RESEARCH ARTICLE

Custom Shoe Sole Design and Modeling Toward 3D Printing

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Abstract: This study introduces a design procedure for improving an individual's footwear comfort with body weight index and activity requirements by customized three-dimensional (3D)-printed shoe midsole lattice structure. This method guides the selection of customized 3D-printed fabrications incorporating both physical and geometrical properties that meet user demands. The analysis of the lattice effects on minimizing the stress on plantar pressure was performed by initially creating various shoe midsole lattice structures designed. An appropriate common 3D printable material was selected along with validating its viscoelastic properties using finite element analysis. The lattice structure designs were analyzed under various loading conditions to investigate the suitability of the method in fabricating a customized 3D-printed shoe midsole based on the individual's specifications using a single material with minimum cost, time, and material use.

Keywords*:* Customization, Shoe, Sole, 3D printing, 4D printing, Viscoelastic, Polyurethane

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1. Introduction

The use of additive manufacturing and three-dimensional (3D) printers is very popular these days[1-3], and they have various applications in various industries, including aerospace[4], automotive[5], soft robotics[6], construction[7], food printing[8], and tissue engineering[9,10]. One of these is the custom manufacturing of products. 3D printing opens the way to novel footwear items by integrating new materials and digital production. At present, the technology now makes it easier to produce high-performance sports shoes and customized sandals using 3D printed shoe components. This enables shoe manufacturers to join the market rapidly by exploring new designs and offering more personalization options. Despite these benefits, the use of 3D printing in footwear remains limited, as the technology currently is yet to enable mass customization incorporating high-level nonlinear materials behavior and geometrical designs to accommodate the intensive and high productivity needs of individuals in the market. However, the development of footwear 3D printing is driven by trends in digital production and desire for personalized experience. Considering midsoles, they are typically constructed throughout the shoe as a solid component with the same level of support. The designers may optimize cushioning properties throughout the whole shoe by adjusting various sections of a midsole, producing better performance footwear. The present study shows an approach to improve the efficiency of shoes in different uses through the optimal geometry design of a 3D printing material tailoring different purposes.

Due to unhealthy lifestyle, like high fat diet and lack of enough exercises due to working from home, a higher number of people are nowadays prone to various types of diseases, which lead to obesity, which in turn increases body mass index (BMI). People with high BMI frequently suffers from the problems of foot ulceration due to excessive walking or standing for a long time.

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The need is to have a perfect shoe which will not only provide comfort, but also maintain the functionality in diverse daily activities[11]. It can also be inferred from the open literature that shoe sole plays a critical role in rehabilitation of lower limb[12] while it improves walking function[13] and reduces foot lesions. Patients often complain of foot pain and fatigue after prolonged walking, followed by pain in the knee and ankle that generally deteriorates the quality of life[14]. The effects of custom-made sole on the life quality of individuals both physically and mentally are proven[15]. Due to difference in foot structures of people, customizable midsole has come into picture, which provides more comfort as compared to prefabricated counterparts. One solution is 3D printing of custom shoe midsole, where 3D scanning techniques helps in getting the exact shape and size of the foot which act as input to design. Custom soles are more suitable for plantar structure of patient[16] and can further be improved if traditional support structure is optimized; therefore, further damage reduction at a lower cost, material waste, and fabrication time[17,18].

In the past years, there has been considerable amount of research in footwear industry to provide best comfort shoes for different walks of people from various fields, such as the sports or health sector; many researchers continue to deliver crucial information based on the experimental and theoretical works[19]. The stiffness reported as a crucial factor accounts for 70% of the comfort for diabetic users[20]. High plantar pressure generated on foot can be impacted by changing the stiffness of the shoe sole material[21,22]. A study has shown the efficacy of customized sole in reducing the peak of load by 40% at metatarsal region[23]. Custom-made insoles have proven to provide considerably better stress distribution and much less maximum stress (around 40%) compared to flat insoles, which is very important in fabrication and selection of comfortable insoles[24]. Furthermore, the effect of custom-made 3D-printed foot orthoses in the treatment of pain result in the foot of workers due to prolonged standing has been studied[25]. Analysis of the participants' test results revealed that after wearing customized 3D printing orthoses, feeling of discomfort, pain, and heavy legs were reduced significantly.

Increase of thickness makes the stress distribution more uniform and decreases the maximum stress value up to 10%. However, simply increasing the thickness does not necessarily lead to less maximum stress after a certain thickness of the insole[26] that is where more sophisticated lattice design from 3D printing could play a significant role. 3D printing has been recently focused as the most flexible technology in making midsoles due to its unit features in designing and developing variable density and stiffness products with changing the infill pattern in two and three dimensions, changing the infill across the sole, changing wall thickness of infill walls and changing infill density and height of each voxel. Hence, the midsole designed could not only be customized to the individual's foot, but also is customized to the types of activity, such as walking, running, or jumping. The same level of performance will be hard to do or impossible with machining and conventional subtractive manufacturing.

Recent studies were conducted on different lattice structures by changing its unit cell size and shape to check the behavior of their mechanical property, deformation behavior, and compressive property[27-29]. Different lattice structures with closed and open unit cells of same size were investigated in these studies and found that lattice structure with a closed unit cell has higher stiffness compared to the open lattice. A comparison analysis of lattice structures made from different unit cells by additive manufacturing were conducted[30]. The compression tests were performed on four different topologies such as Diamond, Grid, X shape, and Vintiles to investigate the mechanical property of all four topologies. It has been found that the Grid lattice delivered the highest stiffness compared to others which can be helpful to use in heel part of the insole as it requires stiffer material. Diamond shape lattice structure has shown the most uniform stress distribution property which can be helpful for reducing the plantar pressure.

Shoe firms have been moving away from leather to shoes that are almost entirely polymeric. Thermoplastic urethane (TPU) is a soft material that is highly resistant to wear and abrasion, and is already used widely in many industries, including footwear. The visco-hyper-elastic property of TPU is preferred due to their elasticity property and resistance they offer when subjected to compression. The TPU also meets the requirements for medical devices with regard to cytotoxicity and skin sensitization in accordance with the DIN EN ISO 10993-5 and 10993-10 standards. The major advantage of soft-filament materials is the flexibility that makes them deformed under a load and its ability to revert back to their original state when the load is removed. This property makes it possible to fabricate durable 3D objects with high deformation stability. In addition to its softness and flexibility, TPU is also known for its functional properties of being durable and being able to withstand ambient temperatures up to 80°C. TPU is therefore practical for both consumer and industrial use.

