressure at the inside of the foot may be higher. Putti et al measured plantar pressure using an in-shoe foot pressure measurement and reported no peak pressure differences between females and males[9]. Demirbuken et al measured plantar pressure using the same system and detected higher toe peak pressure in females compared to males and an age-dependent increase of plantar pressure at the female toes and forefoot [10].

Technical improvement of the measurement system was demonstrated for evaluation of the plantar pressure during natural activities. The Pedar system (Novel gmbh, Munich, Germany) and F-scan system (Tekscan, Inc, Boston, MA) are the main models of the in-shoe plantar pressure measurement system in the previous studies [13][14]. However, they are relatively heavy (The Pedar system; 400 g, F-scan system; 400 g) and bulky (The Pedar system; 600 g, F-scan system; 300 g). To evaluate natural walking, the size and weight of a measurement device should be as light and small as possible. The newly developed in-shoe device in the current study weighs 17 g and has a volume of 15 m, making it possible to perform standing and walking with less interference than previous products. Additionally, conventional products have 50 Hz of sampling rate, whereas this device has 200 Hz of sampling rate. Therefore, the new system could have less chance to miss some instant and important changes of the plantar pressure during activities. The newly introduced device can be applied to faster movements, such as running and sports activities.

The COP is defined as the centroid of the total number of active sensors, which suggests the spatial
distribution of pressure over time[15]. It has been suggested that the COP provides greater insight into dynamic foot function compared to pressure at discrete regions[16]. Buldt et al reported a difference between the planus and a normal foot in relation to the medial shift of the lateral-medial force index during terminal stance[17]. In this study, COP movements were similar across healthy adult subjects such that they translated from the hindfoot through the middle of the midfoot, and finally toward the base of the first toe. Future studies comparing healthy feet with diseased, such as flat foot and hallux valgus, are warranted.

Although this study did not include cases of hallux valgus (HV), females had a higher plantar pressure at the hallux than males. Nix reported a meta-analysis that estimated that female HV prevalence (30%) was 2.3 times greater than in males (13%)[18]. Studies have reported plantar pressure in HV in the past; however, their results have been inconsistent. Some have reported a high plantar pressure on the hallux[19][20], while others have reported an inverse correlation between severity and plantar pressure at the hallux[21]. There are various causes of HV; however, this gender-based difference in pressure can be suggested as one of the causes.

The findings of this study should be considered after taking into consideration three limitations. Plantar pressure measurement systems are limited in that they only measure force perpendicular to the sensor surface. Therefore, other relevant forces including shear force cannot be measured. However, the current study examined the force during standing and walking when a vast majority of force is applied perpendicular to the foot. The influence of other related forces might be considered when more active sporting activities are involved, i.e. turning, stop-and-go motions. Footwear characteristics such as sole bending stiffness are likely to influence the parameters. To avoid this impact, the same shoes of different sizes were used in the current study; however, care should be taken when using different shoes in future studies. Lastly, although statistical significance was achieved in the comparisons, the sample size might be insufficient to apply this study result to the general population of wider age and/or other cultural backgrounds. It should be noted that the current study results stem from subjects who were relatively younger than most foot and ankle patients, but older than most active sport athletes.
The current study result could be used to develop gender specific design of insole or shoes. Wearing appropriate shoes may help prevent foot and ankle diseases. In addition, checking the COP movement may help improve gait balance and gait posture. In order to invent therapeutic ones, further detailed evaluations of plantar pressure in pathological feet are needed, and the new measurement tool might be applicable.

Conclusions
Females tend to put more pressure on the front and medial side of the foot during natural standing and walking than males.

Abbreviations
COP: center of pressure; AP: antero-posterior; ML: medio-lateral; HV: hallux valgus

Declarations
Ethics approval and consent to participate
The study protocol was approved by the institutional review board of Kobe University Graduate School of Medicine (No. B190150). Written informed consent was obtained from each subject.

Consent for publication
Not applicable.

Availability of data and materials
The datasets used and/or analysed during the current study are available from the corresponding authors on reasonable request. Please contact authors for data requests (MD, PhD. Yuichi Hoshino - email address: yuichi-h@mta.biglobe.ne.jp).

Competing interests
The authors declare that they have no competing interests.

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Authors' contributions

TY, YH and NK were involved in study conception and design, data collection, data analysis and interpretation, and drafting the manuscript. KN, KI and KN were involved in data interpretation and contributed to drafting the manuscript. DA, TM and RK was involved in study design, data interpretation, and contributed to drafting the manuscript. All authors have read and approved the final manuscript.

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Tables

Table 1 Demographic data

| Demographic data | Females | Males | P Value |
|------------------|---------|-------|---------|
| Age (years)      | 32 ± 9  | 33 ± 6| 0.45    |
| Height (m) *     | 1.58 ± 0.05| 1.73 ± 0.07| < .01  |
| Weight (kg) *    | 51.4 ± 5.7| 68.9 ± 9.8| < .01  |
| BMI (kg/m²) *    | 20.5 ± 2.1| 23.1 ± 2.7| < .01  |
| Shoe size (cm) * | 23.8 ± 1.0| 27.0 ± 1.1| < .01  |

Gender comparison of demographic data, *p < .01 significantly higher, Paired t-test. Values are given as mean ± SD.

Table 2 The state of standing and walking peak pressure
Gender comparison of the state of standing and walking peak pressure, *p < .01 significantly higher, Paired t-test. Values are given as mean ± SD (kPa).

**Table 3 The COP movement**

| Gender comparison of the COP movement, there was no significant difference between genders, Paired t-test. Values are given as mean ± SD (mm). |
|---|
| **The COP movement** |
| **Females** | **Males** | **P Value** |
| **AP** | 164.9 ± 29.3 | 164.4 ± 34.2 | 0.64 |
| **ML** | 15.4 ± 4.8 | 16.1 ± 4.5 | 0.44 |

AP; antero-posterior, ML; medio-lateral.

Figures
Plantar pressure measurements (A) Ten of the sensors are attached underneath the insole and connected to the measuring unit. The sensors are only 1mm in thickness and total 12g in weight. (B) The measuring unit is only 17g in weight and collects data at 200Hz. (C) The sensor is placed underneath the insole and connected to the measuring unit on the top of the foot.
Figure 2

Plantar pressure during walking Plantar pressure in each the toes, forefoot, midfoot and hindfoot area during walking. The maximum loading in each part reached its peak starting from the hindfoot, the midfoot and the forefoot, consistently.
Figure 3

The evaluation of plantar pressure (A) The value of the sensor a in the figure was defined as Hallux. (B) Areas for analyzing weight-bearing point in anteroposterior direction. The evaluation was divided into four parts: toes, forefoot, midfoot, and hindfoot, and the average value was calculated. (C) Areas for analyzing weight-bearing point in medio-lateral direction. The average value was calculated separately for the inside and outside.
The COP movement A typical case of COP movement during walking. The COP movements were similar across subjects such that it translated from the hindfoot through the middle of midfoot, finally toward the base of first toe.