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Analysis of plantar pressure of midsole prepared by 3d printed biomimetic structures with different densities

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Abstract

This study investigates the impact of 3D printed midsoles with biomimetic structures of varying densities on plantar pressure during static and dynamic motions. The midsoles were designed with three densities of Tyson polygon (TS) structures: 1TS, 2TS, and 3TS. Plantar pressure tests were conducted on midsoles during static and dynamic motions such as walking, running, and jumping. The data were analyzed based on hypotheses related to samples, motions, and 10 plantar pressure zones. As results, for static motion, all midsoles improved pressure distribution and reduced peak pressure compared to barefoot conditions, with 1TS being the most effective. During dynamic motions, 1TS and 2TS effectively distributed plantar pressure in the midfoot and heel areas, while 3TS provided better support and stability during high-intensity activities like jumping. Statistical analysis revealed that 1TS offered comfort and flexibility but lacked support, 2TS balanced support and cushioning, and 3TS provided superior support and stability but reduced elasticity during jumps. In dynamic motions, 1TS excelled in walking, and 2TS performed best in high-intensity activities such as running and jumping. In the meta areas (M2 and M3), 1TS reduced pressure by over 30% during walking and nearly 40% during running, while 3TS showed similar reductions during jumping, with BF showing higher pressures compared to running. Thus, this study highlights the effectiveness of 1TS and 2TS in reducing pressure in the meta and midfoot areas, emphasizing the importance of selecting the right midsole density for optimal comfort and performance across different activities.

Keywords: Plantar pressure analysis, Midsole of running shoe, 3D printed midsole, Biomimetic structures, Statistical analysis

Introduction

Plantar pressure analysis is vital for evaluating midsole effectiveness (Xu et al., 2017). Optimizing the characteristics of running shoe midsoles is crucial for enhancing performance and preventing injuries (Hoitz et al., 2020). To enhance the characteristics of a running shoe midsole, its hardness can be adjusted or special designs can be applied. The changes in midfoot stiffness can impact running more than walking (Fu et al., 2022), and high offset and structured midsoles can reduce injury risk in female runners. The design of running shoes is crucial for enhancing athletic performance and preventing injuries, with the midsole being a key component providing cushioning, stability, and shock absorption. Comprehensive midsole design evaluation includes assessing cushioning performance, support and stability, and comfort. Thus, recent studies have focused on midsole design, examining 3D pressure-distributed structures and biomimetic designs, and their impact on running performance. Cheng et al. (2022) found that midsole structure and material significantly affect biomechanics. However, if parameters are not chosen carefully, finite element analysis can produce unrealistic models despite its usefulness. Clermont et al. (2023) and Zhang et al. (2023) validated data reliability but also revealed that different methods yield varying results (Xiao et al., 2022; Zhang et al., 2023). New biomimetic designs effectively reduce peak plantar pressure during jumping, but 3D shear did not improve running economy as expected.

The materials and structures of traditional running shoe midsoles have been continuously improved for better performance and comfort. Historically, ethylene vinyl acetate (EVA) foam was widely used, providing a balance between comfort and responsiveness but deteriorating over time. The previous studies showed that EVA midsoles absorbed more energy initially but lose cushioning ability after extended use, such as after 45 km. While thermoplastic polyurethane (TPU) midsole offered high energy return and durability, maintaining cushioning performance longer than EVA, making it ideal for long-distance running shoes. Additionally, 3D printed midsole allowed for precise and customizable midsole designs, providing breathability and durability. This 3D printing technology represented a significant advancement over traditional fixed materials and structures, offering more tailored solutions for individual users (Clermont et al., 2023; Lippa et al., 2016; Rodrigo-Carranza et al., 2024). Biomimetic engineering in midsole design enables the creation of intricate structures that mimic natural biological properties, combining biology and engineering for high-performance systems. Lattice structures, important for mechanical and thermal properties, are key in midsole design (Chen & Lee, 2022; Manaia et al., 2023). Biomimetic techniques have improved shock absorption in ostrich-inspired shoe soles (Zhang et al., 2022). Metamaterials like biomimetic structures depend on structural composition for their mechanical properties (Chouhan & Bala Murali, 2023). Tan et al. (2023) developed a flexible, energy-absorbing metamaterial inspired by mammalian paw pads, offering better flexibility, durability, and pressure distribution than conventional materials. The interest in 3D printing soft materials is growing due to their performance in footwear technology (Clermont et al., 2023; Zolfagharian et al., 2021). 3D printing, which builds objects layer by layer, allows for the use of porous biomimetic structures in midsoles. Studies (Ali et al., 2020; Fadeel et al., 2022) show that 3D-printed polymer lattice structures enhance sneaker comfort and performance by customizing midsoles to the user's foot structure.