The fast print speeds and compatibility with springy and flexible materials such as TPU, silicone, and elastic polyurethane, common for athletic shoes, have made resin-based 3D printing technology a sustainable manufacturing option. At present, vat photopolymerization is the most popular category of 3D printing methods for footwear manufacturing[31]. This category includes resin-based technologies, such as stereolithography and digital

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light processing, and Carbon's digital light synthesis (DLS)[32]. These methods are based on a similar technique, in which a light source (laser, light-emitting projector or diodes) is applied to a liquid resin layer by layer, thereby consolidating it. Besides resin-based technology, shoe manufacturers also employ powder-based technologies, such as Multi Jet Fusion (MJF) from HP and Selective Laser Sintering (SLS)[33]. The MJF and SLS are more frequently utilized in the manufacture of insoles, as opposed to resin-based technologies used in midsoles.

In this study, we present three different lattice patterns designed with same wall thickness and amount of a DLS 3D printing-based material. The midsoles were positioned according to the foot sole to create a specific design taking into consideration the visco-hyper-elastic material effects as per individual specifications. The type of lattice depends on the required demands of the individual applications. These patterns were also compared in different loading scenarios under different input loads simulating the type of activities to judge the efficiency of viscoelastic lattice design in distributing the stress. The results of the conducted simulations showed that the physical properties of customized 3D-printed midsoles are affected by the pattern type with the same amount of material and properties. The contribution of our study is as follows:

a) The 3D-printed grade TPU material properties were validated in ABAQUS finite element analysis (FEA) platform.
b) A specific design for the customized 3D printing was introduced along with flexible patterns, considering the viscoelasticity property of material.
c) A procedure was presented to design and 3D print a customized midsole in terms of specific individual features, such as body weight and type of activity, using merely one type of material at minimum cost and material use.

The rest of this paper is organized as follows: Section 2 is dedicated to the detailed methodology of 3D-printed customized midsole design and the materials characterizations; Section 3 provides the description of the FEA and simulation results and discussion; and Section 4 summarizes the study.

2. Methodology

2.1. Custom midsole design workflow

The pressure distribution is practically consistent in ordinary people. Originally, the body mass appeared on the heel area than that on the middle foot as it transitioned to the forefoot and then was received by that of the toe region in the end[34]. In ordinary humans, the maximum pressure is located on the second metatarsal. The variation of the plantar pressure in normal individuals is from region of heel contact to area off toe. **Figure 1** shows an image[35] where ground reaction forces generated on the foot are derived by foot movement using an experimental gait analysis.

To build an individual shoe sole for a person, plantar pressure needs to be lower which is possible using different lattice structures and a single 3D printing material. As midsole is subjected to low velocity impact test, visco-hyper-elastic materials are most suitable as they offer high elasticity and show positive results on dynamics humans' body.

The effects of sole designs on the plantar pressure and the ground reaction force over a period of time have been studied[36]. The results revealed the reaction force value changes by changing the stiffness and damping structure. It was also observed that both elastic and viscos properties of sole give torque to ankle and knee joints and make the body propulsion. The aim of midsole design is to reduce plantar pressure generated on different areas of foot and give more relaxation to the person's body while they do activities in footwear.

Therefore, in the present work, the shoe sole was designed by considering different activities of person, such as walking, running and jumping, and for this trend, viscoelastic material was selected and subjected to low-velocity impact test that results in a graph of load over time. This load versus time graph gives the idea about how shoe midsole is helpful to reduce the plantar pressure in people based on their specific activity. The novelty of the present study compared to other currently commercial models is the investigation of functional customization that does more than just geometry consideration with the incorporation of viscoelastic material properties into performance evaluation for specific user demand.

A detailed workflow of design and simulation proposed in this study is illustrated in **Figure 2**. The

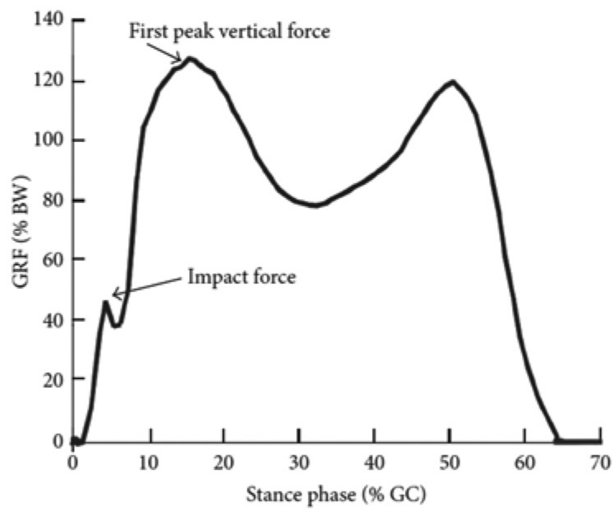

Figure 1. Reaction force generated on feet (from ref.[35] licensed under Creative Commons Attribution 4.0 License).

