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Original Article

Effects of cushioning pads on heel and forefoot plantar pressure reduction in walking and running♣

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Abstract

Excessive walking and running can cause foot injuries due to continuous high impact force and pressure on the foot sole, especially in the heel and the forefoot regions. This problem can be relieved with insoles made of various cushioning materials. The cushioning pads of insoles at forefoot and heel regions significantly influence plantar pressure and reduce the forces during walking and running. However, no studies have compared the mechanical properties of different cushioning materials as regards decreasing the plantar pressure and forces during these activities. The effects of different cushioning materials on the reduction of force and pressure at forefoot and heel regions, especially during running, were compared in this study. Mechanical properties of insoles for compression, hardness and cushioning were evaluated and analyzed. Moreover, the plantar pressures measured by the Pedar X system were collected and compared among volunteers. It was found that the EVA additional pad improves the cushioning by the insole. However, an insole made of PE was the best pad for reducing plantar pressure during both walking and running activities. In addition, the relationship between plantar pressure reduction and compressive property of insoles was found.

Keywords: cushion insole, mechanical properties, plantar pressure, walking, running

1. Introduction

Walking and running cause impact forces to a foot of about 1-3 fold the body weight, and consequently many people suffer from knee, ankle, and foot injuries (Kernozek, Vannatta, Gheidi, Kraus, & Aminaka, 2016; O'Leary, Vorpahl, & Heiderscheit, 2008). Shock loads induce high plantar pressures, especially at the heel and the forefoot (Windle, Gregory, & Dixon, 1999). There are not only injuries, but also high plantar pressures from walking and running can cause discomfort and microtrauma of the underlying tissues (O'Leary *et al.*, 2008), with pain in the feet and in the lower body (Kernozek *et al.*, 2016). High pressure results in spur or plantar heel pain and can cause bone fractures (Ribeiro *et al.*, 2011; Windle *et al.*, 1999). Therefore, many studies have been conducted to reduce impact forces, especially at the heel and the forefoot regions.

Cushioning property of sports shoes is necessary and important during such high-impact force activities. Generally, the midsole structure of a sports shoe plays the most important role in reducing the impact forces. Because of this, shoe manufacturers have studied and developed shoes to reduce the shock loads (Dinato *et al.*, 2015). However, depending on the shock absorption properties of the materials used and the design, some shoes have limitations in their shock absorptionability. Therefore, some studies have

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developed cushioning insoles to enhance the cushioning properties of the shoes (Chiu & Shiang, 2007; O'Leary *et al.*, 2008). The ASTM F1614 is a standard test for assessing cushioning properties of sports shoes, insoles and other footwear (Dinato *et al.*, 2015; Shimazaki, Nozu, & Inoue, 2016; Silva *et al.*, 2009; Srewaradachpisal, Dechwayukul, Chatpun, Spontak, & Thongruang, 2020). Previous studies have conducted tests of different cushioning materials including ethylene-vinyl acetate (EVA), rubbers, and other alternatives. However, the various cushioning property (force reduction) was not studied on the efficiency of reducing plantar pressure.

The plantar pressure during walking among elderly using PPT insoles at the forefoot was found to be reduced more than when using a metatarsal pad (Lee, Landorf, Bonanno, & Menz, 2014). Developing the insole by adding the Plastazote® foam layer can also reduce the pressure to the forefoot (Chang, Wang, Huang, Lin, & Lee, 2012). The flat Plastazote® insole of 15 shore A hardness could reduce the plantar pressure better than an EVA insole of 40 shore A, but Plastazote® was 2 mm thicker than the EVA (Chang, Liu, Chang, Lee, & Wang, 2014). There is also a study showing that insoles made of foam materials can reduce the pressure better than the nonfoam viscoelastic materials (House, Waterworth, Allsopp, & Dixon, 2002).

For running, Sorbothane® insoles are famous for use as a shock absorber and vibration damper, and they can reduce the shock compared with that when running barefoot or with rather hard shoes (O'Leary *et al.*, 2008). The insoles with polyurethane added to the forefoot region resulted in better forefoot pressure reduction than using a metatarsal pad (Hähni, Hirschmüller, & Baur, 2016). It has also been found that Sorbothane® insoles reduced plantar pressure better than other specific trade-name materials. Sorbothane® insole can reduce the plantar pressure by 23-27% compared to not wearing any insoles (Windle *et al.*, 1999).

Usually, the insoles are fabricated of more than one type of material (Chang *et al.*, 2014, 2012; Chiu & Shiang, 2007; Hähni *et al.*, 2016; House *et al.*, 2002; Lee *et al.*, 2014; O'Leary *et al.*, 2008; Windle *et al.*, 1999; Zhang & Li, 2014). Those insoles have various thicknesses, shapes and multi-layers, leaving a knowledge gap of how each of the insole materials affects plantar pressure reduction, especially in running. In addition, details of insole mechanical properties, especially cushioning properties relating to the plantar pressure and force reduction, have not yet been reported.

