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Research Paper

An investigation of plantar pressure changes from different textured insole and arch structure in flat and normal feet groups

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ABSTRACT

The arch plays the role of buffering the impact and stress caused by the body. Flat-footed people do not have a normal arch when standing or walking, due to the fact that the tissues holding the joints in the foot together (called tendons) are loose. Injuries may occur since there is no arch to reduce the impact force, with their foot having complete or near-complete contact with the ground. The purpose of this study was to explore the effect of using textures and arch insoles on improving the pressure distribution and balance of flat feet sole. The experimental results show that although the texture insoles can change the situation of flatfoot pressure unevenness, it cannot effectively improve the flat feet balance problem. However, with modest arch support, it lowers the flat base peak, especially on the big toe, forefoot and heel. At the same time, it can improve the discomfort of the inside of the mid-foot when standing for a long time. Moreover, since the extent of arch collapse is not the same for each foot, the left and right foot showed different phenomena of uneven plantar distribution, supporting again that arch collapse has a significant effect on the uneven plantar pressure.

Key word: Textured insole, ANOVA, plantar pressure, flatfoot.

INTRODUCTION

The human foot is not only one of the most elaborate structures but also most complicated organ. Inappropriate use of foot may result in diseases on foot, and even affect people's health. Every day when people are standing, walking or involving in other sports, the foot continuously suffers from the reaction force due to their own body weight. Macwilliams et al. (2003) argued that, through foot pressure signals, the so-called plantar pressure, one may find out the medical causes of a certain disease in patients. Orlin and McPoil (2000) considered that exploring the plantar pressure of the foot and ankle during gait and other functional activities can be used to assess and treat various foot-related injuries in patients. Undoubtedly, obesity has a direct effect on foot pressure (Butterworth et al., 2015). Bypassing the body weight factor, it can be effective in reducing foot injury if foot pressure is evenly distributed across the foot area (forefoot, mid-foot and hind foot) (Sneyers et al., 1995). The study shows that under the normal gait situation, the largest pressure points are located in the second and third metatarsal regions, while the submaximal pressure points occur in the calcaneal region (Kanatli et al., 2003). Roy (1988) points out that the maximum plantar pressure and forelimb lesions have a great correlation, such as thumb valgus patients in the lateral metatarsal area. All of the above support that whether the plantar pressure is evenly distributed or not, it is an important issue.

The plantar pressure was closely related to the arch of the foot, which plays the role of buffering the impact and pressure on the body when people are walking or jogging (Rome and Mch, 1991). Kaye and Jahss (1991) further argued that the arch of the foot helps to reduce the human foot injury and fatigue while bearing weight. The flatfoot population lacks arch foot to cushion the pressure from the ground, due to the arch collapse problem caused by many congenital and acquired factors, and in the long run their

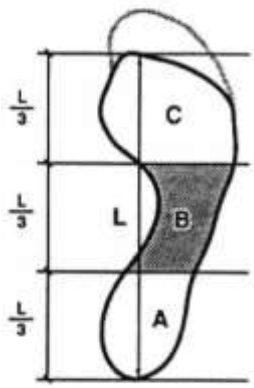

Figure 1: Areas of fore-foot, mid-foot, and rear-foot (A: rear-foot area; B: mid-foot area; C: fore-foot area).

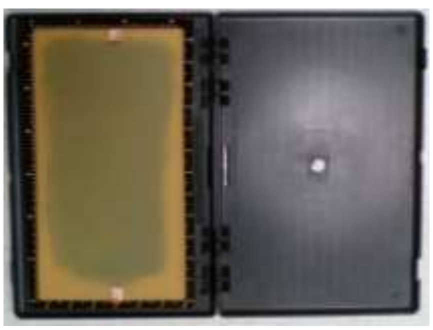

Figure 2: MP-5 footprint device.

foot as well as health might be greatly affected. Furthermore, the extents of arch collapse tend to be different for the left and right foot, which might damage the balance and affect the walking, due to asymmetric gait (left and right foot gait abnormalities). Chen et al. (1995) proposed that placing rough textured sand in socks can significantly change the subject's foot sensory feedback, increasing the sensitivity of the foot in patients with touch-sensitive defects and reducing the severity of the body swaying when standing. More specifically, the result showed that the pressure of forefoot and mid-foot increased significantly while the pressure of toes decreased significantly. Kelleher et al. (2010) further supported that the addition of textured coarse textures on the insole surface can alter the sensory feedback from the foot. Charlie et al. (2016) argued that wearing with a 3mm-heighted texture insoles can help improve the asymmetric foot pressure, and that the weight burden and hoop status of asymptomatic gait patients were immediately improved when the insoles were worn.

Based on the above research so far, no scholars have studied the effect of plantar pressure on the subject in combination with arch and texture insoles. Therefore, this study, on the one hand, tends to evaluate the effect of applying texture on the changes of plantar pressure of flat feet people, and on the other hand, tends to improve the flat arch collapse, foot pressure distribution uneven and standing instability and other issues.

In this study, a number of volunteers were first invited to take the plantar flatness test for deciding the extent of their foot flatness. Then, we used the self-made foot pressure sensing insoles (including different insoles and arch Support insoles) to obtain plantar pressure distribution. To explore the subject plantar pressure changes, six different types of insoles with/without an artificial arch were used. Finally, ANOVA, a statistical analysis method, was used to differentiate the difference between two groups. This study is organized as follows: materials and methods, subjects, data collection and data analysis. Thereafter, the results of the experiments are summarized. The final discussion are then drawn.

MATERIALS AND METHODS

Here, we first explained the device used in this study, including MP-5 footprint device and self-made pressure sensing insoles. Thereafter, we explained the characteristics of the participants invited and the procedure to collect the data. Finally, we discussed the data collected.