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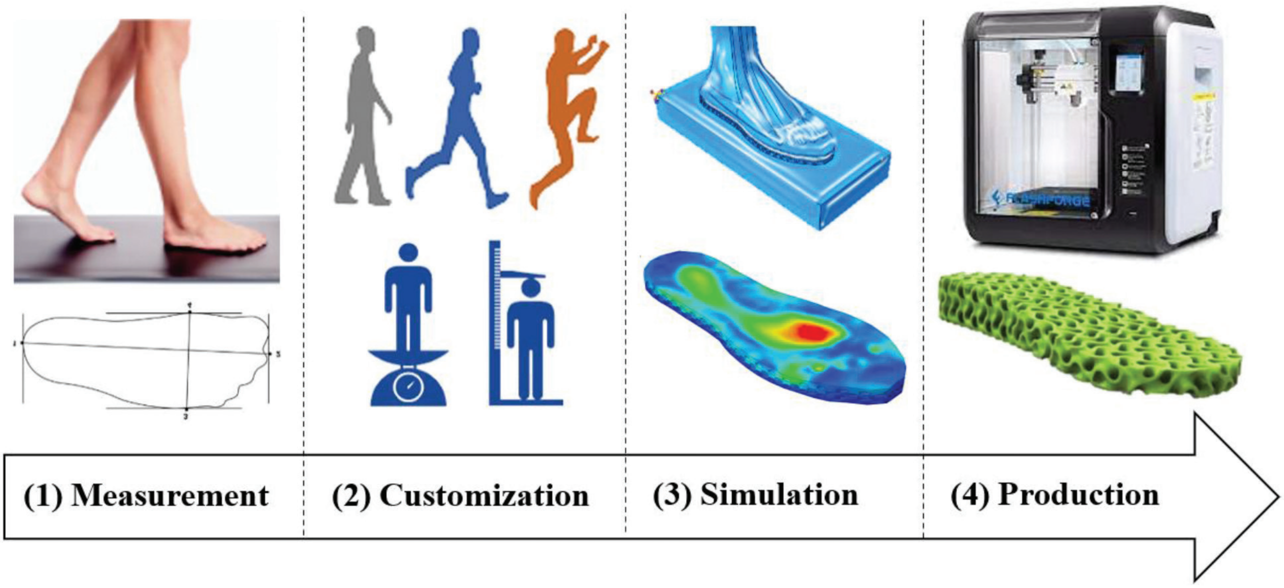

Figure 2. A schematic workflow of custom 3D-printed midsole production.

process starts with receiving the foot shape of an individual using scan or even the shoe size. Then, the lattice of different shapes, for example, three here, are designed and generated in computer-aided design (CAD) software. It should be noted that the cell size of lattices is chosen arbitrarily while their effect is considerable for a further study to deliver more regional stiffness in sole as per individual specifications, such as diabetic patients. Next, a simulation is carried out in an FEA platform called ABAQUS, considering the nonlinearity and viscoelastic properties of the 3D printing material to reflect the stress distribution on the midsole surface in contact with plantar subjected to increasing, downward-directed displacement, which leads to contact with the rigid ground surface and compression of the lattice. Finally, the desired lattice providing less stress compatible to the user application, that is, walking or running, are suggested for 3D printing.

2.2. Materials preparation and characteristics

DLS technology is a new printing method for 3D printing of soft polymers. Elastomeric polyurethane (EUP40) is a type of soft polymer that can be printed by this method. This material has an elongation length of about 275%, shear strength 23 kN.m, shore hardness 68A, and T_g (glass transition temperature) 8°C[37]. These properties have led to EUP40 being classified as a rubber-like viscoelastic material. For this reason, the neo-Hookean and Yeoh's rubber-like model as well as Carol are used to study the behavior of the material as:

$$W = \sum_{i=0}^{s} C_i (I_{1i} - 3)^3 + \sum_{i=s+1}^{n} D_i (I_{1i} - 3) \tag{1}$$

$$W = aI_1 + bI_1^4 + c\sqrt{I_2} \tag{2}$$

The viscoelastic behavior of EPU40 for 3D printing of midsole is characterized at different strain rates and it was used in this work to simulate the results having validated using FEA in ABAQUS. To find the stress-strain relationship in quasi-static state, homogeneous uniaxial tensile test with low strain rate were conducted[37]. Furthermore, to confirm the ability of traction, that is, high elongation in the failure of EUP40 in the set of experiments, the strain rates of 0.032/s, 0.128/s, and 0.576/s at speeds of 50 mm/min, 200 mm/min, and 900 mm/min were conducted, respectively, to achieve high elongation.

The validation of stress-strain results at different strain rates are shown in **Figure 3**. According to this figure, increasing the strain rate has increased the stress in the same strain by 100%. This behavior of material indicates that models (1) and (2) are suitable to use to understand the behavior of the midsole material. Finally, after performing quasi-static tests, cyclic tests, relaxation tests, and experimental study of material behavior, the parameters of the two models are presented in **Table 1**.

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3. Results and discussion

Three lattice designs with the same amount of materials for the sake of comparisons were created

Table 1. Elastic and viscous parameters for Carroll's, neo-Hookean, and Yeoh's models

Carrol model	a	b	c	-
	2.868e-01	1.4183e-07	7.846e-01	-
Neo-Hookean+ Yeoh's model	C_1	D_1	D_2	D_3
	8.201e-01	5.792e-01	4.464e-01	3.382e+00

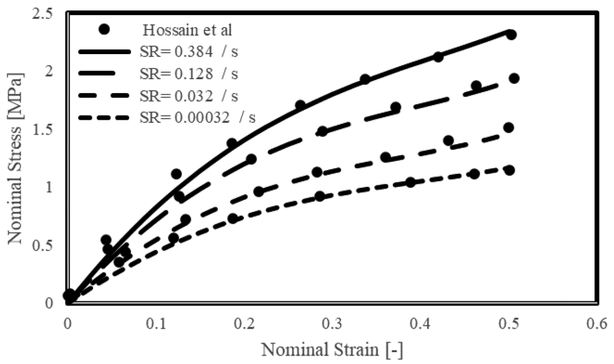

Figure 3. Viscoelastic 3D-printed EPU40 stress-strain results.

in the CAD software and converted into step format before being imported into ABAQUS (Dassault, France) for the FEA study. Different elements were used for ground, foot, and midsole where ground block and foot were meshed by 5 mm R3D4 and R3D3, respectively, and midsoles were meshed by 3 mm C3D4 tetrahedral elements as shown in **Figure 4**. The boundary conditions of different parts are shown in **Figure 5**, where the ground block is constrained in all directions. The input force was defined for three different scenarios of walking, running, and jumping of an individual with 1820 mm height, 84.6 kg weight, and equivalent BMI of 25.3 in **Figure 6**[35]. A dynamics/explicit solver with time steps corresponding to input force was used for calculating the simulation results in various individual specifications during walking, running, and jumping. According to the simulation of ordinary walking[12], the stresses of plantar were within the linear elastic range of EPU40 material. The properties of the foot and the ground were assumed rigid, and for shoe midsole, the EPU40 properties were defined (**Figure 3**).