Therefore, this work focused on the mechanical properties of the target insoles that potentially reduce plantar pressure in both walking and running. In this study, we performed laboratory mechanical tests to evaluate hardness, compression, and cushioning properties affecting plantar pressure in a volunteer group. The hypothesis was made that high cushioning property insoles could reduce the impact force and the plantar pressure effectively, especially in running activities. The results from this study will be important for design and development of high-performance insoles in the future.

2. Materials and Methods

2.1 Participants

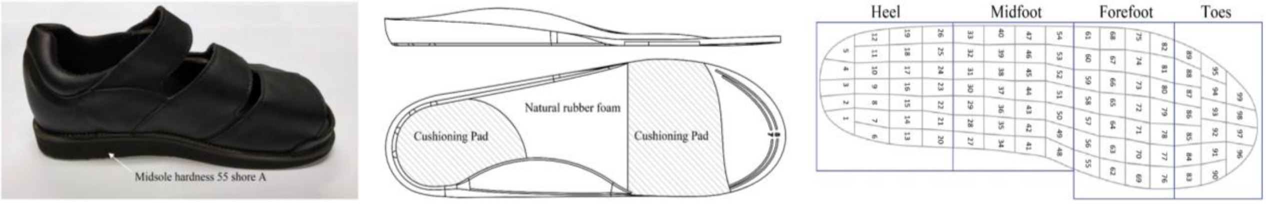
The volunteer subjects were recruited and accepted for this clinical study if they were: (i) healthy, (ii) aged between 23 and 45 years, (iii) able to wear shoe size No. 42, and (iv) familiar with running on a treadmill. The subjects were excluded if they had (i) foot problems within three months preceding the test, or (ii) underlying diseases related to the heart, blood vessels or respiratory system. The study protocol was approved by the Human Research Ethics Committee (HREC) of Prince of Songkla University (Reference HSc-HREC-62-20-1-3) and all participants signed the written informed consent prior to the study.

2.2 Design and forming of shoes and insoles

All participants wore the same shoes to prevent effects of differences in shoes on the plantar pressure. The midsole of shoe was made from EVA with hardness of 55 shore A, as shown in Figure 1a. The insole in this study was made from natural rubber (NR) in foam form by hot compression molding, which is easy to control for shape, arch and thickness. The top surface of the insole was attached with a prefabricated fabric of 1 mm thickness. The heel and forefoot are high impact force areas, thus these areas, as shown in Figure 1b, were designed to have different cushioning pads of Polyethylene Foam (PE), Ethylene Vinyl Acetate foam (EVA) or soft rubber (RUB), designated as Insole 1, Insole 2 and Insole 3, respectively. All the cushioning pads had the same 4 mm thickness in both heel and forefoot regions.

2.3 Mechanical testing of the insoles

The compressive properties of insoles were determined with a universal testing machine (Model Instron 8872, Instron (Thailand) Co., Ltd, Thailand). Specimens were cut from the heel (10 mm) and the forefoot (7 mm) regions of insoles with 28.5 mm diameter in accordance with ASTM D575-91. The testing included 30, 40 and 50 percent strains with the cross-head speed of 10 mm/min for both loading and unloading.



(a) (b) (c)

Figure 1. (a) Shoe with midsole hardness 55 shore A, (b) Locations of cushioning pad (from PE, EVA and RUB) of insoles, (c) Defining the plantar into four regions

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The hardness of insoles was measured according to ASTM D 2240 with a Shore A durometer (Model digi test II, Bareiss, Germany) at three different points of the heel and the forefoot regions.

A custom-built drop-testing machine was used to acquire the cushioning properties of an insole according to ASTM F1614, a standard test for finding the cushioning properties of athlete shoes. The 8.5 kg impact striker with a diameter of 45 mm was dropped onto the sample at impact energy of 5 J. A 10 kN piezoelectric load cell (Kistler 9321b) equipped with a data acquisition board (National Instruments USB-6008) was used to obtain the data of force against time during the impact.

2.4 Plantar pressure assessment

The experiments were conducted at the physical therapy unit, Songklanagarind hospital, Prince of Songkla University, Thailand. Demographic data of all participants were recorded, such as age, weight, height and foot size. The Pedar-X insoles (Novel GmbH, Munich, Germany) were placed between the foot and the insole of each shoe. Before obtaining data in each trial, participants were asked to stand on each leg for calibrating and zero setting of the Pedar-X instrument in unloaded condition, according to the manufacturer's instructions. The subjects were asked to stand on the SportArt treadmill (T645S, SportsArt America, USA) for pretest, then walk at 3 km/h for 2 minutes before changing to running mode at 6 km/h for 2 minutes. Subjects started the test without insole, then they were asked to wear the different insoles for walking and running. Plantar pressure was recorded at a frequency of 100 Hz. The data for each condition were analyzed by dividing the foot into four regions: heel, midfoot, forefoot and toes, as shown in Figure 1c (Nouman, Leelasamran, & Chatpun, 2017). Novel–Win multi-masking software (Novel GmbH, Munich, Germany) was used to analyze the results for maximum force, contact area, the highest and mean pressures as well as the center of pressure in both walking and running.