Therefore, this study explored the potential for different cushioning performances from biomimetic structures. In previous study, we manufactured three types of midsole designs for running shoes using biomimetic metamaterials inspired by aquatic plants, mammals, and herbivores: Tyson polygons, honeycombs, and horseshoes. After confirming the feasibility of outputting these patterns in cube form, we 3D printed the midsoles using TPU filament. The Tyson polygon structure demonstrated the best output performance and design flexibility (Li et al., 2023, 2024). Thus, aim of this study was to investigate the plantar pressure effect of 3D printed midsole applied biomimetic structures with various densities during static and dynamic motions. The 3D printed midsoles were modeled in three different densities based on the Tyson polygon (TS) biomimetic structure and printed using fused deposition modeling (FDM) and TPU filament. Additionally, these midsoles were worn and tested by plantar pressure test during static motions and three dynamic motions as walking, running, and jumping. Based on these results, further statistical analysis was conducted to compare the different 3D printed midsoles, motions, and 10 plantar zones. And two hypotheses were established for statistical analysis. First, there are significant differences in foot pressure between different midsole densities (1TS, 2TS, 3TS) under the same dynamic motions. Second, there are significant differences in foot pressure between different dynamic motions (walking, running, jumping) under the same 3D printed midsole conditions. By analyzing midsoles with biomimetic structures, we seek to identify the most effective design for achieving evenly distributed pressure and reducing peak pressures.

Experimental

Preparation of 3D printed midsole applied biomimetic structures with different densities

This study aims to manufacture midsoles for running shoes using FDM 3D printing with TPU material. First, we modeled three types of midsole applied three different densities of biomimetic structural designs by 3D modeling software (Rhino 7, Rhinoceros 3D, USA) based on the standard women's foot shape (235 mm size) and saved the designs in.stl format. Subsequently, we converted the models to.g-code using slicing software (Cubicreator 4 V 4.4.0, Cubicon Co., Inc., Korea) and printed them by a FDM 3D printer (Cubicon single plus, Cubicon Co., Inc., Korea) using TPU (eTPU-95A, eSun, China). The hardness and diameter of the filament were Shore 95 A and 1.75 mm, respectively. 3D Printing conditions were as follows: nozzle temperature 225 ℃, bed temperature 65 ℃, printing speed 60 mm/s, infill density 100%, and infill pattern Zig Zag. The three types of 3D printed running shoes midsole applied biomimetic structures using three different densities were named Tyson Polygon 1 (below 1TS), Tyson Polygon 2 (below 2TS), and Tyson Polygon 3 (below 3TS), respectively. And we prepared three pairs of midsoles for each type to ensure a certain effect of the bottom material's recovery performance during the experiment. The images and information of the samples are shown in Table 1.

Plantar pressure test

The plantar pressure test was performed by recruiting 13 healthy female subjects. The decision to focus solely on females was informed by research indicating their higher susceptibility to lower extremity injuries and distinct sport coordination compared to males (Almonroeder et al., 2017). The participants had an average age of 28.8 ± 7.95 years, an average height of 158.90 ± 1.21 cm, an average weight of 54.27 ± 1.50 kg, and average foot size of 232.31 ± 0.72 mm. This homogeneous sample aimed to reduce confounding variables and enhance study validity. All subjects gave their written informed consent. This study was approved by Dong-A University's Institutional Review Board (IRB no. 2–1,040,709-AB-N-01–202311-HR-048–03).

For the plantar pressure test, the plantar pressure analyzer (Materialise, Belgium) with 8 m path and foot scanner (Alchemaker, Korea) were used to record the data of

Table 1 Specification of different densities of 3D printed midsole

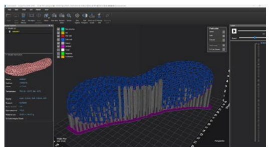
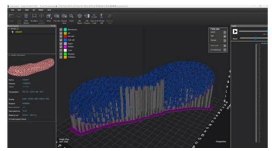
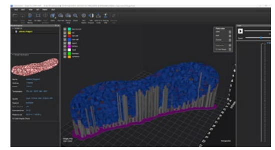
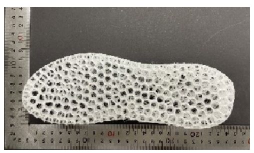
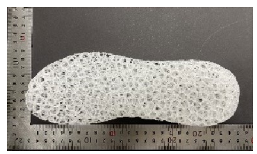
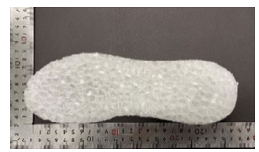
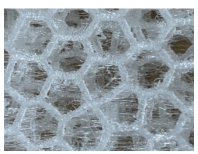
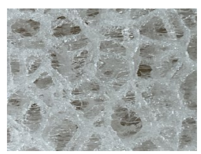
Sample code	Slicing image	Sample image	Structure	Printing time (h/m/s)	Weight (g)
1TS				24/04/47	37.76 ± 0.96
2TS				23/04/13	35.08 ± 1.94
3TS				34/28/03	86.44 ± 2.99

