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Effect of insole-footwear combination on foot biomechanics: A finite element study

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Abstract

The aim of this study was to investigate the biomechanics of foot after wearing different footwear types incorporated with insole using Finite Element (FE) analysis. The studied models included barefoot, combination of insole and rigid footwear, combination of insole and elastic footwear without mid-foot cavity, and combination of insole and elastic footwear with mid-foot cavity. The results showed that insole and rigid footwear could reduce foot pressure, ankle joint pressure, and bone stress, but still not redistributing the foot pressure. The insole and elastic footwear without mid-foot cavity could significantly reduce forefoot pressure while the foot pressure was shifted toward mid-foot region instead. The insole and elastic footwear with mid-foot cavity could alleviate pressure in the mid-foot region better than footwear without mid-cavity.

Keywords: Footwear, Insole, Foot pressure, Foot bone stress, Ankle joint stress, Biomechanics

1. Introduction

Foot pressure is a significant clinical parameter in diagnosis foot abnormality, and biomechanical deformity. The abnormality and deformity can be caused by skeleton misalignment or soft tissue related problems. Magnitude and pattern of foot pressure depend on various factors such as body weight, and foot contour. High magnitude of pressure concentrates on foot may lead to severe clinical complications, especially in diabetic patients [1-6]. This includes foot ulceration, plantar callus [7], and detrimental to foot structure [8]. Redistribution of foot pressure is a key to reduce the pressure which can prevent long-term complications. In order to perform this, it requires the non-invasive medical device, which is called orthosis, covering the entire foot. Most of the orthotic devices are made of polymers such as Natural Rubber (NR), Ethylene-vinyl acetate (EVA), polyurethane (PU), and polyester. These materials are mechanically good in energy absorption that reduce the ground reaction force acting on foot.

Many *in vivo* and *in vitro* studies revealed the significant use of insole in redistributing foot pressure which could reduce pain and improved patient comforted [9-11]. In addition, several literatures also emphasized the development of insole shape, and materials to improve effectiveness of insole. For example, Chantarapanich et al. [12], who focused on insole design, had carried out the effect of insole slope on bone joint stress, foot bone stress, and foot pressure distribution using Finite Element (FE) method. This highlights that the higher insole slopes tended to increase the stress, especially at the ankle joint and foot.

In addition, Hähni et al. [9] investigated the effect of forefoot incorporated insole device, found that the insole with forefoot cushioning or metatarsal reduced the pressure in the forefoot region. Hellstrand Tang et al. [3] compared three different insoles types, composed of 35 shore-A hardness EVA, 55 shore-A hardness EVA, and hard core with a top layer of soft 12-shore A hardness microfiber. It revealed that 35 shore-A EVA hardness and 55-shore-A EVA hardness insoles reduced the pressure on the foot. With the spacious applications of three-dimensional printing (3DP) in medicine, it fabricated the insole by mould-less method. This allows patient-specific insole to be manufactured in a short time. Xu et al. [11] has compared effectiveness of the patient-specific insole and pre-fabricated insole and found that patient-specific insole can reduce the pressure on the forefoot region by distributed it over the mid-foot region. Luo et al. [13] designed optimal insoles for reduction of pedal tissue trauma, and characterized the mechanical properties of the tissues using FE analysis.

Although, the insole has played a significant role in the reduction of peak pressure in critical regions of the foot, nevertheless, footwear is another part performing a similar function. A research that focuses on footwear design to reduce foot pressure or correct the foot problem is rarely found [6]. To date the footwear related to design has usually been performed using FE method such as Liu et al. [14] conducted FE study on four porous structures for cushioning design of shoe which revealed the significant in reduction of foot peak pressure.