2.5. Statistical analysis

All statistical analyses were performed using Minitab 18.0. The sample size was calculated based on previous studies that it should be a minimum of 12 subjects to analyze peak plantar pressure between difference insoles (Zhang & Li, 2014). In this study, One-way ANOVA was used in statistical hypothesis testing of differences in foot pressure, contact area and maximum force of different insoles, to describe the relationship, and to summarize the differences by insole for each area of the foot. A p-value in an ANOVA for the plantar pressure that was less than 0.05 indicated significant difference.

3. Results

Twelve male volunteers participated in this study and the participant characteristics are presented in Table 1. In each experiment, all participants were allowed to walk and run without interruption.

Table 1. Demographic data of volunteer participants

Subject (n=12)	Mean±SD	Range
Age (years)	28.17±3.41	23.0-35.0
Weight (kg)	67.95±6.57	54.2-80.0
Height (cm)	173.83±4.49	168-183
Foot length (cm)	26.46±0.58	25.0-27.0
Foot wide (cm)*	10.63±0.53	9.5-11.0

* measure in the widest forefoot.

3.1 Mechanical properties of insoles

Mechanical properties of the insoles were assessed for compression, hardness and cushioning. The compressive stress-strain curves of insoles at three levels of strain are shown in Figure 2. The sample thickness at the forefoot (7 mm) is less than that at the heel (10 mm), resulting in a higher stress, even at the same strain level. The behavior of three insoles showed viscoelasticity, with hysteresis loop area for insole2 (EVA) during load-unload cycle being the largest, followed in rank order by insole3 (RUB) and insole1 (PE).

During the 30% strain (Figure 2a-2b), insole2 had the highest stress corresponding to the hardness of this insole, as shown in Table 2. However, when the maximum strain exceeded 40% (Figure 2c-2f), it was found that the insole3 instead had the highest stress. Insole1, the softest foam, had the lowest stresses at all strain levels. The shock-absorbing ability in Table 2 was tested according to ASTM F1614. In these data, the least peak force indicates the best cushioning. It was found that all insoles helped reduce the shock load, and insole2 showed the best absorption followed by insole1 and insole3, in rank order.

3.2 Parametric studies using volunteers

Assessment of the various insoles affecting plantar pressure was tested using volunteers and analyzed with Pedar X. It was found that the maximum forces in running were approximately 1.6 times higher than in walking (Figure 3a). The maximum force decreased in the order of insole3, insole2 and insole1, in both activities. An analysis of the maximum force using one-way ANOVA showed $p > 0.05$, so there were no significant differences in the maximum forces for each activity. Wearing an insole gave a larger contact area than a shoe without the insole with $p < 0.01$ indicating statistical significance (Figure 3b). The peak and the mean plantar pressures were the highest for shoes without insoles. Insole1 with PE pads at both the heel and the forefoot gave lower plantar pressures than insole2 and insole3 (Figure 3c-3d): insole1 was very useful for significantly reducing plantar pressure ($p<0.01$).