The impact forces representing the individual specifications in walking, running, and jumping were applied for the three lattices, and stress and displacement distributions results are shown in **Figures 7 and 8**, respectively. It is observed that the highest-pressure peaks

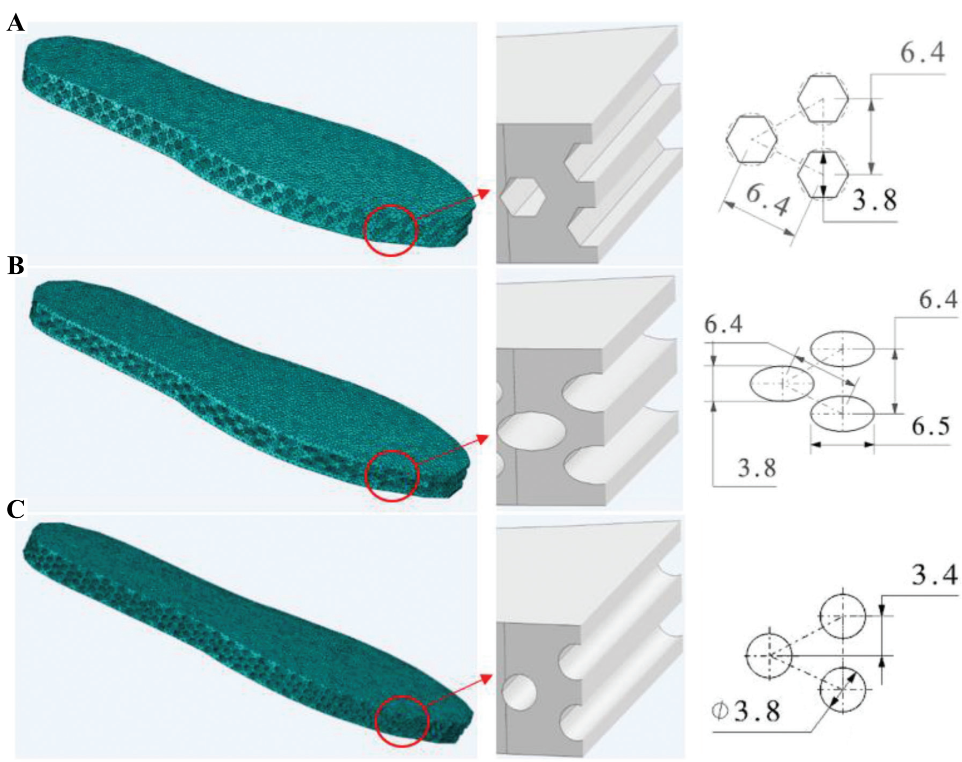

Figure 4. Different lattice meshes of midsole designs: (A) hexagonal, (B) elliptical, and (C) circular.

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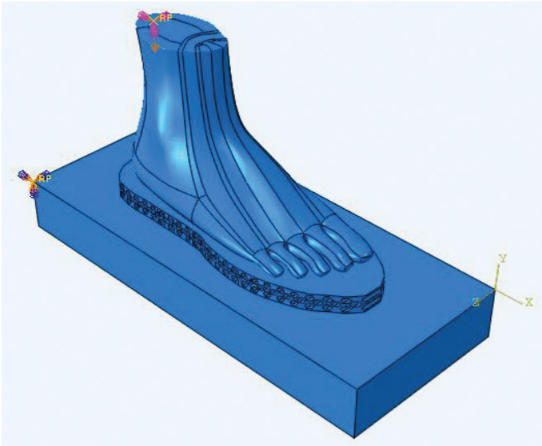

Figure 5. The boundary conditions and contact illustration of foot on midsole.

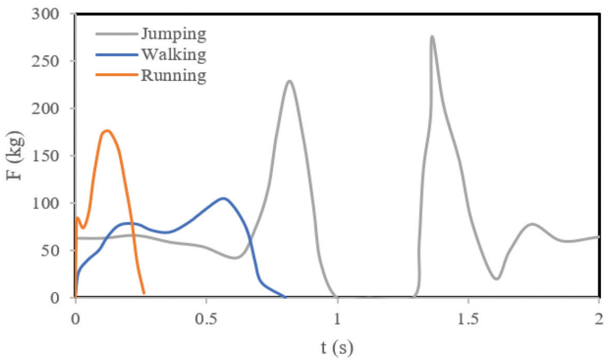

Figure 6. Input forces representing the individual specifications.

were at the heel and medial forefoot for all modes of walking, running, and jumping. From the data, it is clear that the medial forefoot and heel absorbed the maximum pressure during the jumping activity in comparison to the other two activities. The absolute peak data represent the maximum pressure at a specific point in the segmented area. For running, the peak pressure at medial forefoot and heel meaning both the regions are high pressure peak areas.

Furthermore, the results revealed the elliptical lattice has the highest stress, which accordingly undergoes higher displacement. This is due to the different structure in the shape of the lattice compared to the circular and hexagonal ones. According to **Figure 9**, it can be concluded that as the number of polygonal sides decreases or the ratio of large diameter to small diameter (in horizontal geometry) increases, the amount of stress and displacement increases.