Mechanically, the proper footwear design is expected to assist insole in the reduction of foot pressure. The footwear should contribute to energy absorption to prevent ground reaction force acting on foot. As a result, the objective of this paper is to investigate the biomechanics of foot after wearing different footwear types incorporated with the insole. In order to investigate soft tissue, bone,

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and joint effect, *in vitro* investigation would be conducted using FE analysis. This could reduce complication of *in vivo* investigation which could create barrier in bone and joint measurement. Understanding the effect of these insole and footwear on foot pressure would be beneficial to Prosthetist/Orthotist (PO) and clinicians to design footwear-insole for orthotic patients.

2. Materials and methods

The first author is an Asian male, having body weight of 90 kg, and body mass index (BMI) of 27.8 kg/m^2, who volunteered to use the body of foot and ankle as a studied subject. The medical record of the first author has no prior injury, deformity, or osteoarthritis. The footwear and insole models were from the commercially available products (Smilefeet, Health Innovation & Design Co., Ltd., Thailand). The studied models included barefoot, combination of insole and rigid footwear, combination of insole and elastic footwear with mid-foot cavity, and combination of insole and elastic footwear without mid-foot cavity. All analyses were performed using FE method.

2.1 Three-dimensional modeling of bone and foot

The foot and ankle region of the first author was scanned using a 64-slice computed tomography (CT) scanner to acquire a set of digital radiographic data. These data were recorded in Digital Imaging and Communications in Medicine (DICOM) file format. The files were used to create three-dimensional models using an image processing algorithm combining with Computer-Aided Design (CAD) software (VISI, Hexagon AB, Sweden). The three-dimensional models included tibia, calcaneus, foot bone, and foot skin. In addition, all foot bones were united together to simplify the FE calculation. Since ankle articular cartilage could not be well detected with a CT scanner, the model of articular cartilage was then fulfilled using the CAD software. The total length of the domain ranging from cut tibia section to foot was 182 mm.

Footwear and insole CAD models were acquired from a physical product using a combination of 2D and 3D scanning technologies. The wireframe models were created prior as a structure of footwear and insole before converted to the 3D parametric model used for FE analysis. The footwear is made of polymer whereas the insole is made of PU with elastic gel attached under the heel region. The anterior-posterior length of footwear and insole was 258 mm whereas the medial-lateral length at mid-foot was 71 mm. The bone, foot skin, footwear, and insole CAD models were aligned in normal standing posture. All CAD models included in this study were shown in Figure 1.

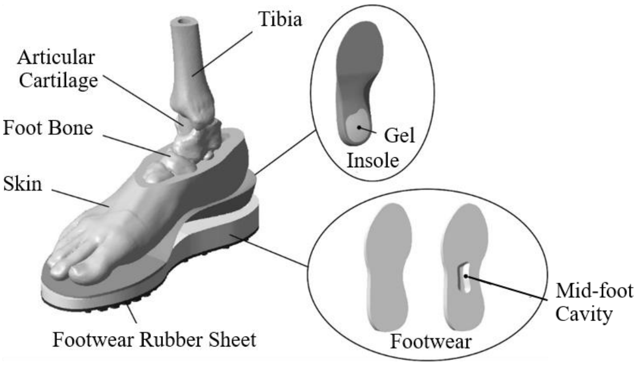

Figure 1 3D CAD Model used in this study, the figures illustrated in the circles are viewed from backside

2.2 Finite element model

The aligned CAD models were used to create nodes and elements for FE analysis. The element type employed in the analysis was four-node tetrahedral. The generation was done using the functions in the FE software (MSC Marc Mentat, MSC Software, Inc., USA). The models of bone, foot skin and, insole are identical in all FE models, the number of nodes and elements were controlled to have the identical number. There is an exception for footwear which the number of nodes and elements is slightly varied as the geometry is different. The number of nodes and elements of each model employed in the FE analysis was determined from convergence test. In order to perform the convergence test, various number of element was generated and peak pressure of the foot was observed changes of the result.

2.3 Material properties

All material models were assumed to be homogenous, isotropic, and linearly elastic. The values of material properties assigned to FE analysis were adopted from previous literatures whereas the material properties of gel and insole which made of elastic polymer were acquired compression test of cylinder fabricated samples by using Universal Testing Machine (UTM) at Material Testing Center, Faculty of Engineering at Sriracha, Kasetsart University, Thailand. All materials properties assigned to the FE model are shown in Table 1.