Fig. 1 Plantar test images of (**a**) BF, (**b**) 1TS, (**c**) 2TS, and (**d**) 3TS

the plantar pressure, force, and stress distribution. Subjects wore the same experimental clothing and conducted the experiment by wearing 3D printed midsoles with socks (JT Co., Korea). The experiment was conducted in four status: barefoot (below BF), 1TS, 2TS, and 3TS. It was analyzed in random order to minimize potential sequencing effects. The four attire conditions of the experimenters are shown in Fig. 1.

To verify the results of the midsole's plantar pressure in different motions, the experiment was conducted with one static motion and three walking, running, and jumping as dynamic motions. The experimental methods for each movement are as follows. For the static motion, the plantar force was measured while standing and looking forward on the plantar pressure analyzer for 10 s. During the walking and running motions, the peak plantar pressure for the right and left foot was measured five times each while participants walked back and forth five times at speeds set to 100 bpm and 150 bpm using a metronome. The average value of these measurements was used for analysis. For the jumping motion, the subject jumped onto the plantar pressure analyzer from a 20 cm high box on one foot. This was measured five times for each foot, and the peak plantar pressure was recorded. The experimental methods for the four movements are illustrated schematically in Fig. 2. The experimental procedure was conducted as follows. After collecting anthropometric data, plantar pressure data were measured in the order of BF, 1TS, 2TS, and 3TS, followed by measurements for the static motion and the walking-running-jumping as dynamic motions. To collect accurate data, participants was tested using a metronome during each motion and practiced three times before the actual measurements. Additionally, the collected data of peak plantar pressure was analyzed by dividing it into 10 zones of plantar pressure area. The 10 zones were classified into four areas: Toe, meta, midfoot, and heel. These are illustrated in Table 2.

Statistical analysis

Statistical analysis was conducted using the mean and standard deviation of the values obtained from the plantar pressure test of the 13 subjects. The Shapiro–Wilk test was conducted to evaluate the normality of the data distribution. If the data does not meet the criteria for normal distribution, consider using data transformation techniques or non-parametric tests. In addition, statistical analysis was conducted to compare among

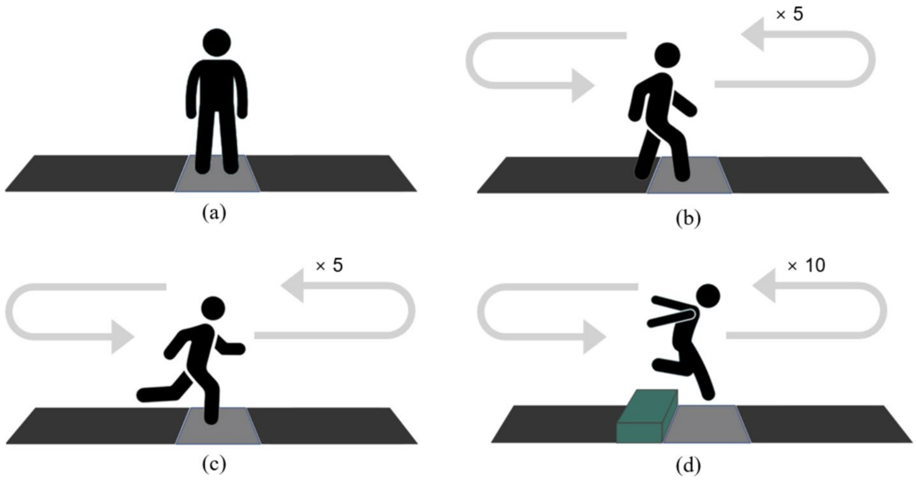
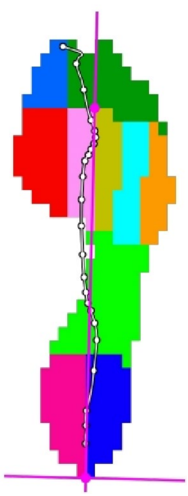