Device

MP-5 footprint device

There are a number of ways to measure the extent of foot flatness of a participant. In this study, the arch index (AI) proposed by Cavanagh and Rodgers (1987) was used. It was decided by the ratio of the area of mid-foot to the area of the entire foot excluding the area of toes, as shown in Figure 1. Based on Equation (1), an participant will be classified as the group of high arch people if AI value is less than or equal to 0.21, the group of low arch people if greater than or equal to 0.26, and the group of normal arch if in-between 0.21 and 0.26:

$$\text{Arch index} = B/ (A+B+C) \qquad (1)$$

To obtain the areas of different blocks (fore-foot, mid-foot, rear-foot), the MP-5 footprint device (Figure 2) was used. Figure 3 shows an example of a footprint image obtained from the MP-5 device. Two types of information can be obtained from this image. One is the information of the areas of fore-foot, mid-foot, and rear-foot, allowing us to calculate the AI value. The other type of information is the significant plantar areas of the foot(the deeper one dives, the greater the pressure exerted upon), the significant sub-regions to measure the plantar pressure, which will be used

Figure 3: A footprint image obtained from the MP-5 device.

Figure 4: MP-1 plantar pressure test strip.

Figure 5: An example of a participant's test strip.

in our design of self-made pressure insoles. To understand the distribution of the most stressful points for most subjects, 10 participants were invited to walk 250 steps by

Figure 6: Blocks of left and right foot plantar.

wearing the MP-1 plantar pressure test strip (Figure 4). An example of a participant's test strip was shown in Figure 5. The experimental results show that the maximum pressure of the subjects lies in the forefoot area and the second largest pressure is in the area of hallux and heel. In addition, the difference between the flatfoot and normal people is in the arch of the foot, which is located in the part of the mid-foot. The plantar of each foot is divided into 6 blocks: hallux (HA), medial forefoot (MF), lateral forefoot (LF), medial mid-foot (MM), lateral mid-foot (lateral mid-foot, LM), and the heel (rear foot, RF). In total, as shown in Figure 6, there are 12 blocks for both feet.

Self-made pressure insoles and artificial arch

As mentioned above, the plantar of left and right foot is divided into 12 blocks. For each block, a piezo-resistive force sensor was embedded into an insole (12 sensors for both feet), which was inserted into the shoe. As the foot size of each individual differs, so the person's detection point is different, mainly based on the individual's footprint obtained. These sensors were linked with an Arduino, a family of single-board microcontrollers, which was responsible for sending the data collected from the piezo-resistive force sensors to the computer. We noted that the plantar pressure of each individual differed, as each possessed different footprint image. The detection locations of the piezoresistive force sensors were mainly decided by the test strip of each participant (see Figure 5). A 3D printer was used to generate various height insoles so as to investigate the effect of different heights of texture on plantar pressure change. Each insole consists of 18 identical texture granules on the sole, as shown in Figure 7. In this study, there were three different texture granule heights of insoles: 0, 3 mm or 6 mm. Inside the insole, we kept a place where we could put an artificial arch for flat-foot people. The arch is 7 cm long, 1.5 cm wide and 1.5 cm high. In total, for each foot, there were six different types of insoles, listed as follows:

1) The insole with a texture height of 0 mm and no arch support.

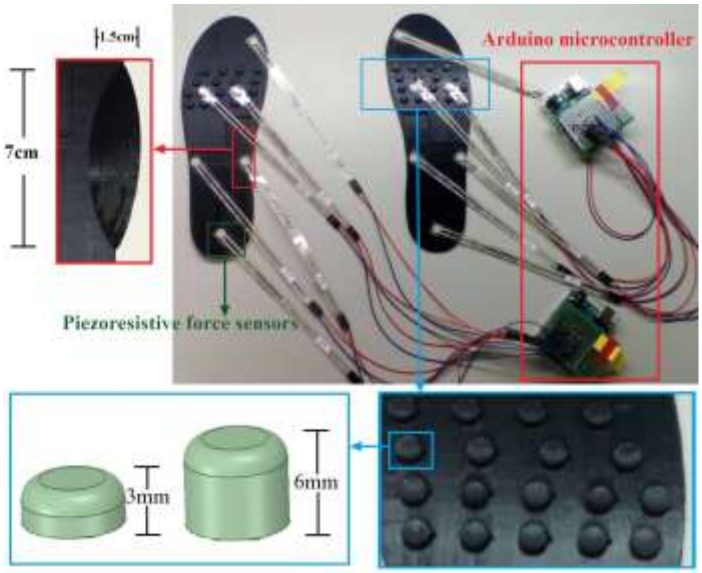

Figure 7: Self-made pressure insoles.

2) The insole with a texture height of 0 mm but with arch support.
3) The insole with a texture height of 3 mm and no arch support.
4) The insole with a texture height of 3 mm but with arch support.
5) The insole with a texture height of 6 mm and no arch support.
6) The insole with a texture height of 6 mm but with arch support.

Subjects

More than 26 volunteers who had not any foot or lower limb diseases in the past six months were included in the experiment. Some had both feet flat while some only have a single foot flat. Among these participants, nine had both flat feet (to be referred to as group I), nine both normal feet (to be referred to as group II), three left flat feet (to be referred to as group III) and five right flat feet (to be referred to as group IV). The above classification was based on the arch index proposed by Cavanagh and Rodgers (1987).

The arch indexes of these participants are shown in Tables 1 and 2. With an average age of 22 ±1 years (group I: height 175.5±6.6 cm, body mass 72.3±12.2 kg, BMI 23.4±4.6; group II: height 172.1±4.8 cm, body mass 69.5±8.4 kg, BMI 23.4±4.1; group III: height 173.6±2.5 cm, body mass 68.3±5.4 kg, BMI22.6±1.2; group IV: height 172.1±5.6 cm, body mass 73.3±6.5 kg, BMI 24.7±2.5).