2.4 Contact conditions and boundary conditions

All foot structures including articular cartilage were attached to each other with no relative displacement. Foot skin was also fully attached to the foot bone. Foot skin-insole and insole-footwear could slide relatively to the insole, the contact condition between these couples was assigned as relative displacement. In order to simplify FE calculation, all relative displacement surface couples were set as frictionless.

A single-legged stance was set as a condition in the FE analysis. Therefore, the 90 kg force (882.9 N), which is an actual body weight of the volunteer, was applied at the top surface of the cut tibia surface. All degrees of freedom of the footwear's bottom surface were fully constrained. Figure 2 shows boundary conditions of the FE analysis.

Table 1 Material properties used in FE analysis

Model	Elastic Modulus (MPa)	Poisson's ratio	Reference
Tibia	17,000	0.28	[15]
Foot bone	7,800	0.30	[15]
Cartilage	12	0.45	[15]
Skin	5	0.49	[15]
Insole and Footwear Rubber sheet	26.7	0.30	Testing Data
Gel	23.2	0.30	Testing Data
Footwear	149	0.30	[16]

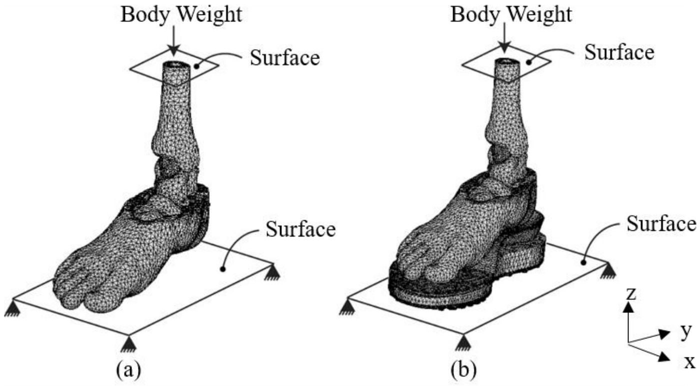

Figure 2 Boundary conditions of the FE models (a) barefoot analysis model, and (b) combination of insole and footwear analysis model

2.5 Numerical validation

The results were validated with the *in vivo* experimental results from Mei et al. [17]. The planar pressures of the barefoot case were compared in the forefoot, mid-foot, and heel regions. The pressure values obtained from both studies were normalized by BMI. Different pressure magnitudes would then be compared to validate the reliability of the FE model used in this study.

3. Results

3.1 Convergence test result

The convergence test result for each FE model shows in Figure 3. There is slight difference in peak pressure and the peak pressure occurred in the identical region. The peak pressure for barefoot and insole and rigid footwear located in forefoot in all FE cases. The peak pressure for insole and elastic footwear with and without mid-foot cavity located in midfoot in all FE cases. The optimal number of element and its corresponding nodes was as follows: 110,047 elements and 27,841 nodes for barefoot, 92,132 elements and 24,703 nodes for insole and rigid footwear, 293,468 elements and 77,634 nodes for insole and elastic footwear without mid-foot cavity, and 283,291 elements and 75,292 nodes for insole and elastic footwear with mid-foot cavity.