Figures 10 and **11** show the changes in strain energy and viscous energy loss over time, respectively. According to these results, in each of the stepping specifications, the highest energy is related to the elliptical geometry. The greater effect of the elliptical geometry is due to the topology of this structure that is more prone to crushing and consequently undergoing a higher amount of displacement, stress, and energy. According to **Figures 10** and **11**, the maximum values of strain energy and viscous energy loss are observed in elliptical, hexagonal, and circular lattices,

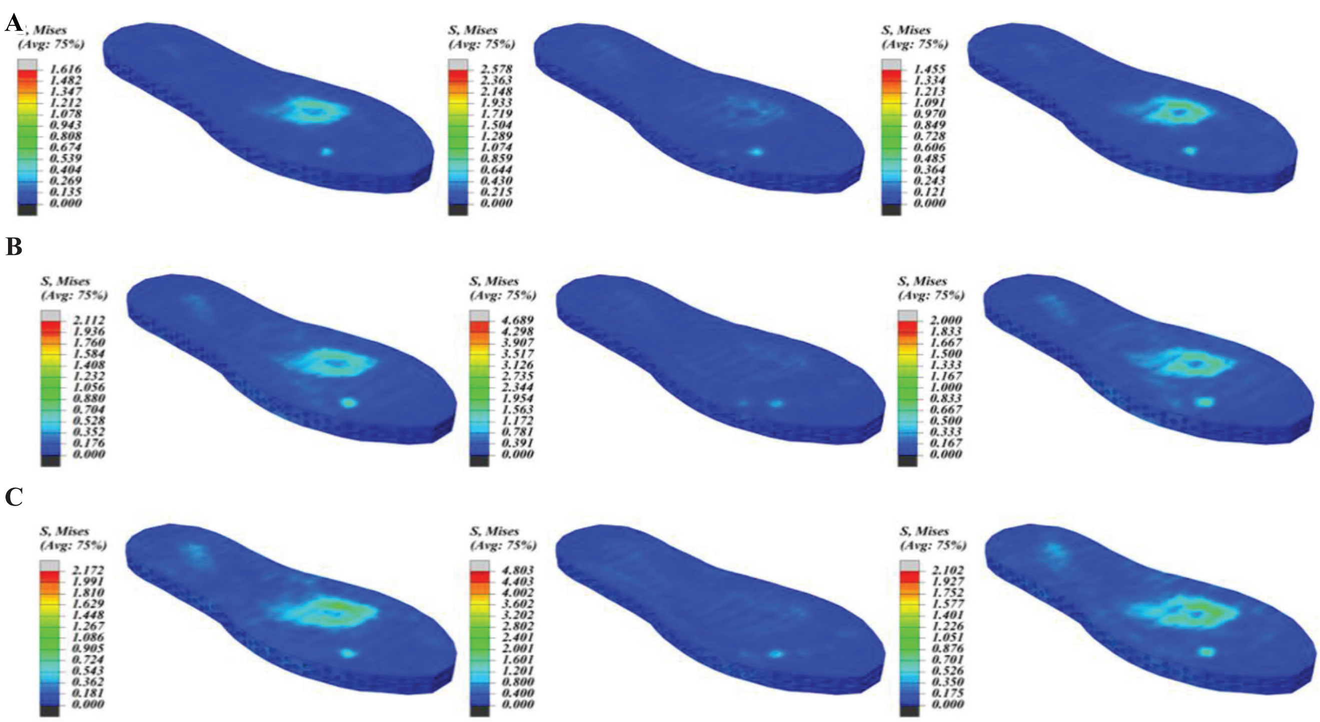

Figure 7. Maximum stress distributions of midsoles for different lattices (circular, elliptical, and hexagonal, from the left to right, respectively) at different scenarios of (A) walking, (B) running, and (C) jumping.

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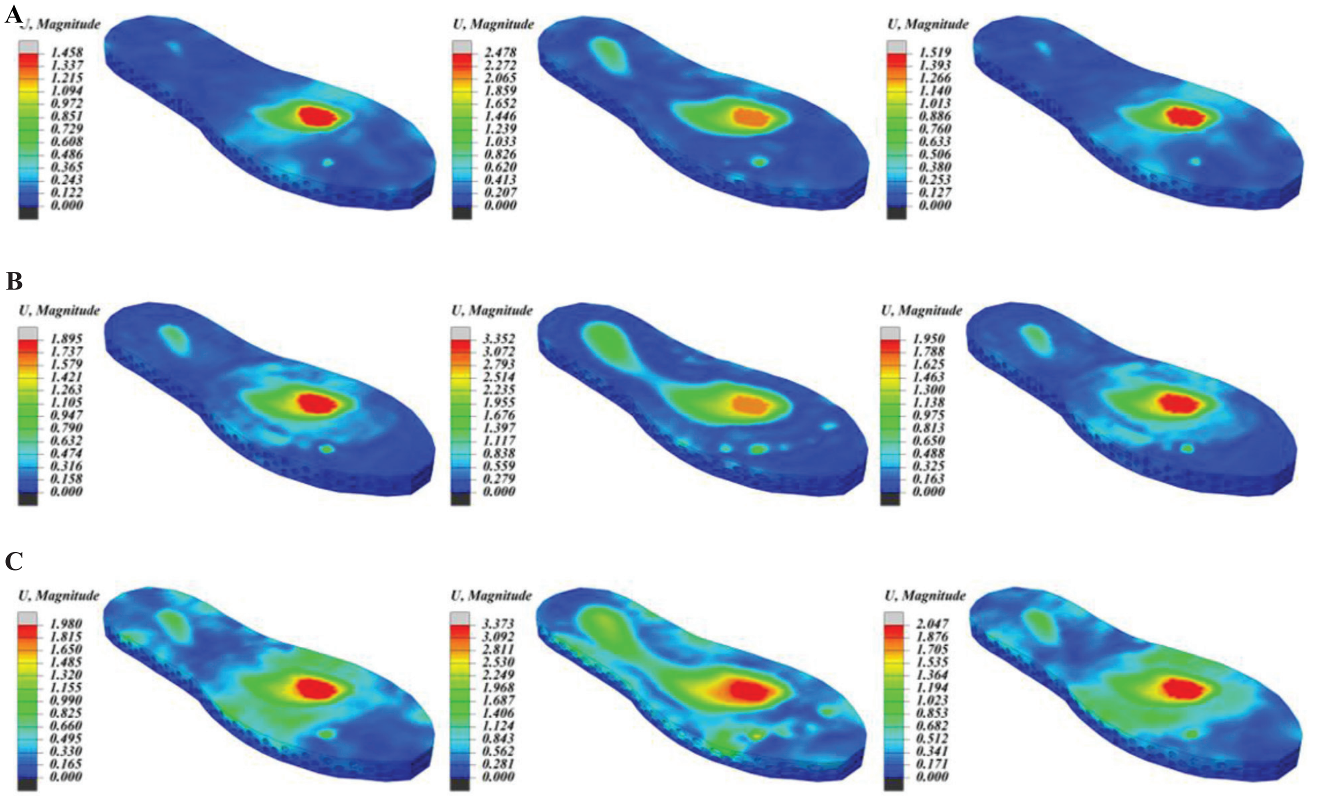

Figure 8. Maximum displacements of midsoles for different lattices (circular, elliptical, and hexagonal, from left to right, respectively) at different scenarios of (A) walking, (B) running, and (C) jumping.