Data collection

During the experimental process, all of these participants were invited to wear each pair of these six different foot pressure sensing insoles, respectively. Starting from the pair of insoles with a texture height of 0 mm and no arch support, each participant was asked to stand 60 s to collect the plantar pressure data. The subjects were allowed to sit and rest for 5 min between any two runs of experiments. The total experimental time was 31 min for each participant. Analysis of variance (ANOVA), a statistical analysis tool, was used to investigate the effects of different insole textures on the plantar pressure of flat feet and normal feet by the P-value and the alpha value. The alpha value in this study was set to 0.05. Basically, it was concluded as a significant difference when the P-value was less than 0.05. We noted that it could be concluded as a different but not significant difference when the P-value was higher than or equal to 0.05, but less than 0.3. In addition, three extra measurement criteria were used to assess the difference between the control and experimental groups: mean pressure (MP), peak pressure (PP) and standard deviation (STD).

RESULTS

Difference of plantar foot pressure between flat and normal feet

The purpose of this study was to investigate the plantar foot pressure difference between the flat and normal feet people. In this experiment, the results of these groups of people wearing 0 mm insole and no arch support were contrasted. The general finding was that, for both flatfeet and normal feet people, the highest MP and PP was at the rear foot area, indicating that people tended to put weight at the rear foot area (see Figure 8a and b). An obvious

Table 1: Group I and group II subjects arch index.

Subjects	Classification	AI of the left foot	AI of the right foot
A	Both flat feet	0.353	0.293
B		0.291	0.308
C		0.354	0.261
D		0.374	0.267
E		0.261	0.275
F		0.356	0.336
G		0.276	0.306
H		0.293	0.266
I		0.265	0.263
J	Both normal feet	0.229	0.228
K		0.259	0.251
L		0.254	0.254
M		0.250	0.256
N		0.244	0.238
O		0.242	0.255
P		0.216	0.259
Q		0.238	0.236
R		0.257	0.259

Table 2: Group III and group IV subjects arch index.

Subjects	Classification	AI of the left foot	AI of the right foot
S	Left flat foot	0.353	0.256
T		0.303	0.247
U		0.293	0.251
V	Right flat foot	0.235	0.263
W		0.249	0.300
X		0.241	0.289
Y		0.217	0.267
Z		0.239	0.265

difference, as expected, was the plantar pressure difference at the mid-foot area as people in the flat feet group showed both high MP and PP, while people in the normal feet group showed nearly zero pressure. This was due to the fact that the former had the arch deformity problem whereas the latter had arch to support their body weights.

An interesting result was that the plantar pressures of the flat feet group were comparatively higher than those of the normal feet group at the areas of hallux and medial forefoot. It was observed that both MP and PP of the flat feet group at these two areas were almost double more than those of the normal feet group. The result implied that people of the flat feet group tended to put their weights on the front of their feet, causing them to lean forward while standing, due to the defect of the arch. For a long run, this might cause great damage to the hallux and mid-foot of the flat feet people, which in turn might put them in the risk of hallux valgus and plantar fasciitis.

Another measurement criterion is the standard deviation (STD) of plantar pressure, a measure of how far a set of values are spread out relative to the mean value for that set of values. Generally speaking, the smaller the STD value, the better the dynamic stability of the body. The result showed that the STD value of the flatfeet group was higher than that of the normal feet group (see Figure 8c). The STD of the flat feet group at the area of the hallux was observed to be approximately 4.5 times higher than that of the normal feet (flat feet: ±12.51, normal feet: ±2.28). The STD of the flat feet group at the medial forefoot was 79% higher than that of the normal feet (flat feet: ±10.50, normal feet: ±5.86). The defect of the arch does not only causes an abnormal distribution of the foot pressure, but also results

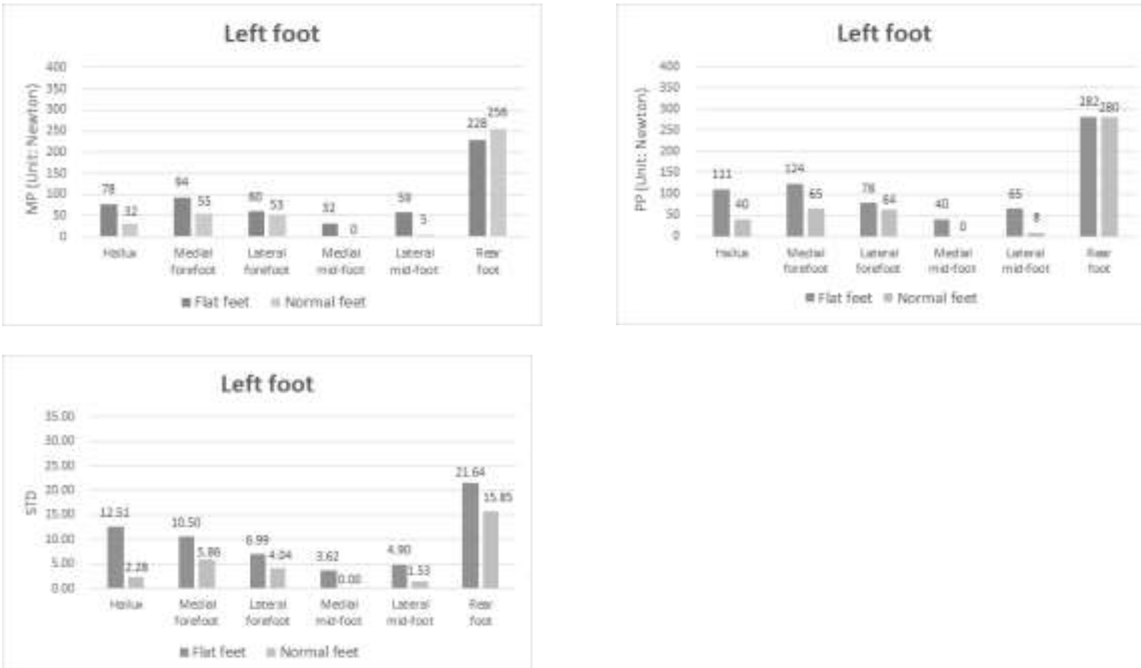

Figure 8: Flat feet and Normal feet Left 0 mm insole MP, PP and STD.

in a poor body stability when standing and stretching.

