International Journal of Applied Engineering Research

discontinued in Scopus as of 2017

Country	India - SIR Ranking of India
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Publisher	Research India Publications
Publication type	Journals
ISSN	09739769, 09734562
Coverage	2009, 2011-2018
Scope	Information not localized

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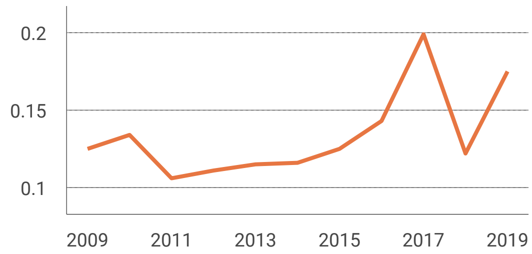

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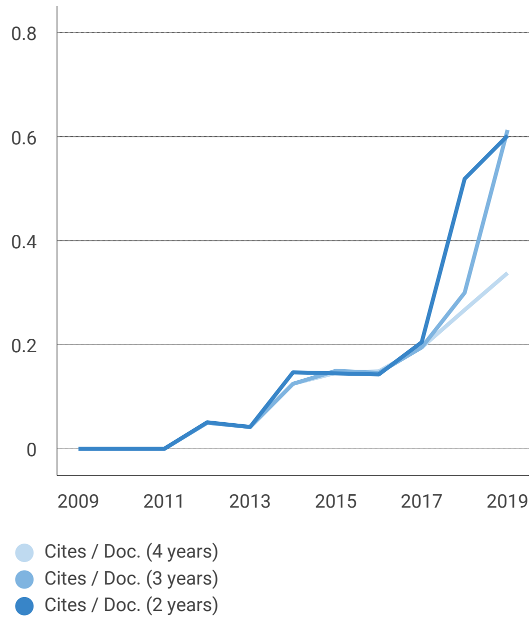

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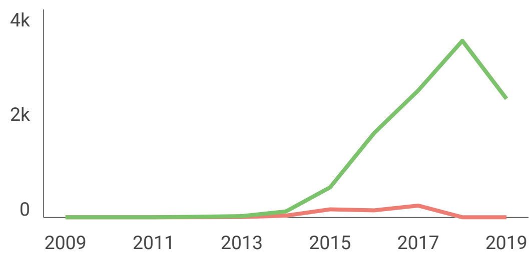

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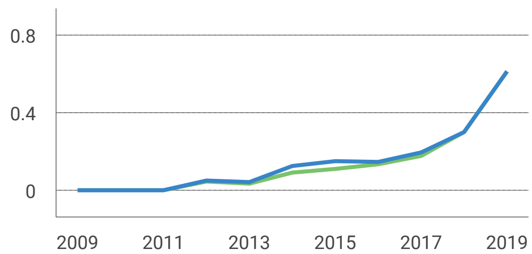

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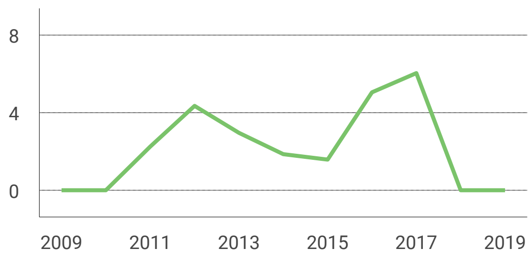

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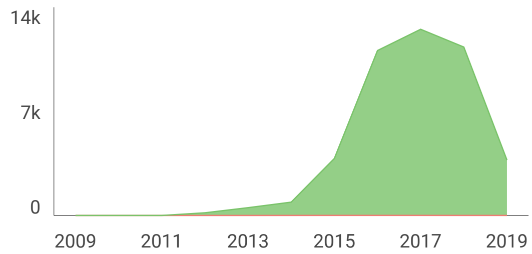