Fig. 2 The scheme of experimental methods for the four motions of (**a**) static—standing, (**b**) dynamic—walking, (**c**) dynamic—running, and (**d**) dynamic—jumping

Table 2 Classification of plantar pressure zone

Image	Area	Sample code	Zone
	Toe	T1	Toe 1
		T2-5	Toe 2–5
	Meta	M1	Meta 1
		M2	Meta 2
		M3	Meta 3
		M4	Meta 4
		M5	Meta 5
	Midfoot	MF	Mid foot
	Heel	MH	Medial heel
		LH	Lateral heel

three criteria: three types of shoe midsoles, three dynamic motions, and 10 zones of plantar pressure area.

For statistical data analysis, utilize statistical analysis software with SPSS 26.0 (IBM, USA) with a significance level at $P < 0.05$. Using data from the right foot as the baseline, conduct repeated measures ANOVA to analyze plantar pressure distribution across four conditions. A significant result (P-value < 0.05) from ANOVA would indicate that different midsole structures significantly affect plantar pressure distribution. Post-hoc tests with Bonferroni correction were performed to identify specific differences between conditions. This approach will clarify which midsole structures differ significantly in plantar pressure distribution. Effect sizes (Cohen's d) were calculated to quantify the magnitude of these differences, thereby facilitating the interpretation of the results. The percentage reduction of foot pressure in each area of different printing midsoles was calculated, and Eq. (1) was used for comparative analysis. The mean and standard deviation of peak pressures for each zone and motion type were also calculated to provide a comprehensive statistical overview.

$$\textbf{\textit{Decrease percentage}} = \left(\frac{\textbf{\textit{Initial value}} - \textbf{\textit{Final value}}}{\textbf{\textit{Initial value}}}\right) \times 100\% \tag{1}$$

Results and Discussion

Plantar force of static motion wearing different densities of 3D printed midsole

We conducted plantar pressure test of static motion wearing different densities of midsoles, including BF, 1TS, 2TS, and 3TS. For static motion, the plantar force diagram was used to compare the four parts of front and rear of both feet as a heat map. Additionally, a graph was used to compare the plantar force of these four parts while standing for 10 s. Figure 3 shows the plantar force diagram of static motion. The data were distributed into 4 parts (Q1-Q4), and the average plantar pressure force applied for 10 s was calculated as a percentage in each of the 4 parts. In addition, the data used a person data closest to the average among the 13 participants. Figure 4 indicates the plantar force for 10 s.

As shown in Fig. 3, the BF condition had maximum pressure in Q1 (26.6%), with values ranging from 0.1 to 24.2 N/cm^2. The 1TS had the lowest maximum pressure (12.9 N/cm^2) and improved force distribution, with the maximum pressure in Q4 (26.2%). The 2TS and 3TS also reduced plantar pressure compared to BF, with the highest pressure in Q4. The pressure distribution ranked as 1TS < 2TS < 3TS < BF, indicating 1TS was the most effective in reducing plantar pressure. Balance between left and right feet was best in the BF (0.1% difference), followed by 1TS (1.6%), 2TS (2.4%), and 3TS (4.8%). Overall, all midsoles improved pressure distribution and reduced peak pressure compared to BF, with 1TS being the most effective and 3TS showing uneven pressure distribution due to pressure concentration.

As shown in Fig. 4, the maximum force distribution for both BF and TS was in the Q4 region, with lower pressure in the Q1 and Q2 forefoot regions. The absolute differences in left and right foot force for BF, 1TS, 2TS, and 3TS were $274.95 \pm 58.66 \sim 357.04 \pm 62.00$ N, $276.61 \pm 51.48 \sim 301.18 \pm 55.19$ N, $277.19 \pm 36.69 \sim 389.00 \pm 50.59$ N, and $235.72 \pm 34.00 \sim 277.73 \pm 28.76$ N, respectively, indicating a trend of 3TS < 1TS < BF < 2TS. BF and 2TS showed a marked imbalance with highest stress in Q4, suggesting a center of gravity shift to the right forefoot, while 1TS and 3TS displayed more uniform force distribution, implying better balance. The BF had the largest plantar force at approximately 360 N in Q4, whereas 3TS had the smallest force, likely due to smaller contact area. BF exhibited the highest force concentration, indicating that 3D-printed midsoles can help distribute force more evenly. Previous studies (Menz & Bonanno, 2021) suggest that even pressure distribution improves comfort and reduces fatigue by preventing pressure points and supporting proper alignment. The 1TS midsole performed best, significantly reducing pressure and enhancing comfort. This