Difference of plantar foot pressure between flat and normal feet

As mentioned above, some people have two feet flat (group I) while some have only one foot flat (groups III&IV). The following study is to investigate the difference in foot pressure between people with both feet flat and only one foot flat. Two further experiments were conducted. In the first experiment, the results of groups I and III wearing 0 mm insole and with no arch support were contrasted. It was observed the difference in these two groups was that people in group I have right foot flat whereas group III have right foot normal (noted that both groups have left foot flat). For the left foot (the flat feet), the result showed that the MP and PP plantar pressures of the people having both feet flat was relatively larger than those with single foot flat. We observed that even there existed some difference in plantar pressures between these two groups of people; however, generally speaking, the difference was not that significant. On the contrary, for the right foot (that is, one has right foot flat and the other has normal feet), the difference of plantar pressure was obvious, in particular at the areas of hallux and medial forefoot. The conclusion is in line with our result in the previous section that people of the flat feet group tended to put their weights on the front of their feet, causing them to lean forward while standing. The phenomenon was more observed when both feet were flat than when only single foot was flat. A major difference was that the STD values of the people with both flat feet at the areas of hallux and medial forefoot were comparatively higher than those with single foot flat, indicating that the defect of the arch caused a poor body stability when standing and stretching (Figure 9). In the second experiment, the results of groups I and IV wearing 0 mm insole and with no arch support were contrasted. The result was similar to that in the first experiment. In a nutshell, in addition to the conclusion that there was significant difference in the flat and normal feet, two other conclusions were reached. The first is that no matter whether people have both feet flat or only one foot flat, there is no obvious difference in their foot pressure on the flat feet side. The second conclusion was consistent with the first regardless the side of foot flat. Based on the above-mentioned finding, all the following experiments will only consider one side of feet flat.

Effect of increasing texture height on plantar pressure

The purpose of this study was to investigate the effect of increasing texture height on plantar pressure changes for the flat-feet and normal-feet people. In this experiment, the results of these groups of people wearing these three different heights (0, 3 and 6 mm) of insoles independently and no arch support were contrasted. For normal-feet people, the experimental results (Figure 10a and b) showed that the mean and peak plantar pressure at each contact point increases with the increase of texture heights, as the texture insole can directly increase the effectiveness (or