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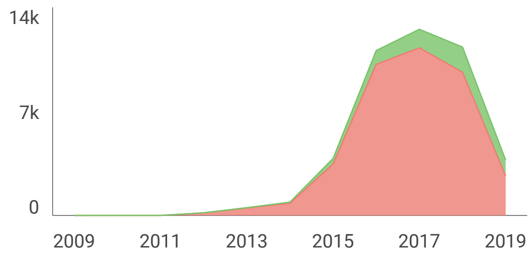

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Print ISSN 0973-4562
Online ISSN 0973-9769

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INDEXING: **SCOPUS(2010-2017), EBSCOhost, GOOGLE Scholar, JournalSeek, J-Gate, ICI, Index Copernicus IC Value 82.67 and UGC Approved Journal - 2017 (Journal No. - 64529)**

Publication Date and Frequency: Twelve issues per year.

DOI No. DOI:10.37622/000000

- **Publication Ethics and Publication Malpractice Statement**
- **Editorial Board Members**
- **Vol. 1 No.1 No.2 No.3** (2006)
- **Vol. 2 No.1 No.2 No.3 No.4** (2007)
- **Vol. 3 No.1 No.2 No.3 No.4 No.5 No.6 No.7 No.8 No.9 No.10 No.11 No.12** (2008)
- **Vol. 4 No.1 No.2 No.3 No.4 No.5 No.6 No.7 No.8 No.9 No.10 No.11 No.12** (2009)

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Volume 12, Number 15 (2017)

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International Journal of Applied Engineering Research ISSN 0973-4562 Volume 12, Number 15 (2017) pp. 5254-5260

A 3-Dimensional Finite Element Analysis of the Insole Shoe Orthotic for Foot Deformities

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Abstract

In the present study, a 3-dimensional finite element analysis (FEA) of the insole shoe orthotic was developed for analysing foot deformities. The solid model of abnormal human foot was composed of the plantar fascia which was encapsulated by soft tissue (indenture feet) against to the rubber EVA insoles. The models were explored into 3D solid using STL file of scan-foot Handy SCAN 700TM. Data of abnormal foot contour was obtained through the scanning process. Subsequently, 3D solid model of the orthotic shoe insole was generated using the Power SHAPE CAD 2015. The finite element (FE) method of 3D meshes was run on the imported solid model using the software ABAQUS 6:13. Contact interaction between the indenter feet and the orthotic insole shoe was investigated as a function of the various sizes of shoe insole. Strategy of curve-based surface modelling (CBS-modelling) was adopted to obtain surface and solid models of the orthotic shoe insole. The size of the gap between the soles of the feet to the width of the designed insole was obtained. The simulation results show that the FEA of the solid model provides the variation of von Misses stress on each insole with a predetermined gap width. In the 3D solid model, the optimum shoe orthotic insole peak has maximum von Misses stress of 1.19×10^{-3} MPa which exists on the heel bone with the gap width of 1.75 mm.

Keyword: Finite Element Analysis (FEA), foot deformities, insole shoe orthotics, von Mises stress

INTRODUCTION

Abnormalities are commonly found in the foot deformities such as pronation, metatarsalgia, flat feet, neuroma, plantar fasciitis, arch pain, and diabetes and these can be closely related to the abnormal distribution of plantar pressure [1, 2]. These deformities were generated from the use of unfitted shoes leading to the foot pain and creating an insole syndrome. Solution to address this problem is by creating a shoe orthotic insole that fits the contours of the foot problems. The making process of the insole may use the method of reverse innovative design (RID) which provides the rapid, precise and accurate geometry [3]. Also, it can get a 3D mesh of the leg disordered scanning with 3D scan foot. In addition, in this method, the use of CAE for obtaining an optimal product design is absolutely necessary prior to the manufacturing process. Now, a computational modelling developed in the CAE is able to enhance the knowledge of the biomechanics of the foot. Here, finite element (FE) analysis of shoe orthotic insole can predict the load distribution between the legs and the designed insole. This also enables the efficient parametric evaluations for the outcomes of the insole shape and material modifications, without fabricating and testing orthotics in a series of patient trial [4].