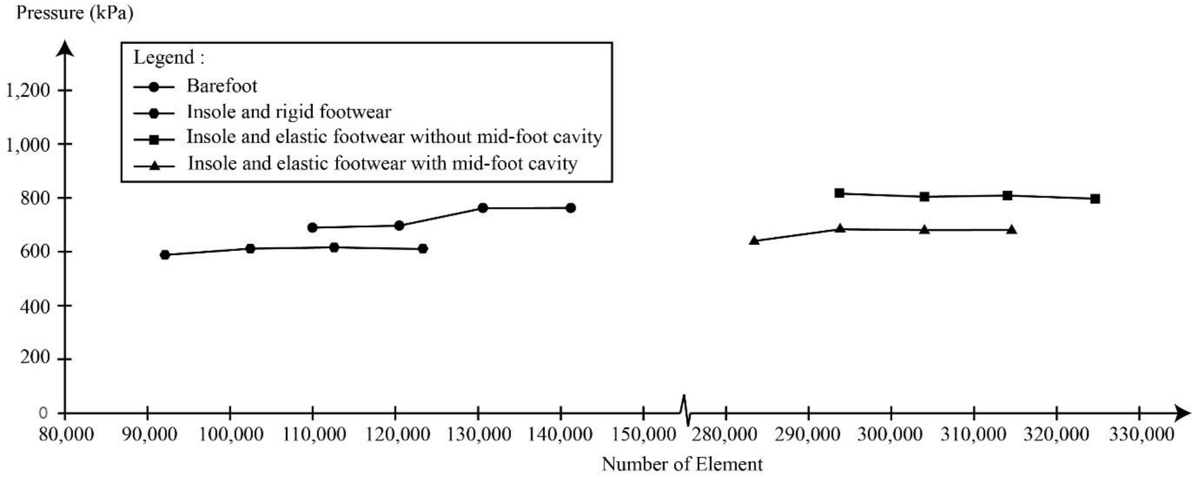

Figure 3 Convergence test result of the FE models.

3.2 Validation

When the foot pressure (FP) is normalized with BMI, it is designated as FP/BMI. The FP/BMI obtained from this studies was calculated from the magnitude of the barefoot case in Table 2 divided by BMI of the first authors (27.8 kg/m^2) which gave FP/BMI in the forefoot, mid-foot, and heel as 24.82 kPa.m^2/kg, 7.55 kPa.m^2/kg, and 12.55 kPa.m^2/kg, respectively. The FP/BMI of *in vivo* experiment was calculated from values of the subject in Mei et al. [17] divided by BMI of the subject of 22.9 kg/m^2 which gave FP/BMI in the forefoot, mid-foot, and heel as 23.45 kPa.m^2/kg, 6.99 kPa.m^2/kg, and 16.20 kPa.m^2/kg, consecutively. The differences in FE results and *in vivo* experiment are graphically represented in Figure 4. The figure shows that the trend of foot pressure from this FE study correlates well to the *in vivo* experiment result. It is high in the forefoot and heel regions whereas low in the mid-foot region. The heel region presents the greatest difference which is 22.5% whereas the forefoot presents the less difference which is 5.8%. The mid-foot difference is 8.1%. Although the pressure difference in the heel is relatively higher than in other regions, however, it is still acceptable as referring to Chantarapanich et al. [18]. Thus, the FE model is considered to be reliable for this study.

Table 2 The numerical validation by comparison the FP/BMI ratios between *in vivo* experiment and FE results of the barefoot case

Barefoot region	**Average peak pressure (kPa)**	**Peak pressure (kPa)**	**Average FP/BMI (kPa.m^2/kg)**	**FP/BMI (kPa.m^2/kg)**
	Mei et al. [17]	**FE analyses**	**Mei et al. [17]**	**FE analyses**
Forefoot	537	690	23.45	24.82
Mid-foot	160	210	6.99	7.55
Heel	371	349	16.20	12.55

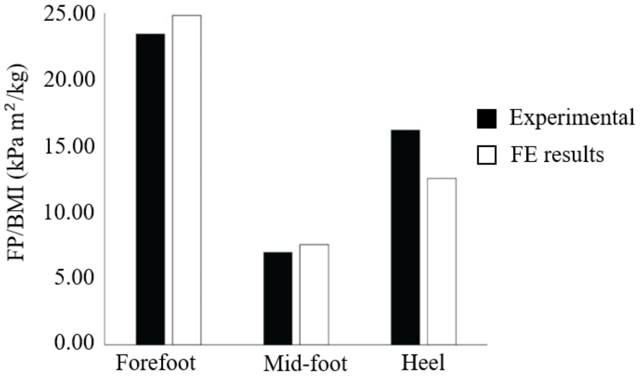

Figure 4 Comparison of the FP/BMI ratios between *in vivo* experiment and FE results of the barefoot case