(a) Groups I &III

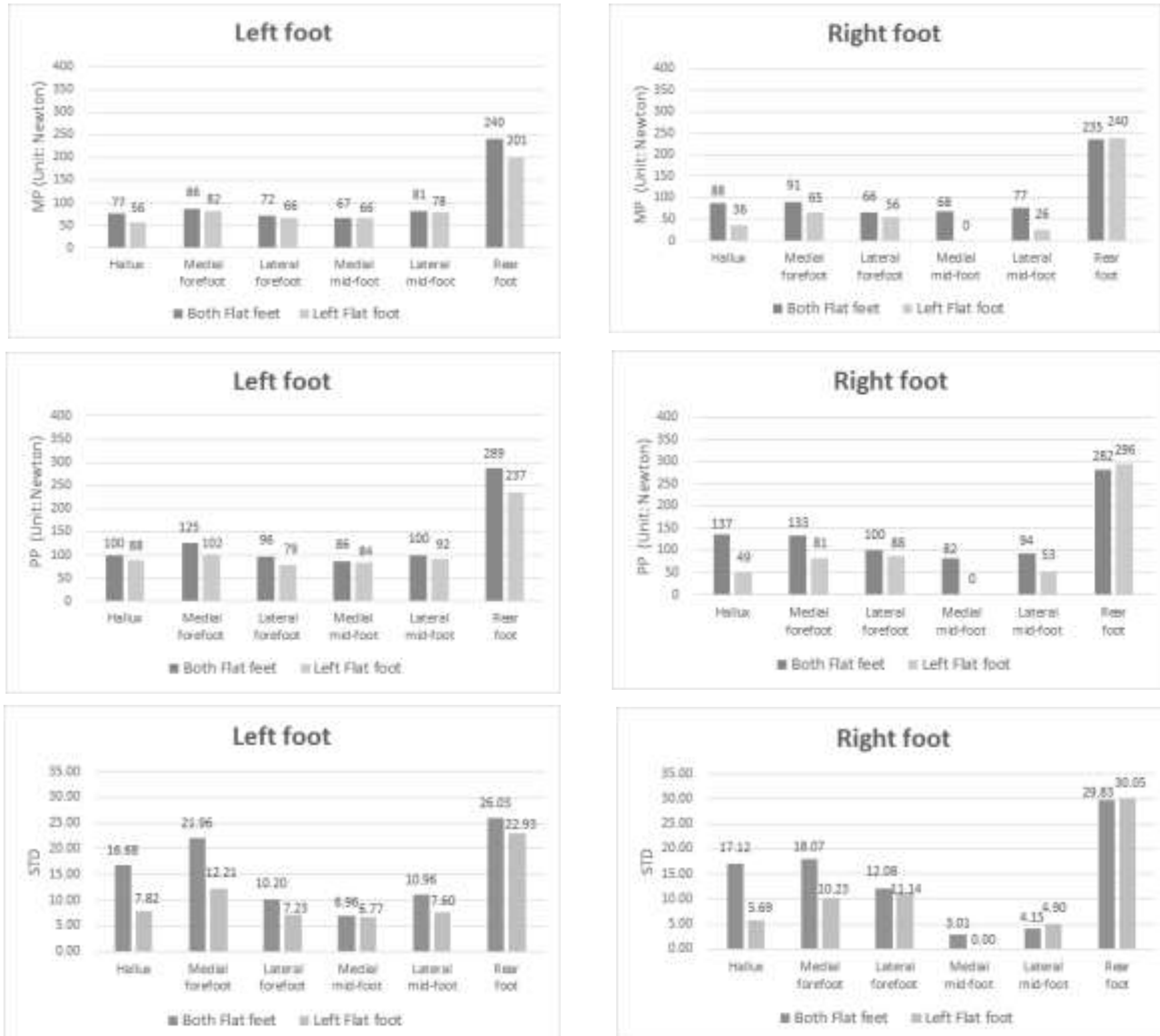

Figure 9: Both Flat feet、Left Flat feet、Right Flat feet0mm insole MP、PP and STD
+ significance of P-value <0.3, that difference does exist but no significant.
* significance of P-value <0.05, that a significant difference does exist.

sensitivity) of detecting plantar pressure. Similarly, for the flat-feet group, the mean and peak plantar pressure increased at the contact points of the texture insoles placed (that is, the medial forefoot and lateral forefoot areas) as well as the rear foot area. However, on the contrary, the mean and peak plantar pressure at the areas of hallux and mid-foot (both medial and lateral sides) decreased as the texture heights increased. The result was interesting such that an increase in the texture height helped in reducing the mean and peak pressure of the hallux and midfoot areas of the flat feet. This implied that using texture insole with some heights help reduce the risk of the hallux valgus and plantar fasciitis problems for the flat-feet people. Another interesting result (Figure 10c) was that the STD values of the flat-feet group significantly decreased at the area of the hallux as the texture heights increased, suggesting that the use of texture insole with some heights do not only help reduce the mean and peak pressure, but also decrease the dynamic instability at the hallux area.

Effect of using artificial arch for flat feet people on plantar pressure

The purpose of this study was to investigate the effect of using artificial arch for flat feet people on plantar pressure. It was observed that the normal feet people did not have arch deformity and only those with flat feet were involved in this experiment. The arch was placed at themedial mid-foot (MM) area. The results of those flat feet people wearing