Further, the remarkable increase in interest for FE analysis of the insole shoe orthotics is reflected in the number of peer-reviewed publications [5-8]. The use of FE analysis has contributed to understanding the behavior of foot biomechanics and performance supports [5-8]. Based on FE analysis, some researchers [5-7] have focused on the effect of thickness orthotics and stiffness on the plantar soft tissue and plantar pressure distribution. However, the design for the orthotics shoe insole that fits the contours of the human foot has been not currently made. Therefore, it is necessary to improve the reliability of the design according to the requirements in RID method.

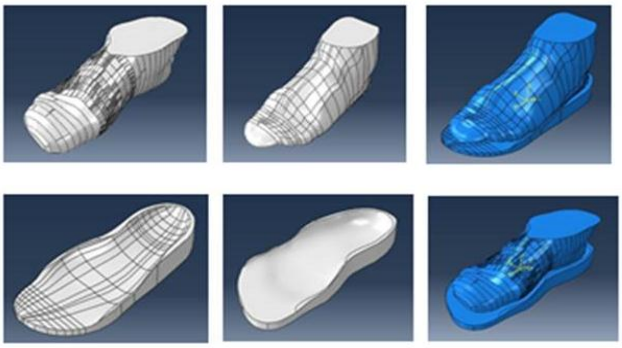
The main aim of this study is to develop an optimum 3D model of orthotic insole shoe which fits the contour of a human foot experiencing foot deformity based on the finite element (FE) analysis. The developed FE model is employed to predict the mechanical interaction between the foot as the indenter for different type of insole shoes. The different type of insole is set based on the gap difference between the wide legs with a wide insole. This finding of the result may help engineers and researchers to find the optimized orthotic insole design for people suffering from the foot deformities.

METHOD

The most important factor in designing a shoe insole is data about the quality of material insole. The foot shoe insole is a part connecting between the human body and the legs. In this present study, the foot insole geometry was modelled by FE and generated from the 3D scan reconstruction process using HANDYSCAN 700^{TM} tools. This method is able to produce 3D meshes for the normal human leg and foot deformities due to the weight of 40 to 90 kg. There are two diabetes patients, respectively with age of 50 and 72 years old. The 3D meshes of foot were initially conducted by placing the foot on the screen so that the scanner was working for providing the output data for the soles of the feet.

The 3D surface and solid modelling strategy of the orthotic insole shoe were adopted on the curve-based surface modelling (CBS-modelling) using the features included in the Power SHAPE 2015. The process provides a curve of the shoe insole that automatically fits the contours of the scanned foot. The curve was then quickly and easily changed into a 3D surface modelling with 3D surface and solid quality. FE model of the orthotic shoe insole was then analyzed in this study as shown in Figure 1. The combination of 3D meshes feet (indenter) and orthotic shoe insole (EVA rubber) was analyzed using ABAQUS 6.13.

It is assumed that a model assembly includes the plantar fascia, encapsulated soft tissue and the Eva rubber of the orthotic shoe insole (*iso_diabetes*). The plantar fascia materials were considered as isotropic, homogeneous, and linear elastic (Table 1). The soft tissue characteristics is shown in Table 2, while the non-linear elastic behavior data of the Eva rubber was taken from previous literature [9,10]. The hyperelastic material models were set to the encapsulated soft tissue. The hypereelastic material as defined in ABAQUS by Moonley-Rivlin was employed to represent the incompressible and nonlinearly elastic nature of bulk soft tissue [11].