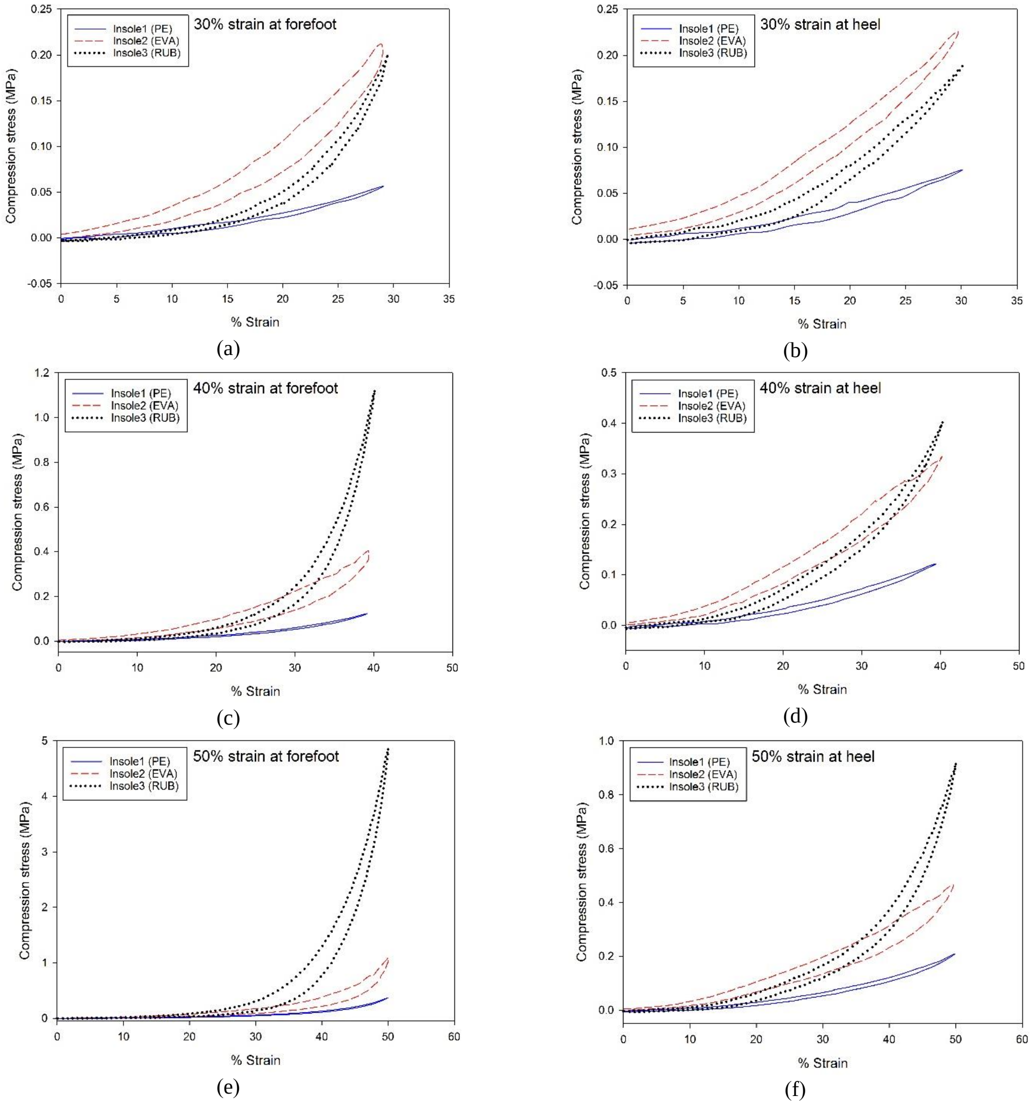


Figure 2. Compression-decompression tests of insole specimens to various maximum strains: (a) forefoot at 30% strain, (b) heel at 30% strain, (c) forefoot at 40% strain, (d) heel at 40% strain, (e) forefoot at 50% strain, and (f) heel at 50% strain

Table 2. Hardness and cushioning properties of shoe and insoles

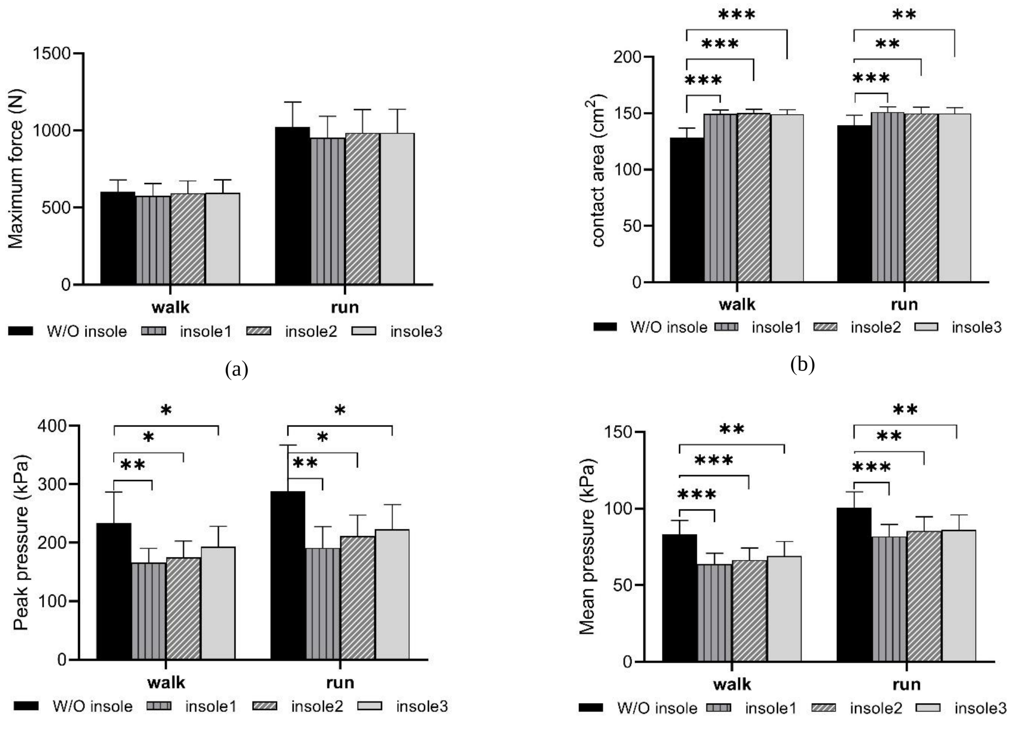
Number	Conditions	Weight (g)	Hardness (Shore A)	Maximum peak force (N) and Reduction force (%)[**]	
				heel	forefoot
1	Shoe (without Insole)	195	55	1,461 (N/A)	1,811 (N/A)
2	Shoe+Insole1 (PE[*])	310	14	1,191 (18.5%)	1,503 (17.0%)
3	Shoe+Insole2 (EVA[*])	315	35	1,126 (22.9%)	1,313 (27.5%)
4	Shoe+Insole3 (RUB[*])	335	18	1,323 (9.4%)	1,605 (11.4%)