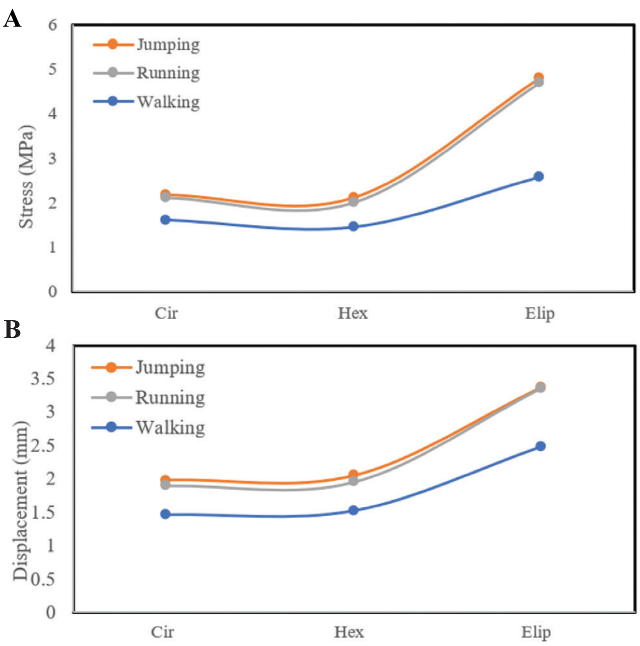

Figure 9. Maximum (A) stress and (B) displacement of midsoles in different scenarios of walking, running, and jumping.

respectively. This result is also arguable according to **Figure 9**, where with increasing displacement values in different lattices and consequently increasing amount of stress applied to the midsole, higher dissipation energy occurs with the same trend. As a result, the elliptical lattice experiences the highest amount of energy dissipation.

In general, hexagonal grids under non-planar loading have a higher energy absorption capacity than in-plane loading. The hexagonal lattice could be useful when the merely energy absorption of non-planar loading is the goal. Yet, the impact force duration is one of the important parameters in energy absorption. When the goal is to protect the human body from injury in walking, running, and jumping under the impact load, the importance of the impact time dominates so as with extending the time of impact its magnitude and the risk of damage it causes to the human body reduces accordingly. By applying the input forces of different gaits of an individual according to **Figure 6**, it can be seen that the amount of energy in **Figures 10** and **11** for jumping mode is much higher than running and walking

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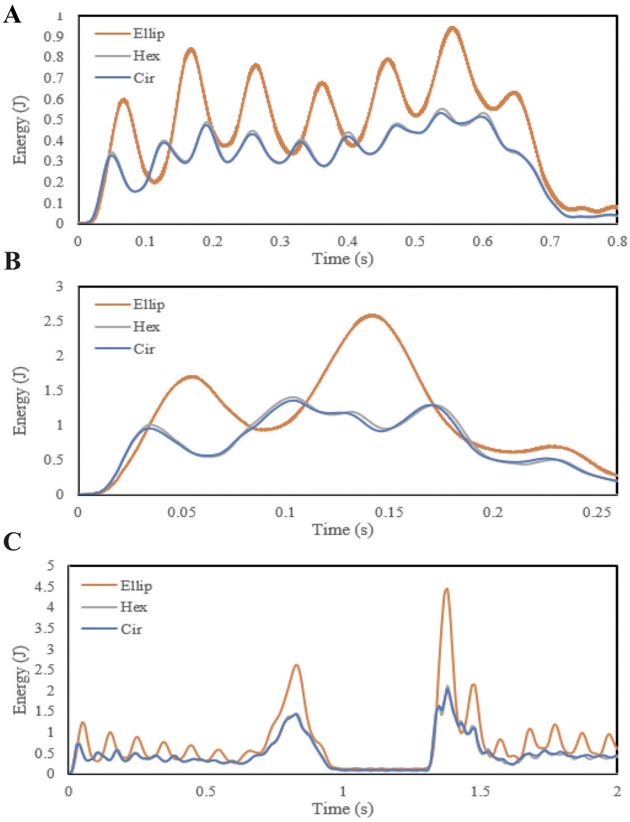

Figure 10. (A-C) Strain energy comparisons.

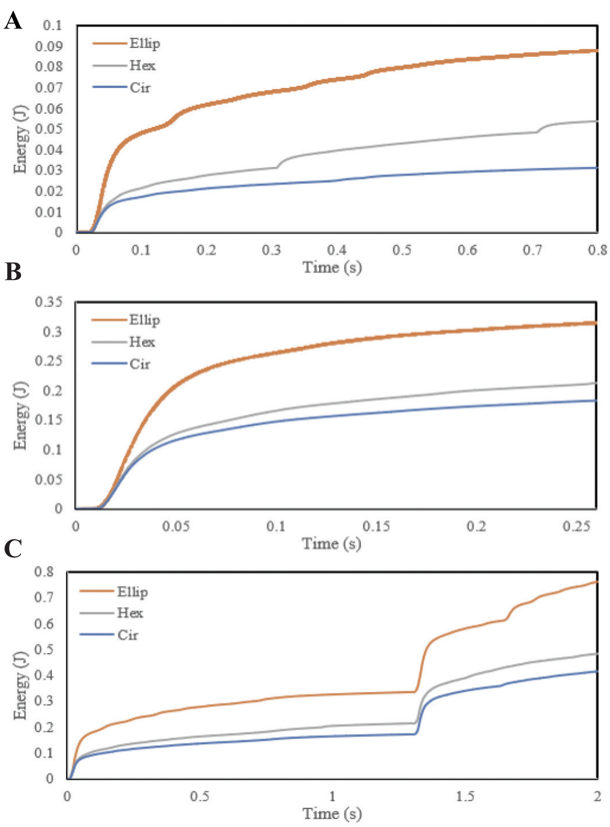

Figure 11. (A-C) Energy dissipation due to viscosity comparisons.

mode due to the effects of the magnitude and time of impact force on the shoe midsole.