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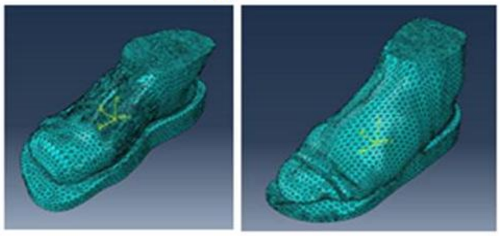

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Figure 1: (a) 3D solid FE model iso_diabetes imported to ABAQUS 6.13, (b) Assembly 3D meshes indenter foot and iso_diabetes

Tabel 1: Material properties of parts used in the finite elemen model [9]

Component	Modulus Young (MPa)	Poisson Ratio	Element Type
Bone	7300	0.3	Tetrahedral Solid
Cartilage	1	0.4	Tetrahedral Solid
Plantar Fascia	350	0.4	Tetrahedral Solid
Ligament	260	0.4	Tension only spar
plate	17000	0.1	Hexagonal solid

Tabel 2: The coefficients of the hyperelastic material used for *iso_diabetes* [11]

C_{10}	C_{01}	C_{20}	C_{11}	C_{02}	D_1	D_2
0.08556	-0.05841	0.039	-0.02319	0.00851	3.65273	0

Young's modulus and Poisson ratio for plantar fascia were set to 350 MPa and 0.4, respectively. The Eva insole material assigned as Rubber 400 has a Young's modulus and Poisson ratio 0.04 MPa and 0.49, respectively. Measurement of plantar pressure distribution has been made to validate the FE model of the foot [9,12,13]. In this study, the contact pressure distribution of the upper of orthotic shoe insole as plantar pressure and the peak value was calculated from the various insole models. Two diabetes patient with high risk scale [14] have been selected and set for the scanning process. The design using CAD and CAE analysis were performed using ABAQUS 6.13. Description of the patient can be found based on table data of diabetic patient as described in [14].

Results of loading on a design variation of the orthotic shoe insoles with a wide gap ranging from 2.0; 1.75; 1.50; 1.0; 0.75; 0.5; and 0.0 mm are examined by FE analysis to obtain the optimum insole design.

It should be highlighted that that the main goal of the paper is to investigate the optimal von Misses stress distribution that occurs in every *iso_diabetic* which has been designed based on the wide gap. And thus a pair of the optimal *iso_diabetis* can be obtained.

RESULTS AND DISCUSSIONS

In the present study, the result of scanning is performed by HANDYSCAN 700^{TM}. It can display the entire surface of the foot of patients with high accuracy up to 0.030 mm. As a note, scanning results can not be directly processed using software ABAQUS 6.13, because of the shape file scanning results with handyscan 700^{TM} still a *.STL files* in 3D surface/solid modeling. Therefore, this file was changed to.dwg or iges files in CAD software.

In order to get the stress distribution, a wide tolerance on each 3D solid *iso_diabetes* is necessary. Wide tolerance is provided on each edge of the surface of the soles of the feet of *iso_diabetes.* The small tolerance with range values from 0.0 to 2.0 mm on each leg for products is performed in order to obtain the design of shoe insole which will be paired with the outsole. It should be noted that wide tolerance which is too large (larger than 5 mm) will change the dimensions of 10 mm. As a consequence, it will provide discomfort for the patient because *iso_diabetes* generated is too loose.

The variation of tolerance specified according to the best of our knowledge was very appropriate and proper, because based on an isometric view in PowerSHAPE 2016 it is shown that the discovered suitability of fit is around 95-97% between the shape and dimensions of leg from two patients with scanning results, 3D solid foot with CBS and *iso_diabetes*. Load variations are determined by the range of 1-2 kg of weight of the patient. For example, a patient with 50 kg, the load set inducing the foot pressure will range from 220; 230; 240; 250; 270; 290; 310; 330; 350 and 352 N both for the left foot and the right foot. In this paper, FE models are designed to provide the contact pressure on the patient when stepping foot orthotic shoe insole.

Figure 2 shows in detail the geometry modelling as well as the boundary condition applied on the FE model. It can be seen that the foot indenter is contacted with the insole shoe. Figure 3 and 4 show the correlation between von Misses stress generated against the load variation for the case of the patient's body *iso_diabetes* design both for left and right foot for patient 1 and 2, respectively. It can be seen that the force on foot (compression stress) as a result of the patient's body weight has a significant impact on the predicted von Misses stress. It is also found that the larger wide tolerance given on a 3D model of *iso_diabetes* gives the smaller von Misses stress. This is as expected because the compression stress given to a patient's leg and touched the surface of *iso_diabetes* with tolerance 0.0 generates high stress values. While for the result of the surface *iso_diabetes* produces 1.5 mm wide tolerance on patients 1 and 2.0 mm for patient 2, respectively. The value of each von Misses stress is shown in Table 3.