* Densities of PE foam, EVA foam and Rubber are 40, 150 and 790 kg/m^3, respectively.

** Reduction force (%) was calculated in comparison to without insole condition.

3.3 Peak plantar pressure at four regions

Figure 4 shows the peak plantar pressure in four regions during walking and running, and it is apparent that the peak during running is mostly greater than that during walking. In both these activities, the peak plantar pressure at the heel and at forefoot regions were significantly different ($P<0.01$) regarding the comparison between with and without the insoles. However, the peak value of insole3 was not significantly different in the forefoot region. Additionally, the peak plantar pressure with insole1 ($P<0.05$) was significantly different from the other insoles in the heel region.

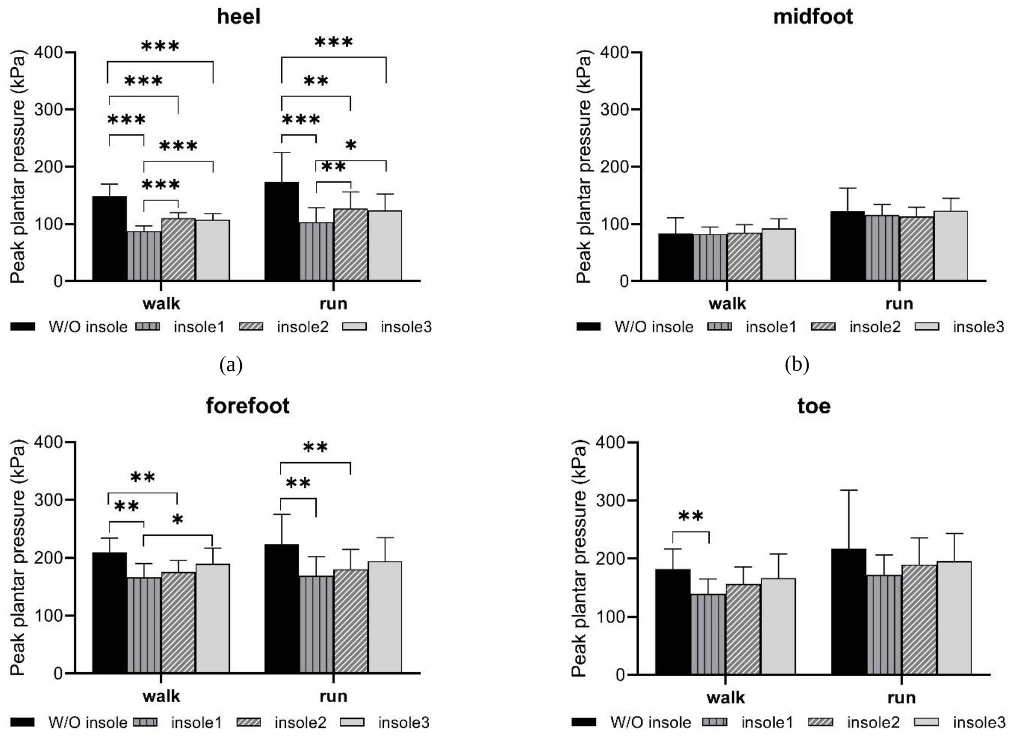


(a) (b)

(c) (d)

The p-value significant *<0.05, **<0.01 and ***<0.001

Figure 3. The results of volunteer testing: (a) maximum force, (b) contact area, (c) peak pressure, and (d) mean pressure



(a) (b)

(c) (d)

The p-value significant *<0.05, **<0.01 and ***<0.001

Figure 4. Peak pressures with the various cushioning pad insoles in four regions: (a) heel, (b) midfoot, (c) forefoot, and (d) toe

It can be concluded from the results of this study that the insole1 (PE) was the best one to reduce plantar pressure in both activities. The data were compared to the case of wearing shoes without insole. The results for insole1 show significant reduction of peak pressure at the heel and the forefoot regions, by approximately 41% and 20% in walking, and by 39% and 25% in running (Figure 4a, ac). Insole2 could reduce the pressure slightly better than insole3 in the forefoot area, but these were comparable at the heel area. At the midfoot region, the 3 insoles did not significantly differ (i.e., p>0.05) in performance. For the toe region, the p-values were significant only for insole1 in walking activity.