(b) Groups I & IV

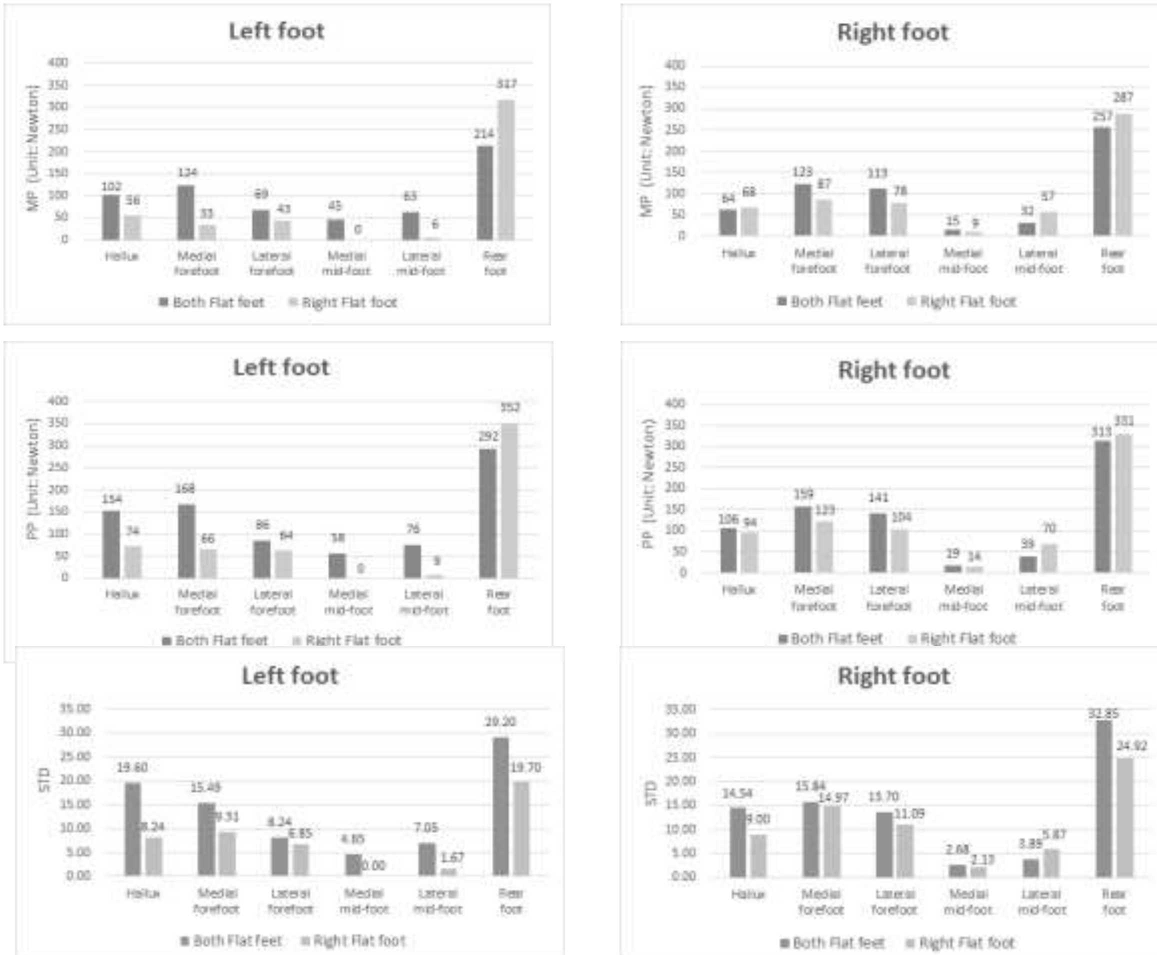

Figure 9: Both Flat feet、Left Flat feet、Right Flat feet0mm insole MP、PP and STD
+ significance of P-value <0.3, that difference does exist but no significant.
* significance of P-value <0.05, that a significant difference does exist.

0 mm-height of insoles with and without no arch support were contrasted.

The result showed that, after putting an artificial arch, there was a significant decrease of MP value at the hallux area (from 78 to 45), at the medial forefoot area (from 94 to 63), and at the lateral forefoot area (from 60 to 54). However, by contrast, there was a significant increase in MP value at the medial mid-foot foot area (from 32 to160), at the lateral mid-foot area (from 59 to 77). It was observed that there was a slight increase of MP at the rear foot area (from 228 to 232). All of the above-mentioned results showed that all the plantar pressure changes were directed to make those who have the arch collapse problem behave like those who do no, indicating an artificial arch can effectively help relief the arch collapse problem. The improvement was more evident if we judged it by PP. There was a significant decrease of PP value at the hallux area (from 111 to 55), at the medial forefoot area (from 124 to 70), and at the lateral forefoot area (from 282 to 265). All of these supported that, if using an artificial arch, the chance of great plantar pressure damage might be greatly relieved. When measured by STD, the result was similar such that there was a significant decrease at the hallux area (from ±12.51 to ±7.60), at the medial forefoot area (from ±10.5 to ±6.12), at the lateral forefoot area (from ±6.99 to ±5.51), and at the rear foot area (from ±21.64 to ±18.63), demonstrating that the use of an artificial arch can effectively improve the body stability for the flat feet people (Figure 11).

A further study is needed to investigate whether there is significant difference of MP, PP, and STD between the flat-foot people with arch support and the normal-foot people. The result showed that these two groups of people almost had the same MP and PP at all areas except at the medial and lateral mid-foot areas. The difference at the latter areas was mainly because of the pressure from the artificial arch, indicating that the flat feet can be restored to a normal