Table 3: Optimal Value von misses stress

No	Patient	Wide Gap (mm)	von misses stress (Mpa)		Conclusion
			left foot	right foot	
Patient1	50	0	0.765	0.7625	reject
		1.5	**0.0132**	**0.086**	**optimal**
Patient2	72	0	1.018	1.0195	reject
		2	**0.02568**	**0.04495**	**optimal**

To validate the results of the present work, in terms of the pressure distribution, the experimental data in the literature [8-9] is compared with FE results. It is highlighted that the von misses stress in normal people's feet have in common layout. The current FE orthotic shoe insole pressure for normal foot shows that the direction and position of the peak von Misses stress are the same with that on the heel bone. The value of peak von Misses stress in this section leads to the excessive pain for people with foot deformities. Thus, in the design of shoe orthotic insole needs, it is necessary to determine what is the optimal gap width between the legs and the insole heel bone.

It should be noted that based on Figures 3-4, the patient with diabetes shows there is a difference from the visual point of view between the legs and the insole compared to a normal person (without diabetes) in terms of the profile of the von Misses stress. This is because in the case of the simulation of a normal person the insole is designed as flat on the soles of the feet, while the insole foot for patient diabetes is made as similar according to the contour of the foot.

The simulation results show that with respect to the tolerance, the optimal design exists in the tolerance 1.5 mm for *iso_diabetes* 1 and 2.0 mm for *iso_diabetes* 2. In terms of the maximum von Mises stress, the value is around 0.02568 MPa for left foot and 0.04494 MPa for the right leg, respectively for patient 2 with a weight of 72 kg, while for patient 1 with a weight of 50 kg, the maximum von Mises stress is 0.0132 MPa for left foot and 0.0086 MPa for right foot, repectively.

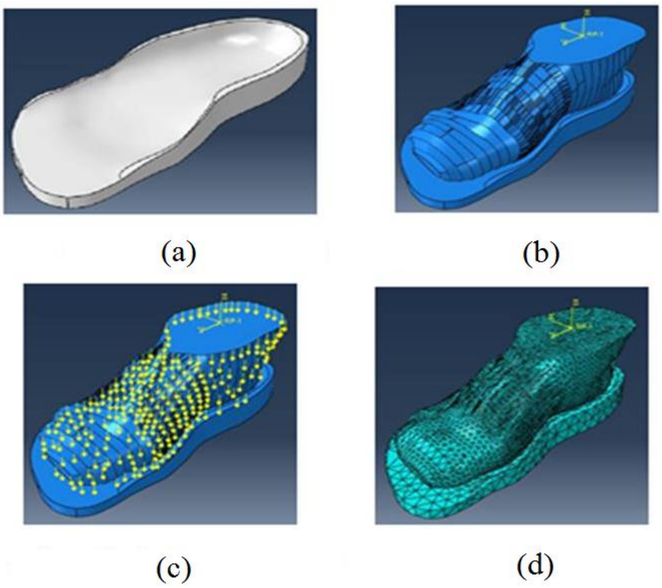
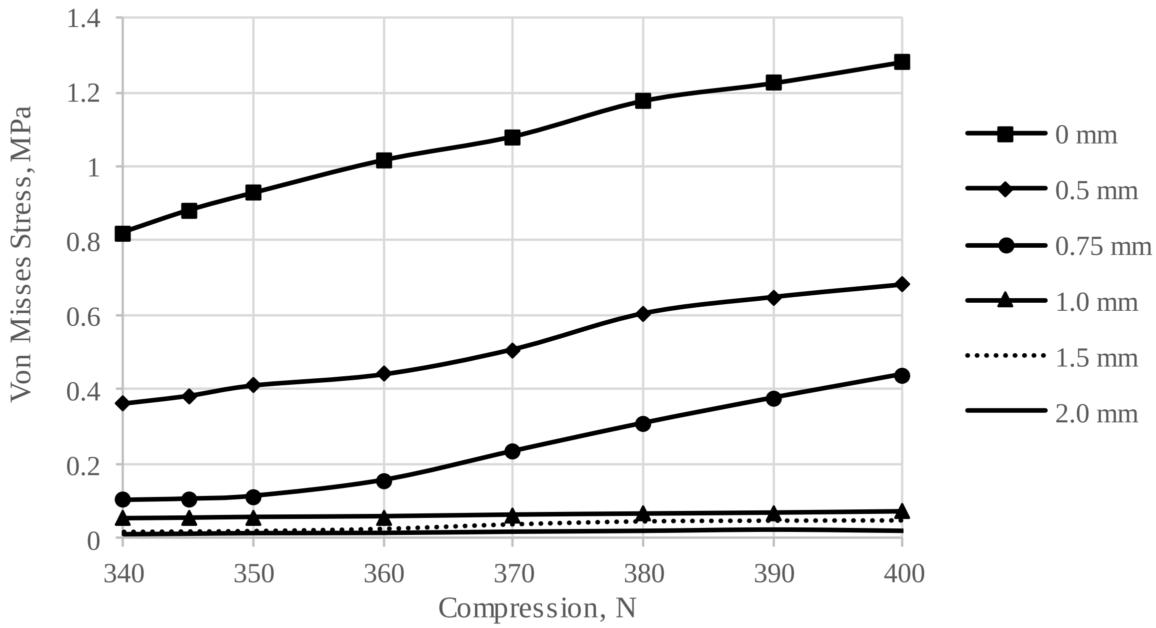