3.4 Center of pressure

The four cases of footwear in walking and running activities demonstrated various plantar pressure mappings and trajectories of the center of pressure (COP), as shown in Figure 5. The plantar pressure in the case without an insole was the highest, and the pressure decreased on wearing the insoles (according to the values and assigned colors). The insoles having PE cushioning pads showed the least plantar pressure. The results showed no difference in COP by case, due to similar shapes and thicknesses of the alternative insoles. The COP during running was shifted to the forefoot and toe areas slightly, from that during walking. In addition, there was no difference in the contact area from wearing different insoles, either in walking or in running.

3.5 Contact area during gait

The contact area was analyzed in the step of heel strike and push-off, the steps creating the maximum pressure at the heel and forefoot regions. The results showed differences in the contact area and in plantar pressure by footwear case (Figure 6). Insole1 showed the largest contact area with the least plantar pressure, while Insole2 and Insole3 had similar contact areas and plantar pressures. Shoes without insoles gave the least contact area with the highest plantar pressures.

4. Discussion

Comparative results show that EVA insoles improve cushioning properties better than insoles made from PE and RUB. From this study, insole2 (EVA) was found to be the one that provides the best cushioning, followed by insole1 and insole3. This EVA material is also a well-known shock-absorbing material in sports shoes (Shimazaki *et al.*, 2016; Wiegerinck *et al.*, 2009). The good cushioning properties of sport surface reduce heel pressure in running or in forehand strike tennis movement (Stiles & Dixon, 2007). Some studies have provided information about cushioning insoles that could affect foot pressure in running (Hähni *et al.*, 2016; Lullini, Giangrande, Caravaggi, Leardini, & Berti, 2020; O'Leary *et al.*, 2008), but the cushioning properties of those insoles were not reported. The cushioning properties of the insoles appear to questionably affect the foot pressure, especially in running. A key finding of the current study is that good cushioning (low impact force) insoles might not be well decreasing the foot pressure in both walking and running. The human body movements are very complex to simulate, so laboratory cushioning tests differ from real life effects during human body movements. Because the cushioning test results of the materials and the human tests differ, previous studies have suggested that direct testing should be performed using a group of volunteers (Windle *et al.*, 1999) (House *et al.*, 2002).

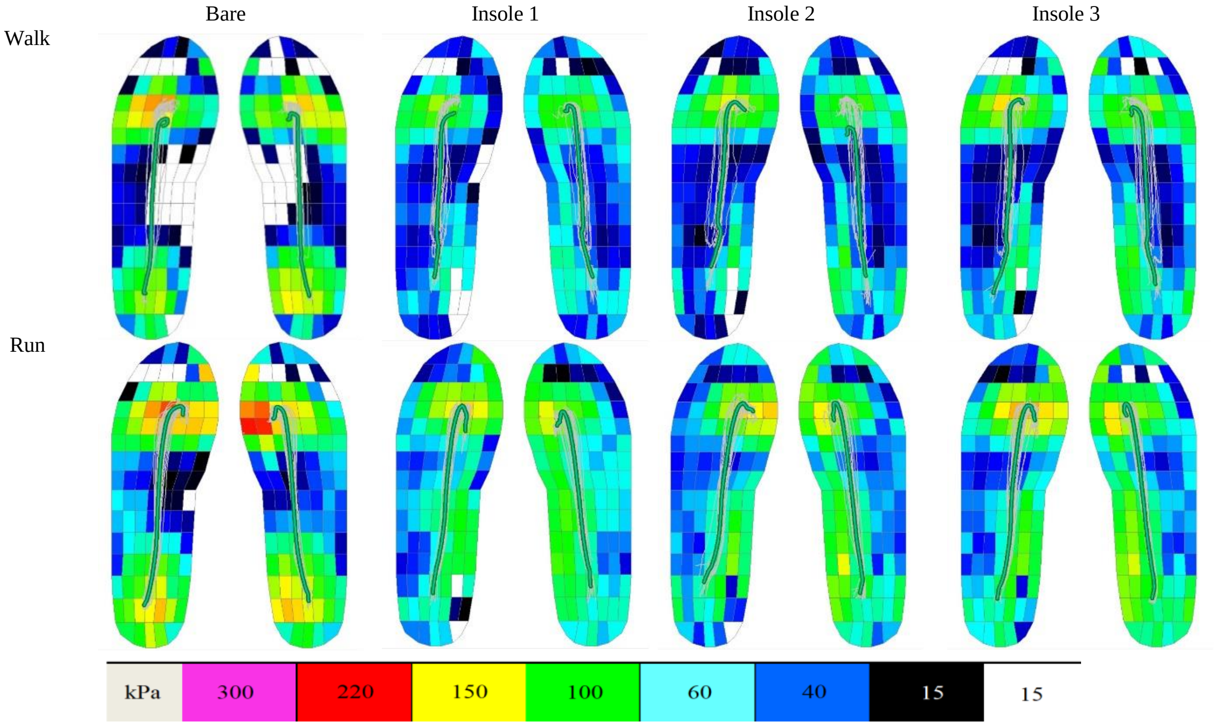


Figure 5. Center of pressure (COP) and the peak pressure for the various cushioning pad insoles