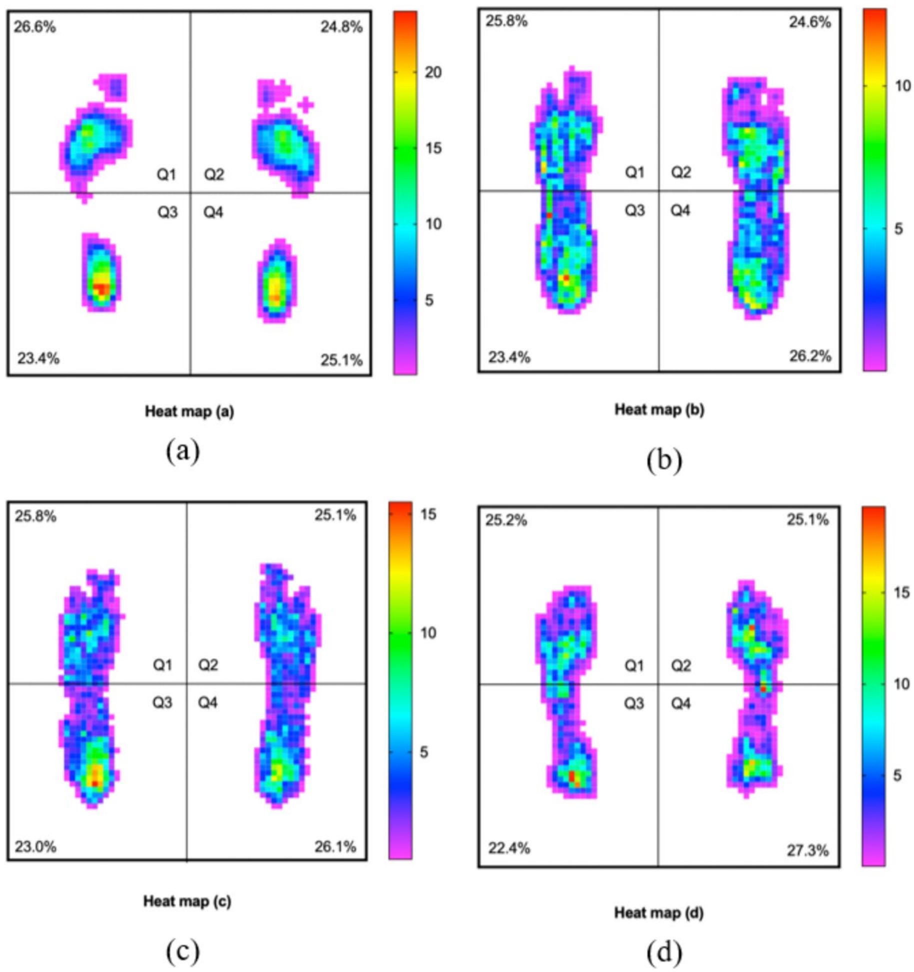


Fig. 3 Plantar pressure diagram for static motion of (**a**) BF, (**b**) 1TS, (**c**) 2TS, and (**d**) 3TS

highlights the importance of selecting appropriate midsole materials and designs to improve plantar pressure distribution and comfort.

Peak plantar pressure per zones with three types of motion wearing different densities of 3D printed midsole

This experiment aims to measure and analyze the peak plantar pressure of dynamic motions in 10 zones of plantar pressure area while different motions. And the peak plantar pressure was confirmed and evaluated that the impact of midsole design. Figure 5 shows peak foot pressure per zone with three types of motion wearing various statuses.

In the investigation of foot pressure distribution across dynamic motions and footwear status, distinct patterns emerged. The results of all dynamic motions showed a tendency for peak foot pressure values to decrease when wearing 3D printed midsoles compared to the BF condition. Notably, during walking, the 1TS midsole effectively distributed foot pressure, resulting in reduced peak pressure. Both the 1TS and 3TS also demonstrated a decrease in peak pressure during walking. In running and jumping motions, foot