3.3 Foot pressures

Figure 5 shows the foot pressure distribution in various cases. It can be seen that the pattern of foot pressure distribution in barefoot and combination of insole and rigid footwear are similar. Table 3 shows the magnitude of peak foot pressure in forefoot, mid-foot, and heel in different FE cases. After wearing insole and rigid footwear, the magnitude of foot pressure reduces by 102 kPa in the forefoot region. Nevertheless, there is no significant reduction of foot pressure in the mid-foot and heel regions. The shift of foot pressure occurs when wearing insole with elastic footwear. High pressure shifts from the forefoot region to the mid-foot and heel regions. The magnitude of foot pressure in the forefoot region significantly reduces but raises in the mid-foot and heel regions.

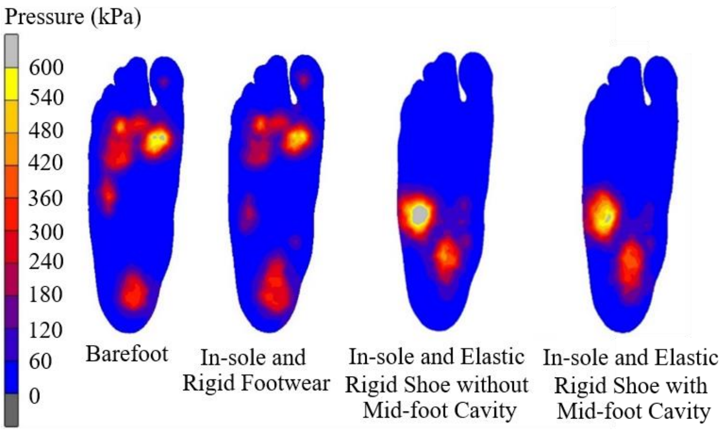

Figure 5 Foot pressure distribution in various cases

Table 3 The peak pressures in each foot region

Case	Foot Pressure (kPa)		
	Forefoot	**Mid-foot**	**Heel**
Barefoot	690	210	349
Insole and rigid footwear	588	228	346
Insole and elastic footwear without mid-foot cavity	74	816	457
Insole and elastic footwear with mid-foot cavity	57	640	415

3.4 Stress in ankle joint and the foot bones

Table 4 gives the maximum stress in the ankle joint decreases after wearing insole and rigid footwear. In particular, the use of insole and elastic footwear with mid-foot cavity can diminish the stress in the ankle joint by 41.8 percent. The foot bones stress also decrease in the same tend as the stress in the ankle joint. In the case of insole and rigid footwear, high stress concentrates on the 3rd and 4th metatarsals bones. When wearing insole and elastic footwear, the maximum stress moves towards the posterior region, between the metatarsal bone and the cuneiform bone. Changes in ankle joint and foot bones stress after wearing various combinations of insole and footwear compared to barefoot are shown in Figure 6 and Figure 7.

Table 4 The maximum stress in the ankle joint and foot bone

Case	Stress in ankle joint (kPa)	Foot bones stress (kPa)
Barefoot	4,511	28,327
Insole and rigid footwear	3,699	21,562
Insole and elastic footwear without mid-foot cavity	2,747	8,565
Insole and elastic footwear with mid-foot cavity	2,626	7,507