It is an undeniable that denser infill patterns supply stronger support to a fabrication to absorb more energy or less the crushing. However, they consume more printing time, energy, material, and subsequent waste. Therefore, this method of customizing the shoe midsole in terms of individual's specifications but using the same amount of materials is efficiency in the reduction of material usage and time of 3D printing. This study proves the feasibility of an adaptive infill patterns application in stiffness and damping tuning required in custom shoes industry. Further clinical and experimental measurements are required as future directions.

4. Conclusion

In this work, various shoe midsoles were designed by considering different activities of person, such as walking, running, and jumping, and for this trend, a 3D printable viscoelastic material was selected and subjected to low velocity impact test that resulted in a graph of load over time. This load versus time graph gives the idea about how shoe midsole is helpful to reduce the plantar pressure on people based on their specific activity. The novelty of the present study compared to other currently commercial models is investigation of functional customization that does more than just geometry consideration with incorporating the viscoelastic material properties into performance evaluation for specific user need. The models with different thicknesses and materials were not considered here and our focus was merely on the interior pattern of 3D-printed midsoles that delivers various functionalities with considerations on cost reduction and the use of a common 3D printer and a single material. The study proved that the 3D printing is effective in making a midsole that caters to requirements of different individuals based on the infill patterns design. This study brings new innovation into customized 3D-printed shoes industries by providing these meaningful insights into the design process.

The results of this study also provide scope of using combination of lattice structure to increase the energy absorption capacity or elasticity, or providing more local support and comfort as per individual requirements, such as diabetic injuries or sports. The midsoles could see evolving improvements through 4D printing that redirects these vertical impact forces into horizontal forward motion, thus delivering a running economy or varying the stiffness to serve at various environmental conditions, such as different relative humidities and temperatures.

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Conflict of interest

The authors declare that they have no conflict of interest.

Author contributions

A.Z. conceived the ideas and drafted the manuscript. M.B. revised the manuscript, reviewed the simulation results, and advised the organization of the main contents. S.R. and M.L. collected the detailed research results.

References

1. Khosravani MR, Zolfagharian A, 2020, Fracture and Load-carrying Capacity of 3D-Printed Cracked Components. *Extreme Mech Lett*, 37:100692. https://doi.org/10.1016/j.eml.2020.100692
2. Zolfagharian A, Denk M, Bodaghi M, *et al*., 2019, Topology-optimized 4D Printing of a Soft Actuator. *Acta Mech. Solida Sin*, 33:418–30. https://doi.org/10.1007/s10338-019-00137-z
3. Shirzad M, Zolfagharian A, Matbouei A, *et al*., 2021, Design, Evaluation, and Optimization of 3D Printed Truss Scaffolds for Bone Tissue Engineering. *J Mech Behav Biomed Mater*, 120:104594. https://doi.org/10.1016/j.jmbbm.2021.104594
4. Joshi SC, Sheikh AA, 2015, 3D Printing in Aerospace and its Long-term Sustainability. *Virtual Phys Prototyp*, 10:175–85.
5. Nichols MR, 2019, How does the Automotive Industry Benefit from 3D Metal Printing? *Metal Powder Rep*, 74:257–8. https://doi.org/10.1016/j.mprp.2019.07.002
6. Zolfagharian A, Durran L, Gharaie S, *et al*., 2021, 4D Printing Soft Robots Guided by Machine Learning and Finite Element Models. *Sens Actuators A Phys*, 328:112774. https://doi.org/10.1016/j.sna.2021.112774
7. Tay YW, Panda B, Paul SC, *et al*., 2017, 3D Printing Trends in Building and Construction Industry: A Review. *Virtual Phys Prototyp*, 12:261–76.
8. Liu Z, Zhang M, Bhandari B, *et al*., 2017, 3D Printing: Printing Precision and Application in Food Sector. *Trends Food Sci Technol*, 69:83–94. https://doi.org/10.1016/j.tifs.2017.08.018
9. Ng WL, Chua CK, Shen YF, 2019, Print me an Organ! Why we are not there yet. *Prog Polym Sci*, 97:101145. https://doi.org/10.1016/j.progpolymsci.2019.101145
10. Askari M, Naniz MA, Kouhi M, *et al*., 2021, Recent Progress in Extrusion 3D Bioprinting of Hydrogel Biomaterials for Tissue Regeneration: A Comprehensive Review with Focus on Advanced Fabrication Techniques. *Biomater Sci*, 9:535–73. https://doi.org/10.1039/d0bm00973c
11. Ma Z, Lin J, Xu X, *et al*., 2019, Design and 3D Printing of Adjustable Modulus Porous Structures for Customized Diabetic Foot Insoles. *Int J Lightweight Mater Manuf*, 2:57–63. https://doi.org/10.1016/j.ijlmm.2018.10.003
12. Cha YH, Lee KH, Ryu H, *et al*., 2017, Ankle-foot Orthosis Made by 3D Printing Technique and Automated Design Software. *Appl Bionics Biomech*, 2017:9610468. https://doi.org/10.1155/2017/9610468
13. Munteanu SE, Scott LA, Bonanno DR, *et al*., 2015, Effectiveness of Customised Foot Orthoses for Achilles Tendinopathy: A Randomised Controlled Trial. *Br J Sports Med*, 49:989–94. https://doi.org/10.1136/bjsports-2014-093845
14. Pita-Fernandez S, Gonzalez-Martin C, Alonso-Tajes F, *et al*., 2017, Flat Foot in a Random Population and its Impact on Quality of Life and Functionality. *J Clin Diagn Res*, 11:LC22. https://doi.org/10.7860/jcdr/2017/24362.9697
15. Kusumoto A, Suzuki T, Yoshida H, *et al*., 2007, Intervention Study to Improve Quality of Life and Health Problems of Community-living Elderly Women in Japan by Shoe Fitting and Custom-made Insoles. *Gerontology*, 53:348–56. https://doi.org/10.1159/000104252
16. Linberg BH, Mengshoel AM, 2018, Effect of a Thin Customized Insole on Pain and Walking Ability in Rheumatoid Arthritis: A Randomized Study. *Musculoskelet Care*, 16:32–8. https://doi.org/10.1002/msc.1199
17. Rasenberg N, Riel H, Rathleff MS, *et al*., 2018, Efficacy of Foot Orthoses for the Treatment of Plantar Heel Pain: A Systematic Review and Meta-analysis. *Br J Sports Med*, 52:1040–6. https://doi.org/10.1136/bjsports-2017-097892
18. Zhu Y, Joralmon D, Shan W, *et al*., 2021, 3D Printing Biomimetic Materials and Structures for Biomedical Applications. *Biodes Manuf*, 4:1–24.
19. Low JH, Chee PS, Lim EH, *et al*., 2020, Design of a wireless smart insole using stretchable microfluidic sensor for gait monitoring. *Smart Mater Struct*, 29:065003. https://doi.org/10.1088/1361-665x/ab802c