Figure 2: Steps for modeling in ABAQUS 6.13: (a) 3D solid of insole, (b) assembly of indenter foot with insole, (c) distribution of pressure on foot contact with insole, (d) assembly of meshing for indenter foot with insole 7



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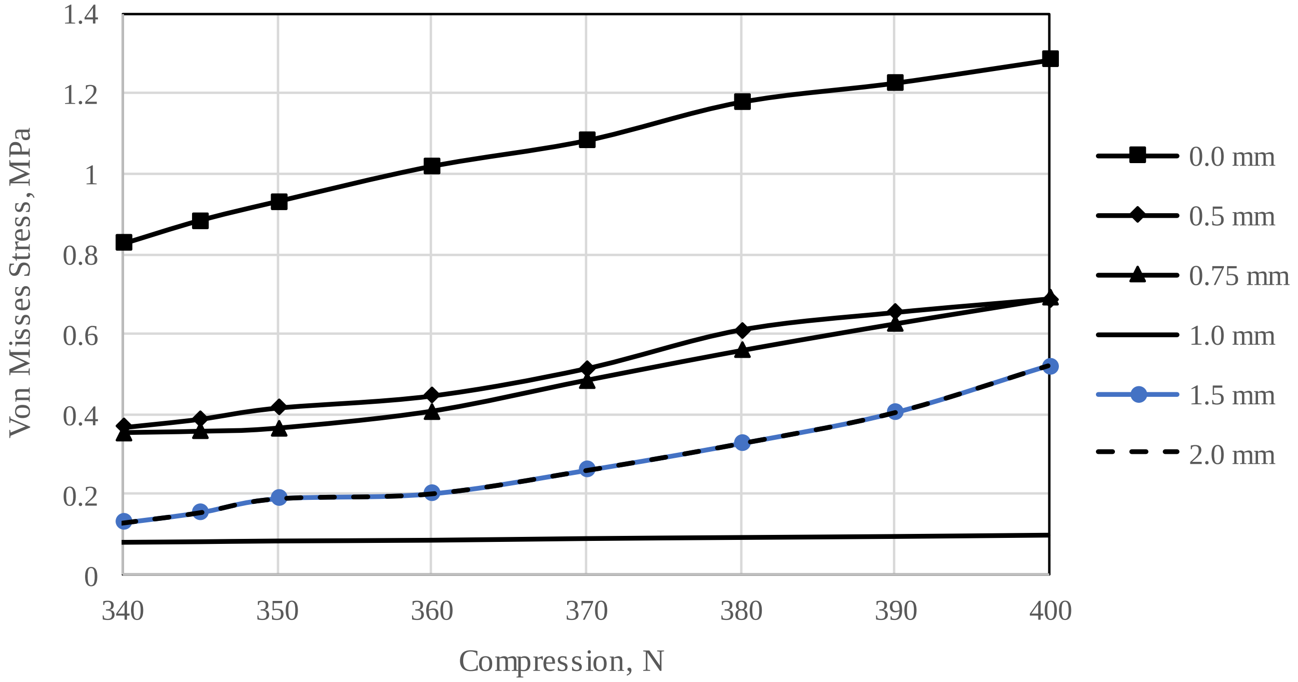