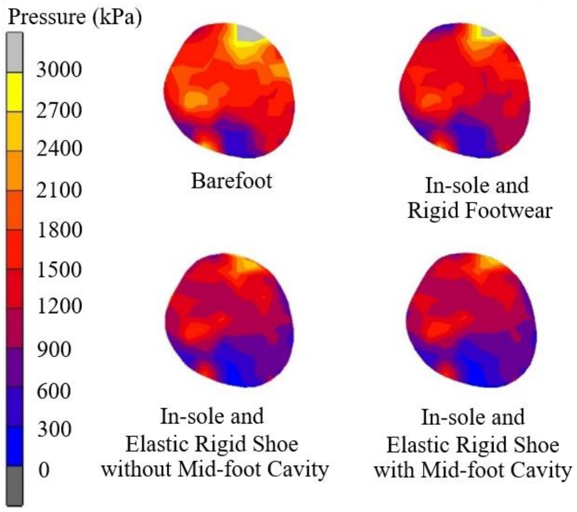

Figure 6 Ankle joint stress

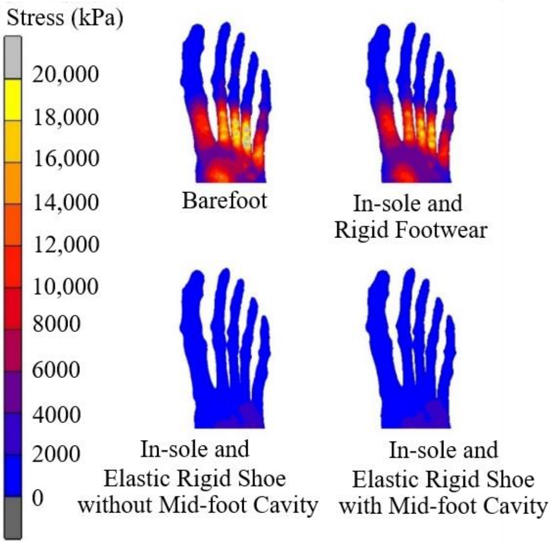

Figure 7 Foot bones stress

4. Discussion

This study used FE as a tool in the biomechanical investigation. FE is a widely used computational tool in *in vitro* biomechanical analysis [19-21]. When the geometry, material properties, and boundary condition are assigned correctly, the obtained solution is considered reliable as mentioned in Chantarapanich et al. [15]. The objective of this study was to investigate the biomechanics of bone and orthosis after wearing various combinations of insole and footwear. Although, a limited number of previous research focused on foot pressure along with ankle joint and foot bone stress, unlike this present study which focused on all of these aforementioned aspects. This would enhance and be better understand the foot biomechanics of both soft tissue and bone structure. To simplify the investigating biomechanics tendency of foot which is undergone four cases of different footwear types incorporated with insole using FE analysis, all material models in this study are assumed to be homogenous, isotropic, and linearly elastic. According to the results, insole and rigid footwear can reduce the foot pressure that conforms to clinical results of Reints et al. [22]. In addition, ankle joint pressure and bone stress reduces after wearing insole and rigid footwear, but it is related not to redistribute the foot pressure toward the mid-foot region. This finding agrees with the experimental result of Mazur et al. [23]. However, foot pressure redistribution should be accompanied with a proper design of insole slope as mentioned by Chantarapanich et al. [12].

Foot pressure would be redistributed and shifted toward the mid-foot region when elastic footwear was applied. The accompanying issue might deteriorate patients who have mid-foot injuries whereas distributing the pressure to the mid-foot region might reduce lesions in the patients with flatfoot [11]. In recent years, relatively limited biomechanical reports were considered both insole and footwear [6], many reports were still analyzed only the effect of insole alone [3, 9, 11]. The finding from this research would raise the development point which should not only focus on the insole itself but should also extend to footwear design.

By comparing between combination of insole and rigid footwear with combination of insole and elastic footwear, it can be seen that the elasticity of the material used to fabricate insole and footwear is considered a major influential factor in the reduction of foot pressure, ankle joint stress, and foot bones stress. The elastic material can absorb strain energy density greater than rigid material. This prevents energy from the ground reaction force from acting directly on foot. The energy would be absorbed inside the footwear by deforming its shape. Thus, rigid plastic should not be used while the proper material such as a thermoplastic elastomer or thermosetting elastomer should be used. Metal should not be inserted as a reinforced structure in an insole.