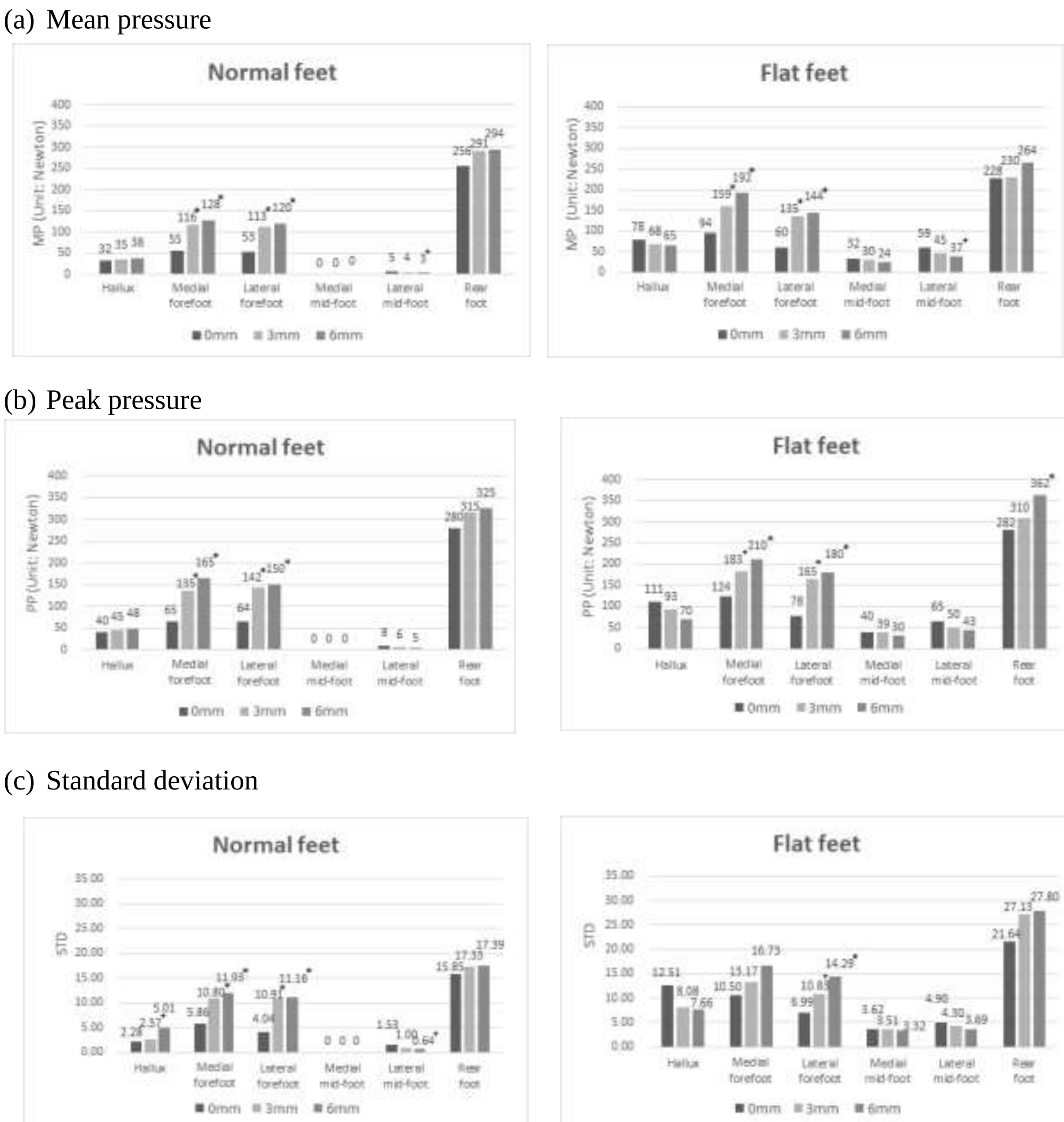

Figure 10: Texture foot pressure distribution comparison figure.
+ significance of P-value <0.3, that difference does exist but no significant.
* significance of P-value <0.05, that a significant difference does exist.

pressure distribution through the arch insole correction. The result was interesting that not only the MP and PP data were similar, but the difference of STD was comparatively small. The difference of STD at the hallux was (flat feet 0 mm + arch: ± 7.60. Normal feet 0 mm: ± 2.28), at themedial forefoot only 4% (flat feet 0 mm + arch: ± 6.12. Normal feet 0 mm: ± 5.86), and rear foot difference 15% (flatfoot 0 mm + arch: ± 18.63. Normal feet 0 mm: ± 15.85), showing that the arch insole is effective in improving flat body stability (Figure 12).

DISCUSSION

The pressure distribution on the soles of the feet is critical to human health. When people stand or walk, the role of the arch is to buffer the body's counterforce from the ground. When the arch is defective, such as a flat feet, it is as if the base of the human body is skewed. Not only does it affect the balance of the body, it can also cause some form of physical harm. For those who have a defective arch, they

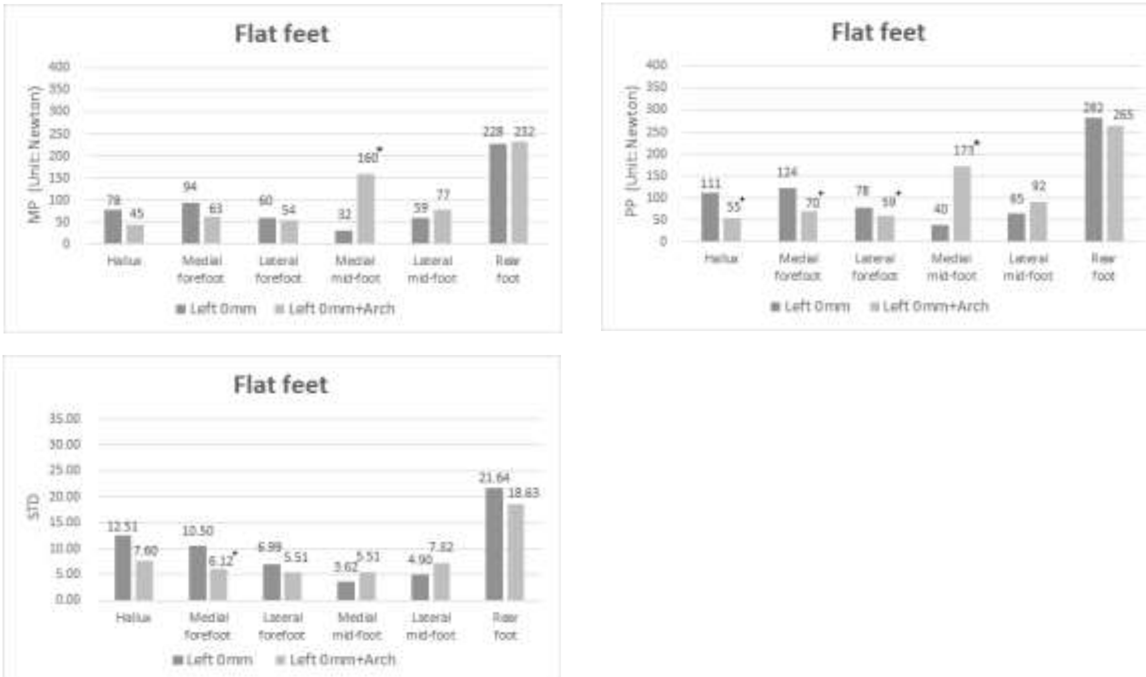

Figure 11: Flat feet left 0 mm, left 0 mm+ Archinsole MP, PP and STD.