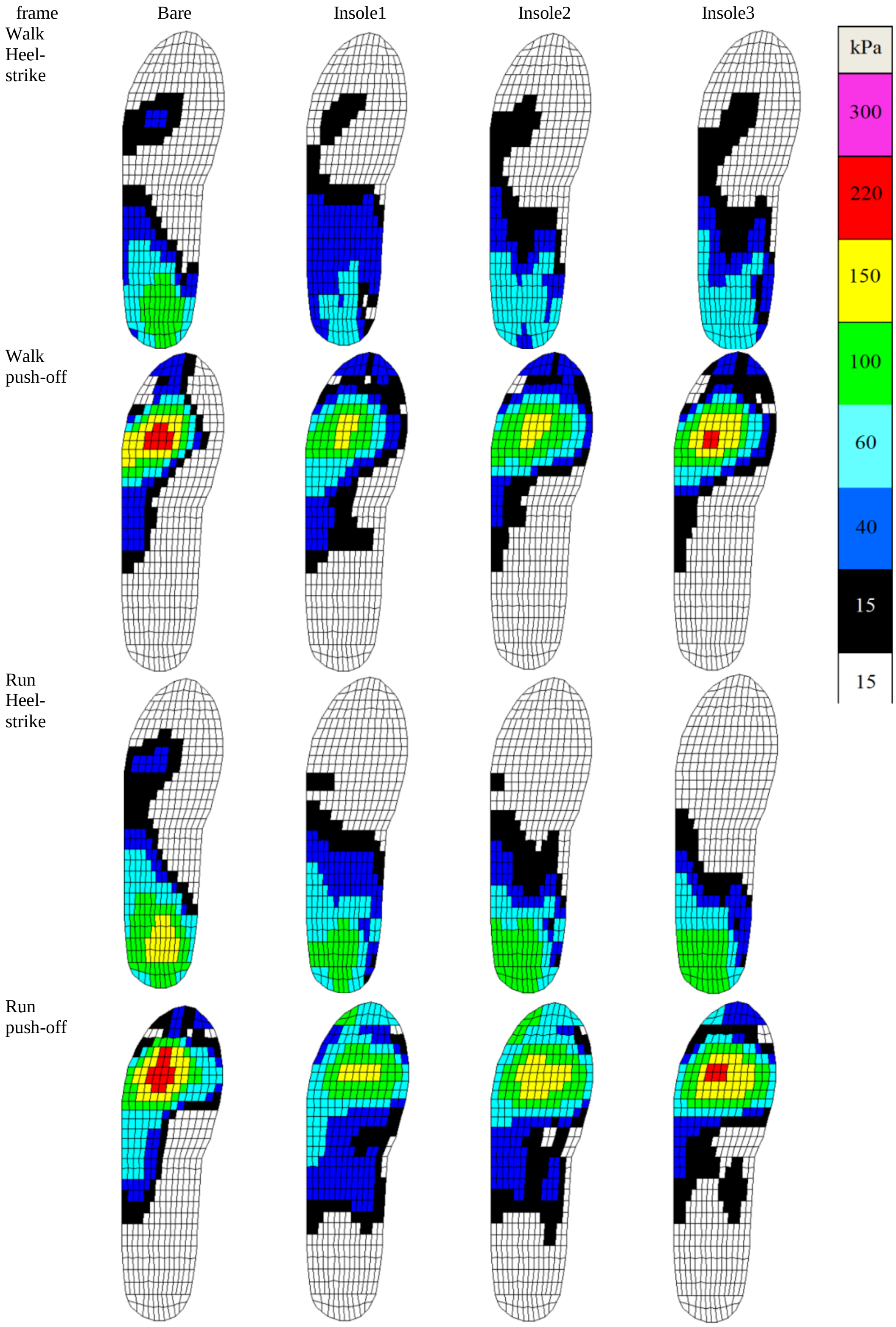


Figure 6. Peak plantar pressure and contact area with the various insoles during gait (heel-strike and push-off)