The mid-foot cavity associates the redistribute of foot pressure. The wall cavity deforms upon body weight, especially when the footwear is made from an elastic material. While the cavity is biomechanically beneficial which leads to excessive deformation of the mid-foot region of the footwear which causes the raise of energy absorption and does the better pressure reduction in the mid-foot region than the case of insole and elastic footwear without mid-foot cavity, as shown in Figure 5. Since the case of insole and elastic footwear with mid-foot cavity gives the most promising relief of pressure in the mid-foot region which then propagates less stress toward both the ankle joint and the foot bones, as shown in Figure 6 and Figure 7 than all the other cases.

For further study, footwear with mid-foot cavity that influenced the redistribution of foot pressure should be focused on exploring an aspect ratio of mid-foot cavity per footwear volume to find the optimal foot pressure redistributing result. Patient-specific or customized footwear is a current trend in the footwear industry using rapid three-dimensional printing (3DP) technology. The previous study of Chantarapanich et al. [24] revealed that the material properties of fabricated parts are not isotropic. These should be aware of printing direction in order to achieve the desired mechanical properties which can reduce foot problems.

5. Conclusions

This research investigates biomechanics of foot after wearing different footwear types incorporated with insole using FE analysis. Insole and rigid footwear can reduce foot pressure, ankle joint pressure, and bone stress. However, it is not redistributed the foot pressure or change foot pressure contour from barefoot. The insole and elastic footwear without mid-foot cavity can reduce forefoot pressure tremendously while the foot pressure is shifted toward the mid-foot and heel regions instead. The elastic footwear with mid-foot cavity can alleviate pressure in the mid-foot region compared to footwear without mid-foot cavity.

6. References

[1] Bus SA, Haspels R, Busch-Westbroek TE. Evaluation and optimization of therapeutic footwear for neuropathic diabetic foot patients using in-shoe plantar pressure analysis. Diabetes Care. 2011;34(7):1595-600.
[2] Bus SA, Zwaferink JB, Dahmen R, Busch-Westbroek T. State of the art design protocol for custom made footwear for people with diabetes and peripheral neuropathy. Diabetes Metab Res Rev. 2020;36(Suppl 1):e3237.
[3] Hellstrand Tang U, Zugner R, Lisovskaja V, Karlsson J, Hagberg K, Tranberg R. Comparison of plantar pressure in three types of insole given to patients with diabetes at risk of developing foot ulcers - a two-year, randomized trial. J Clin Transl Endocrinol. 2014;1(4):121-32.
[4] Kang GE, Zahiri M, Lepow B, Saleem N, Najafi B. The effect of daily use of plantar mechanical stimulation through micro-mobile foot compression device installed in shoe insoles on vibration perception, gait, and balance in people with diabetic peripheral neuropathy. J Diabetes Sci Technol. 2019;13(5):847-56.
[5] Martinez-Santos A, Preece S, Nester CJ. Evaluation of orthotic insoles for people with diabetes who are at-risk of first ulceration. J Foot Ankle Res. 2019;12:35.
[6] Zwaferink JBJ, Custers W, Paardekooper I, Berendsen HA, Bus SA. Optimizing footwear for the diabetic foot: data-driven custom-made footwear concepts and their effect on pressure relief to prevent diabetic foot ulceration. PLoS One. 2020;15(4):e0224010.
[7] Hamatani M, Mori T, Oe M, Noguchi H, Takehara K, Amemiya A, et al. Factors associated with callus in patients with diabetes, focused on plantar shear stress during gait. J Diabetes Sci Technol. 2016;10(6):1353-9.
[8] Tang UH, Zugner R, Lisovskaja V, Karlsson J, Hagberg K, Tranberg R. Foot deformities, function in the lower extremities, and plantar pressure in patients with diabetes at high risk to develop foot ulcers. Diabet Foot Ankle. 2015;6:27593.
[9] Hähni M, Hirschmüller A, Baur H. The effect of foot orthoses with forefoot cushioning or metatarsal pad on forefoot peak plantar pressure in running. J Foot Ankle Res. 2016;9:44.
[10] Xu R, Wang Z, Ma T, Ren Z, Jin H. Effect of 3D printing individualized ankle-foot orthosis on plantar biomechanics and pain in patients with plantar fasciitis: a randomized controlled trial. Med Sci Monit. 2019;25:1392-400.