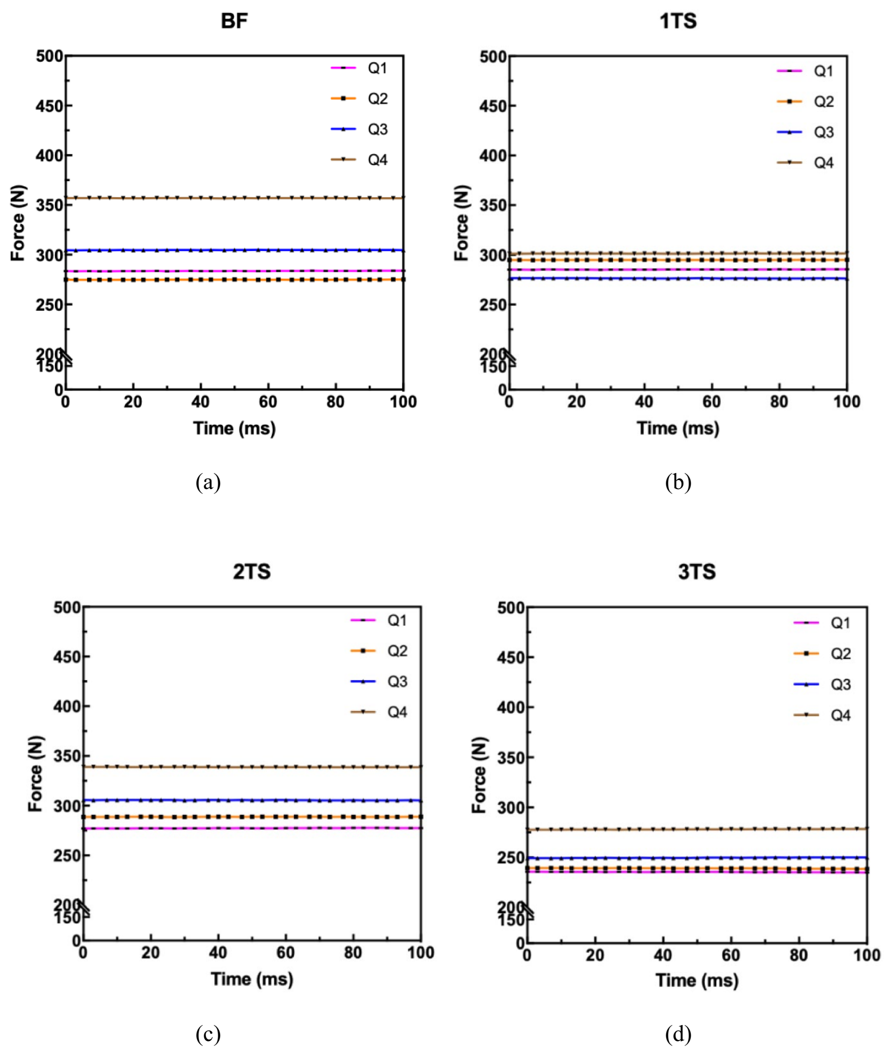
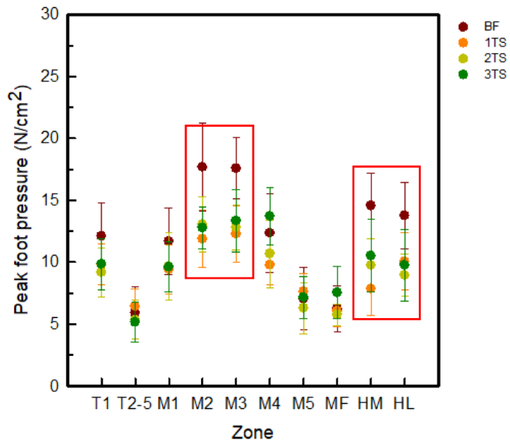


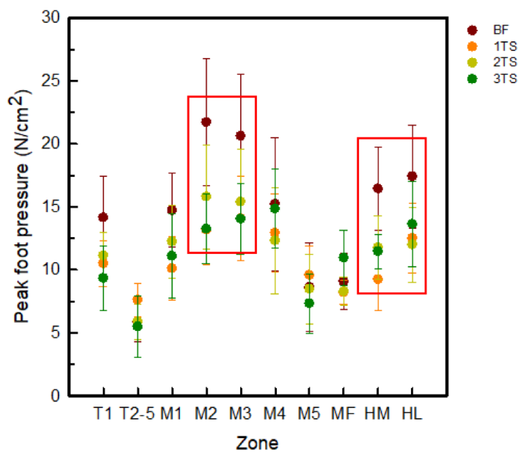
Fig. 4 Plantar force per 4 areas for static motion of (**a**) BF, (**b**) 1TS, (**c**) 2TS, and (**d**) 3TS

pressure decreased for both the 1TS and 3TS midsoles. However, the 2TS midsole was particularly effective in reducing foot pressure in the LH zone. These findings underscore the impact of footwear design and material composition on foot pressure dynamics during different activities. Additionally, when examined by zone, the values of peak foot pressure were most prominent in the four zones: M2, M3, MH, and LH.