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20. Begg L, Burns J, 2008, A Comparison of Insole Materials on Plantar Pressure and Comfort in the Neuroischaemic Diabetic Foot. *Clin Biomech*, 23:710–11. https://doi.org/10.1016/j.clinbiomech.2008.03.055
21. Chatzistergos PE, Naemi R, Healy A, *et al*., 2017, Subject Specific Optimisation of the Stiffness of Footwear Material for Maximum Plantar Pressure Reduction. *Ann Biomed Eng*, 45:1929–40. https://doi.org/10.1007/s10439-017-1826-4
22. Chatzistergos P, Farrugia K, Wright M, *et al*., 2019, Patient Specific Optimisation of the Stiffness of 3D Printed Orthoses for People with Diabetic Foot Syndrome. The Hague, The Netherlands: 8th International Symposium on Diabetic FootAt: World Forum.
23. Cheung JT, Zhang M, Leung AK, *et al*., 2005, Three-dimensional Finite Element Analysis of the Foot during Standing a Material Sensitivity Study. *J Biomech*, 38:1045–54.
24. Sarikhani A, Motalebizadeh A, Asiaei S, *et al*., 2016, Studying Maximum Plantar Stress Per Insole Design Using Foot CT-Scan Images of Hyperelastic Soft Tissues. *Appl Bionics Biomech*, 2016:8985690. https://doi.org/10.1155/2016/8985690
25. Tarrade T, Doucet F, Saint-Lô N, *et al*., 2019, Are Custom-made Foot Orthoses of any Interest on the Treatment of Foot Pain for Prolonged Standing Workers? *Appl Ergon*, 80:130–5. https://doi.org/10.1016/j.apergo.2019.05.013
26. Kim JS, Fell DW, Cha YJ, *et al*., 2012, Effects of Different Heel Heights on Plantar Foot Pressure Distribution of Older Women During Walking. *J Phys Ther Sci*, 24:1091–4. https://doi.org/10.1589/jpts.24.1091
27. Kumar A, Collini L, Daurel A, *et al*., 2020, Design and Additive Manufacturing of Closed Cells from Supportless Lattice Structure. *Addit Manuf*, 33:101168. https://doi.org/10.1016/j.addma.2020.101168
28. Zolfagharian A, Gregory TM, Bodaghi M, *et al*., 2020, Patient-specific 3D-printed Splint for Mallet Finger Injury. *Int J Bioprint*, 6:259. https://doi.org/10.18063/ijb.v6i2.259
29. Kolan KC, Huang YW, Semon JA, *et al*., 2020, 3D-printed Biomimetic Bioactive Glass Scaffolds for Bone Regeneration in Rat Calvarial Defects. *Int J Bioprint*, 6:274. https://doi.org/10.18063/ijb.v6i2.274
30. Dong G, Tessier D, Zhao Y, 2019, Design of Shoe Soles Using Lattice Structures Fabricated by Additive Manufacturing. *Proc Des Soc*, 1:719–28. https://doi.org/10.1017/dsi.2019.76
31. Ng WL, Lee JM, Zhou M, *et al.*, 2020, Vat Polymerization-based Bioprinting-Process, Materials, Applications and Regulatory Challenges. *Biofabrication*, 12:022001. https://doi.org/10.1088/1758-5090/ab6034
32. Redmann A, Oehlmann P, Scheffler T, *et al*., 2020, Thermal Curing Kinetics Optimization of Epoxy Resin in Digital Light Synthesis. *Addit Manuf*, 32:101018. https://doi.org/10.1016/j.addma.2019.101018
33. Sillani F, Kleijnen RG, Vetterli M, *et al*., 2019, Selective Laser Sintering and Multi Jet Fusion: Process-induced Modification of the Raw Materials and Analyses of Parts Performance. *Addit Manuf*, 27:32–41. https://doi.org/10.1016/j.addma.2019.02.004
34. Rai D, Aggarwal L, 2006, The Study of Plantar Pressure Distribution in Normal and Pathological Foot. *Pol J Med Phys Eng*, 12:25–34.
35. Nandikolla V, Bochen R, Meza S, *et al*., 2017, Experimental Gait Analysis to Study Stress Distribution of the Human Foot. *J Med Eng*, 2017:3432074. https://doi.org/10.1155/2017/3432074
36. Koike S Okina S, 2012, A Modeling Method of Sport Shoes for Dynamic Analysis of Shoe-body Coupled System. *Proc Eng*, 34:272–7. https://doi.org/10.1016/j.proeng.2012.04.047
37. Hossain M, Navaratne R, Perić D, 2020, 3D Printed Elastomeric Polyurethane: Viscoelastic Experimental Characterizations and Constitutive Modelling with Nonlinear Viscosity Functions. *Int J Nonlinear Mech*, 126:103546. https://doi.org/10.1016/j.ijnonlinmec.2020.103546

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