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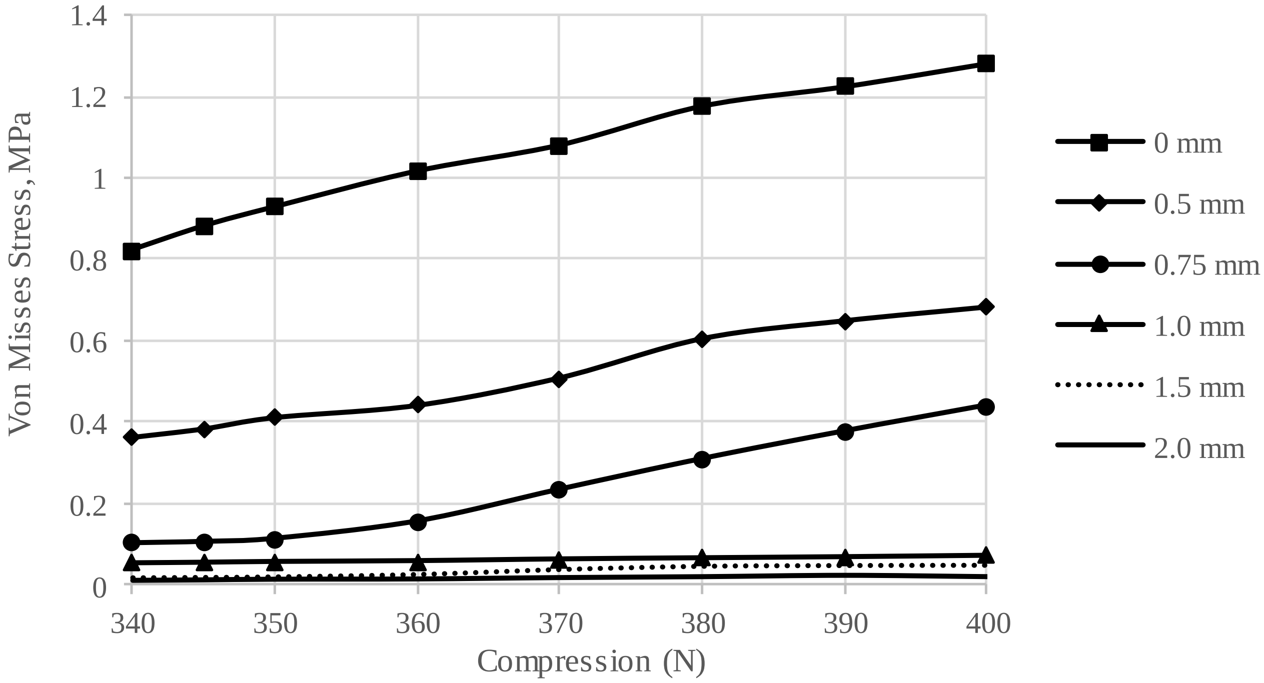
Figure 3: Distribution of von Misses stress for Patient 1 on: (a) left foot, (b) right foot