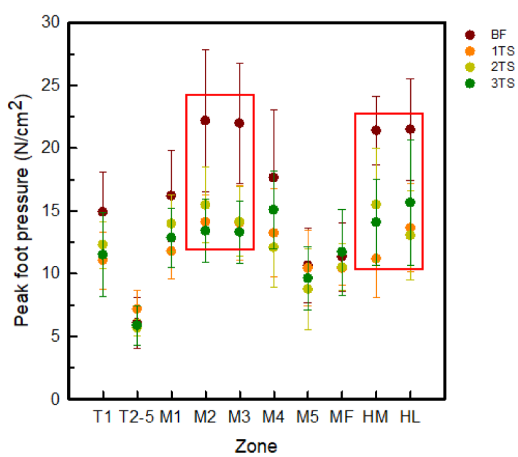
The observed variations in foot pressure distribution highlight the importance of footwear characteristics in mitigating foot stress across diverse motions. Specifically, the 1TS effectiveness in redistributing foot pressure during walking underscores the significance of its design features. Furthermore, the consistent reduction in foot pressure with the 1TS, 2TS, and 3TS midsoles compared to barefoot conditions emphasizes the crucial role of midsole properties in enhancing comfort and reducing foot strain. This experiment demonstrated that midsoles of varying densities significantly improve plantar pressure distribution and reduce peak pressure during walking, running, and jumping. The 1TS midsole performed best in walking and running, effectively dispersing



(a)



(b)



(c)

Fig. 5 Peak foot pressure per zone with dynamic motions of (**a**) walking, (**b**) running, and (**c**) jumping. while different status pressure; the 2TS midsole excelled in high-intensity activities, especially in the LH zone; the 3TS midsole performed well overall but needs further design optimization to reduce pressure concentration. Overall, appropriate midsole design and material selection can enhance foot comfort and reduce fatigue.

Statistical analysis of peak plantar pressure with different densities of 3D printed midsole

The peak plantar pressure was statistically analyzed to compare the significant differences in foot pressure among different densities of three midsole during dynamic motions. Figure 6 shows the peak plantar pressure of four zones with different densities of 3D printed midsole during dynamic motion. By statistically analyzing the significant differences in walking, running, and jumping, we can discuss how midsole density affects dynamic foot pressure feedback in different motions. Thus, hypothesis 1 was used to compare the significant differences in foot pressure under different 3D printed midsole density at the same motion states.

For 1TS, significant differences were found in zones M1, M4, M5, MF, MH, and LH. For 2TS, significant differences were noted in zones T1, M1, MF, MH, and LH. For 3TS, significant differences appeared in zones M1, MF, MH, and LH. All these indicators had *P*-values less than 0.05, supporting that different midsole types significantly affect motion differences. The values were found to support Hypothesis 1. These differences highlighted the sensitivity of these zones to movement. The M1 zone, crucial for support and propulsion, showed significant variations across all motions, particularly between walking and jumping (Huang et al. 2020). The results indicated that the 1TS midsole provided consistent support and even pressure distribution, the 2TS midsole enhanced support, propulsion, and weight-bearing in the MF, MH, and LH zones, and the 3TS midsole improved pressure distribution and stability in the M1, MF, MH, and LH zones during dynamic activities.

As shown in Fig. 7, it showed that the M1 zone was crucial for running and jumping (Yamauchi et al., 2022). The pressure during running is 2.35 N/cm^2 higher than during walking, with $F = 3.891$ and $P = 0.029$, indicating statistical significance. The 1TS midsole had the smallest pressure difference between jumping and walking, indicating a balanced design. The 2TS had the largest difference, The pressure during running is 4.31 N/cm^2 higher than during walking, with $F = 8.720$ and $P = 0.0008$, The significant difference between different activities indicates that, during high-intensity exercise, the pressure in the M1 area is significantly higher with 2TS. In the MF zone, the 2TS provided better motor feedback for arch stabilization (Menz et al., 2021). The 1TS reduced foot pressure impact in the MH and LH zones, while 2TS and 3TS showed significant pressure differences in the medial rearfoot during high-intensity activities. For MH, the2TS pressure during running is 4.74 N/cm^2 higher than during walking, with $F = 40.18$ and $P = 0.0001$, indicating statistical significance.