[11] Xu R, Wang Z, Ren Z, Ma T, Jia Z, Fang S, et al. Comparative study of the effects of customized 3D printed insole and prefabricated insole on plantar pressure and comfort in patients with symptomatic flatfoot. Med Sci Monit. 2019;25:3510-9.

[12] Chantarapanich N, Wongsiri S, Sitthiseripratip K. Influence of insole slope on bone joint stress, foot bone stress, and foot pressure distribution. Songklanakarin J Sci Technol. 2019;41(2):375-82.

[13] Liu X, Yue Y, Wu X, Hao Y, Lu Y, Pellicano F. Finite element analysis of shock absorption of porous soles established by grasshopper and UG secondary development. Math Probl Eng. 2020;2020:1-12.

[14] Luo G, Houston VL, Garbarini MA, Beattie AC, Thongpop C. Finite element analysis of heel pad with insoles. J Biomech. 2011;44(8):1559-65.

[15] Chantarapanich N, Nanakorn P, Chernchujit B, Sitthiseripratip K. A finite element study of stress distributions in normal and osteoarthritic knee joints. J Med Assoc Thai. 2009;92(Suppl 6):S97-103.

[16] MatWeb. DSM Biomedical Elasthane™ 55D Thermoplastic Polyether Polyurethane (TPU) [Internet]. Blacksburg: MatWeb; 2020. [cited 2020 Dec 12]. Available from: http://www.matweb.com/search/datasheettext.aspx?matguid=261c666d057741fe896dbece622b8d42.

[17] Mei Q, Gu Y, Xiang L, Yu P, Gao Z, Shim V, et al. Foot shape and plantar pressure relationships in shod and barefoot populations. Biomech Model Mechanobiol. 2020;19(4):1211-24.

[18] Chantarapanich N, Siripanya A, Sucharitpwatskul S, Wanchat S. Validation of finite element model used to analyze sheet metal punching process in automotive part manufacturing. 7th International Conference on Key Engineering Materials (ICKEM 2017); 2017 Mar 11-13; Penang, Malaysia. Bristol: IOP Publishing Ltd; 2017. p. 1-5.

[19] Campanelli V, Fantini M, Faccioli N, Cangemi A, Pozzo A, Sbarbati A. Three-dimensional morphology of heel fat pad: an in vivo computed tomography study. J Anat. 2011;219(5):622-31.

[20] Telfer S, Erdemir A, Woodburn J, Cavanagh PR. What has finite element analysis taught us about diabetic foot disease and its management? a systematic review. PLoS One. 2014;9(10):e109994.

[21] Taylor D, Kuiper JH. The prediction of stress fractures using a ‘stressed volume’ concept. J Orthop Res. 2001;19(5):919-26.

[22] Reints R, Hijmans JM, Burgerhof JGM, Postema K, Verkerke GJ. Effects of flexible and rigid rocker profiles on in-shoe pressure. Gait Posture. 2017;58:287-93.

[23] Mazur F, Swoboda B, Carl HD, Lutter C, Engelhardt M, Hoppe MW, et al. Plantar pressure changes in hind foot relief devices of different designs. J Exp Orthop. 2019;6(1):7.

[24] Chantarapanich N, Puttawibul P, Sitthiseripratip K, Sucharitpwatskul S, Chantaweroad S. Study of the mechanical properties of photo-cured epoxy resin fabricated by stereolithography process. Songklanakarin J Sci Technol. 2013;35(1):91-8.