In a comparison of insole hardness and compressive stress, insole3 had lower hardness than insole2. However, insole3 had higher compressive stress than insole2, especially at very high strain due to non-foamy structure preventing mechanical collapse. The insole1 has the lowest hardness and compressive strength. Several studies have found that insoles with low hardness tend to reduce the peak pressure due to increasing the foot contact area during walking (Chang *et al.*, 2014) and soft shoes can conform well to the shape of the foot (Lin, Su, Chung, Hsia, & Chang, 2017). The results of this study show that participants using insole1 made of PE had lower plantar peak pressures than with other insoles, in both walking and running. Insole2 made of EVA could reduce plantar pressure at a similar level at the heel region as insole3 made of RUB, but slightly better at the forefoot region. Compressive stress is more closely related to plantar pressure than hardness. Materials with lower compressive strength reduce the plantar pressure better than higher compressive strength materials. The results from this study are consistent with previous simulation studies to reduce the heel pressure in walking (Goske, Erdemir, Petre, Budhabhatti, & Cavanagh, 2006)(Cheung & Zhang, 2005). The compressive properties of insoles refer to stiffness as all insoles in this study were of the same thickness. The previous study to optimize insole's stiffness for least plantar pressure in standing and walking showed that low stiffness insoles tended to reduce plantar pressure better than high stiffness ones (Chatzistergos, Naemi, Healy, Gerth, & Chockalingam, 2017). As no previous work has tested running, different types of cushioning pads were further studied in the current study for running, and it was found that the results had like expected trends or patterns: the current study also found that insole stiffness was associated with the reduction of foot pressure while running.

Wearing soft insoles increases the contact area, as in prior work (Chang *et al.*, 2012; Goske *et al.*, 2006). During the gait (heel-strike and toe-off) Insole1 has the most contact area at the midfoot, followed by insole2 and insole3, corresponding to the stiffnesses. Increasing the contact area means that the soft insole distributes the pressure on the foot quite well. Several studies have assessed the Custom Made Insole (CMI) to reduce foot pressure by increasing the contact area, and it is known that the heel and forefoot areas have higher pressure than others (Cheung & Zhang, 2005; Nouman, Dissaneewate, Leelasamran, & Chatpun, 2019). CMI can relieve the foot pressure by using low-stiffness materials in the heel and toe regions. Beside this, the forefoot cushioning pad reduced forefoot pressure better than the metatarsal pad (Hähni *et al.*, 2016). The addition of cushioning material is also useful in reducing foot pressure without changing the COP and affecting the balance of the body.

The impact load during walking and running can cause several injuries and health problems, including cartilage breakdown, osteoarthritis, knee injuries, and lower back pain (Silva *et al.*, 2009; Srewaradachpisal *et al.*, 2020). Cushioning materials and pads have been developed to protect against these types of damage (Chiu & Shiang, 2007; Shimazaki *et al.*, 2016; Silva *et al.*, 2009). However, this work showed that insole2 with good cushioning properties (low impact force) and high stiffness gave high plantar pressure. The peak plantar pressure in running was obviously higher than in walking for all foot areas. Reducing plantar pressure is important in preventing foot problems, especially to diabetics with neuropathy (Nouman *et al.*, 2019). There is often pain associated with foot pressure in the heel and forefoot regions (Cheung & Zhang, 2005; Goske *et al.*, 2006). Metatarsal bone fractures are caused by high plantar pressure, especially to long-distance runners (Hähni *et al.*, 2016). This problem can affect daily exercise and worsen the quality of life (Chang *et al.*, 2014, 2012). From this work, it has been shown that highest cushioning foot pads do not give the best plantar pressure reduction, but the high impact can also cause injuries and health problem. The benefit of wearing cushioning shoes are greater than the negative effects, but stiffness must also be considered to prevent high foot pressure. In general, cushioning properties are the key factor to any midsole design. Therefore, those performing high-impact activities should wear shoes with good cushioning properties at the midsole, provided by soft insoles, especially around the heel and the toe.

The current study was not conducted at normal running speeds due to shoe restrictions. Running is known to give nearly 1.6 fold higher peak forces than walking. Running at a high speed was not in the scope of this current study. This made it possible for subjects of different body sizes, especially the heavier individuals, to have varying effects. While the insoles tested consisted of only two layers of main material, similar testing could also be applied to custom insoles with multiple material layers. The objective of this work was to determine the mechanical properties of the insole that affect the insole pressure during walking and running. Over the long term, degradation of the insole material could affect the foot pressure, which has been mentioned earlier but was not considered in this study (House *et al.*, 2002). This work demonstrated that insole stiffness was more closely related to foot pressure while walking and running than any other property measured.

5. Conclusions

It can be concluded from the current study that there was no relationship between the cushioning properties (low impact force) of insoles and the plantar pressure reduction in walking and running activities. Reducing foot pressure is based on low compressive properties or low hardness of the insole, as a soft insole can increase the contact area between the foot and the shoe for both walking and running. Therefore, adding soft pads at the heel and forefoot areas will reduce foot pressure better than hard, high-impact cushioning inserts. Future studies will add specific types of cushioning to CMI for diabetic patients. In addition, the lowest stiffness insoles generate the least amount of pressure on the foot in various activities, and this will also be studied.

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