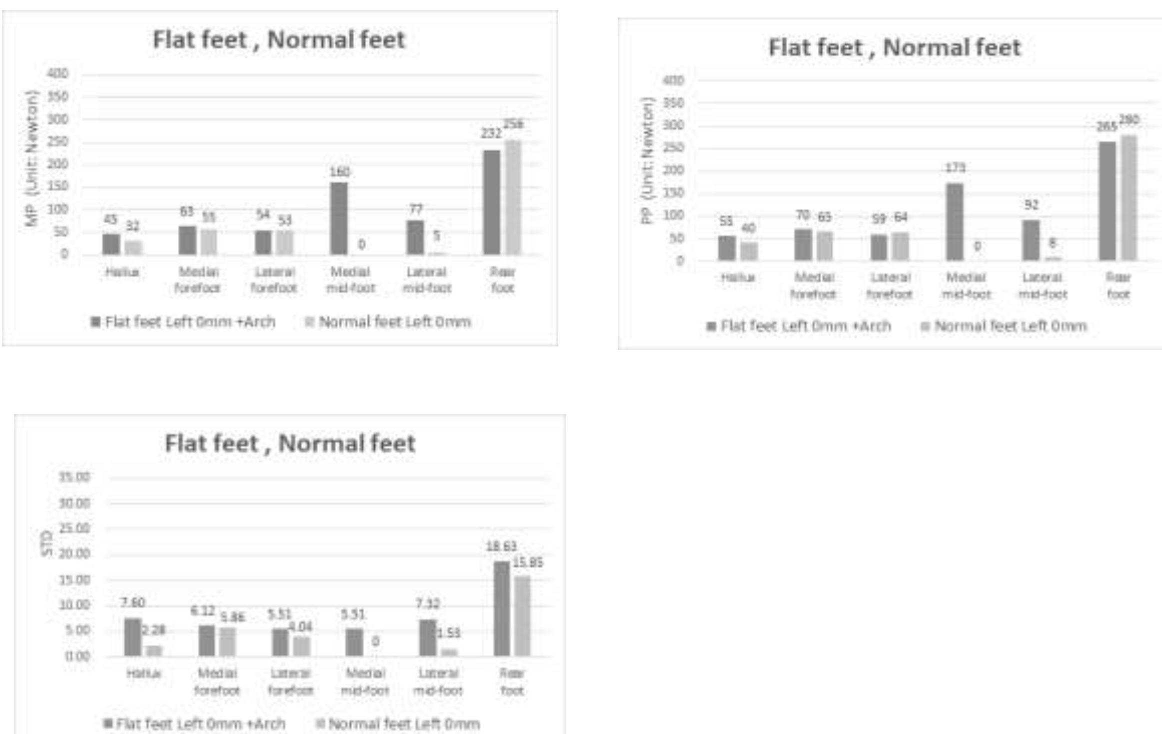

Figure 12: Flat feet left 0 mm, left 0 mm + Archinsole MP, PP and STD.

are prone to feel problems such as pain inside the arch after long standing or exercising. The long-term accumulation of this problem will increase the bearing burden on the feet, legs, knee muscles, and joints of the flat feet and might cause foot problems or nerve or musculoskeletal lesions. It is generally believed that when the flat people walk or run, their hallux, forefoot, and heel are subjected to great plantar pressure. If these pressure can be appropriately distributed, possible foot discomforts and injuries might be reduced (Sneyers et al., 1995).

In this study, an Arduino linked with some pressure sensing strips was used to develop a number of sensing insoles for detecting the static or dynamic plantar pressure and to explore the distribution and body stability of flat feet pressure through some insoles with different texture heights and an artificial arch. We first studied the difference in foot pressure between flat feet and normal feet. The result showed that people with flat feet, when compared with people with normal feet, had a comparatively high plantar pressure on the hallux and forefoot and conversely relatively small on the heels, supporting that people with flat feet had a tendency to lean forward when standing or walking. The heel (RF) is the block where the flat feet and normal feet are subjected to the maximum plantar pressure when standing, and is also the most important block for observing the body balance. For the heel area, we noted that even though the mean pressure of the flat feet people was comparatively lower than that of the normal feet people; however, by contrast, the peak pressure of the former was higher than that of the latter. In particular, the plantar pressure of the subject with flat feet changed continuously during the test process, revealing a poor body stability when standing and stretching. The phenomenon was more notable when both feet were flat than when only single foot was flat. The results of this study show that the use of textured insoles has some degree of help in improving the flat feet problem. By increasing the texture and height of the insole, this phenomenon can be moderately improved. More importantly, the use of textured insoles help increase the dynamic stability of people when standing. However, still quite limited was the effectiveness of relying solely on textures to improve the foot pressure and balance of the flat feet. What's more interesting is that if an artificial arch is added, the high plantar pressure problem on the hallux and forefoot can be effectively improved. We note that, except the contact areas where the artificial arch was placed, there was no significant difference in plantar pressure between the flat feet and the normal groups. Moreover, the degrees of continuous changes of the plantar pressure during the test process improved as well, when an artificial arch was used. The effectiveness of improving the flat feet problem was comparatively more significant when an artificial arch was used than when a textured insole was used. Contrary to our expectation, the effectiveness was not that significant when both artificial arch and textured insole were used. Here, it can be said that this study is still not perfect, and that some possible studies may be proceeded. First, the accuracy and sensitivity of the equipment are still not quite satisfactory. This is because all foot pressure data collection in this study was done through a self-made plantar pressure sensing insole. In this insole, this study uses circuit board soldering methods to connect piezo-resistive force sensors and Arduino. The higher the density of components on the circuit board, the higher the noise interference will be. Accuracy and sensitivity can also be affected to some extent. This study can only reduce its noise interference as much as possible. In the future, the accuracy and sensitivity of data collection might be improved through the integration of sensors and circuits into a chip. Second, limited by the equipment, the plantar pressure detected in this study still belongs to the spot-like local collection. Although the actual data collection before this study, according to the subject's footprints, is to determine the location of the pressure sensing point, however, the determination is manual and more or less still not perfect. In the future, if comprehensive regional data collection is used, it is believed that different data results can be obtained. Third, all collected data are still static (that is, there is no dynamic data, such as running or brisk walking). Fourth, the pressure value collected in this study is a short-term data collection. In the future, we should consider allowing users to use it for a period of time before observing the changes in long-term stress. Finally, in the future, when the study reaches a relatively mature stage, it may be possible to cooperate with hospitals to assist in clinical diagnosis, for example, in patients with diabetes or lower extremity edema, and to investigate the changes in plantar pressure in patients with diabetic foot and lower extremity edema. Ultimately, a customized foot pressure sensing system used by people, time, and place can be established to “immediately” sense and “timely” notifications to reduce some possible injuries.

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