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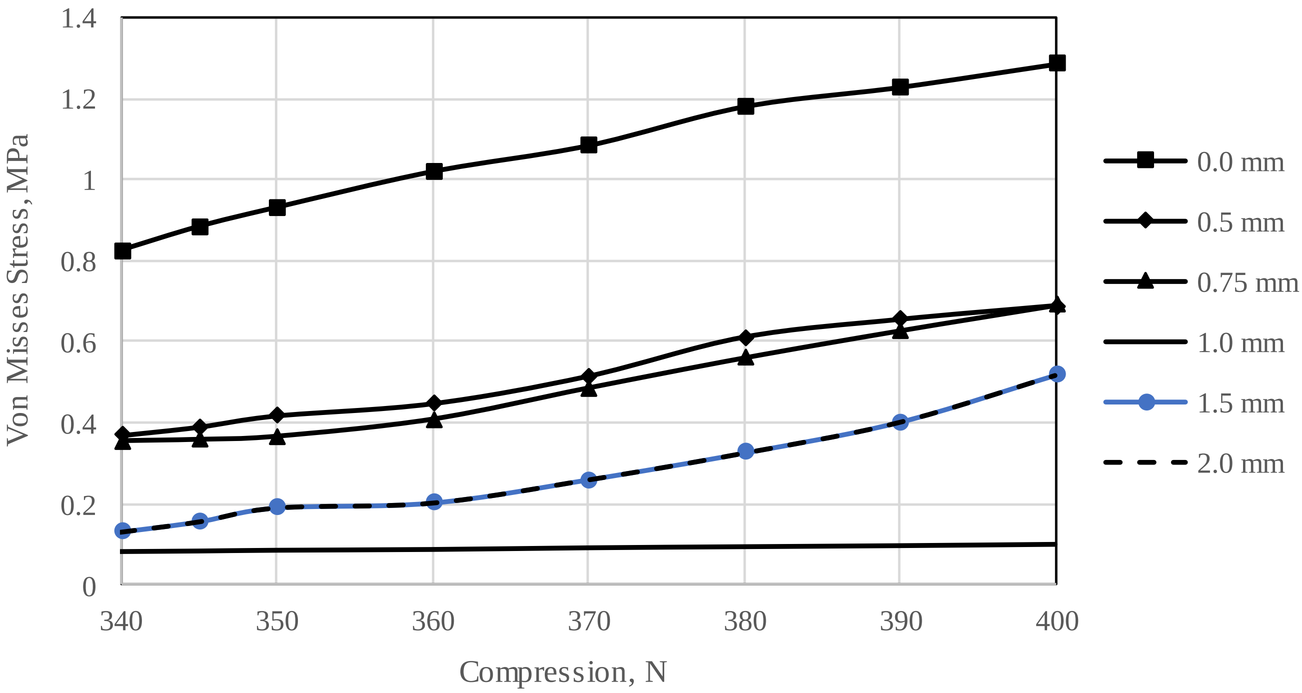

(b)

Figure 4: Distribution of von Misses Stress for Patient 2 on: (a) left foot, (b) right foot

CONCLUSIONS

This study demonstrates *Iso_diabetes* design optimization based on a 3-dimensional finite element analysis with ABAQUS 6.13. In the present study, RID methods were developed to create insole shoe orthotic model. The foot contour for two patients with diabetes were compared with respect to the von Mises stress. Based on the discussion, the conclusion can be drawn as follows:

1. For patients with diabetes, the von Misses stress distribution occurs in the area around the plantar facia and the area around the heel bone.
2. The variation of wide gap of the *iso_diabetes* design has a significant effect on the increase in the distribution of stress especially when the rubber is used as material for Eva orthotic insole during the contact with the legs.
3. The interesting results in the present study is that finite element analysis for optimization of product design of shoe insole developed here can be applied to all those who suffer from foot disorders such as pronation, metatarsalgia, flat feet, neuroma, plantar fasciitis and foot deformity.

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