Overall, the significant difference between the toe and metatarsal zones increased in the 1TS and 2TS due to the increased support provided, resulting in more concentrated pressure distribution in these areas s. The design of the midsole affects the shoe's flexibility and stability. In running, a flexible midsole may be more beneficial for those who prefer natural foot movements, whereas in jumping, a stable midsole could provide better support and stability (Roh et al., 2020). Therefore, the study

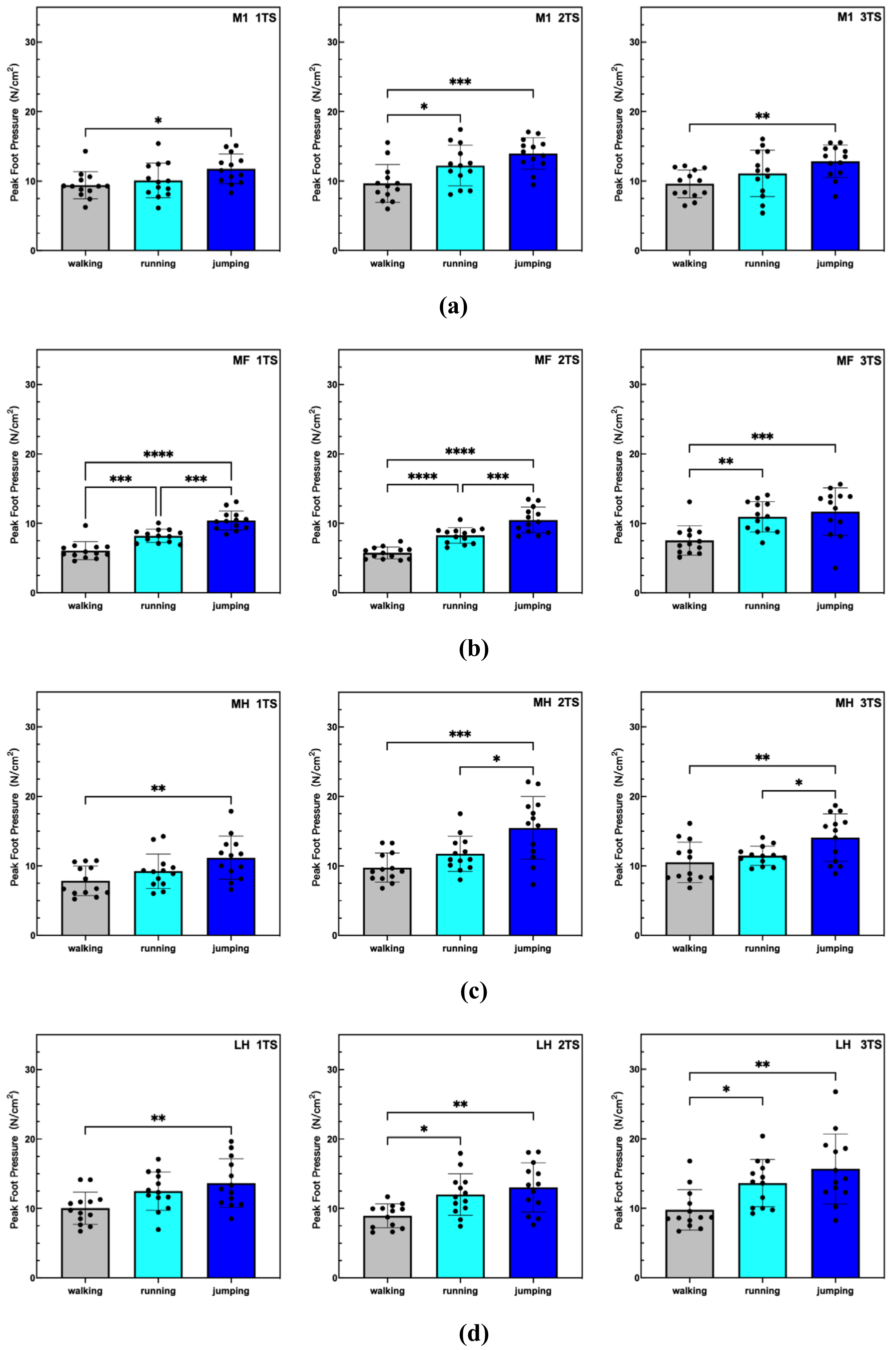


Fig. 6 The statistical graph of peak plantar pressure of four zones ((**a**) M1, (**b**) MF, (**c**) MH, and (**d**) LH) with different densities of 3D printed midsole during three types of dynamic motion

demonstrated that different densities of 3D printed midsoles significantly optimized plantar pressure distribution and reduced peak pressure. The 1TS performed best in walking and running, effectively dispersing pressure. The 2TS excelled in high-intensity activities, especially in the LH zone. The 3TS performed well overall but requires further design optimization to reduce pressure concentration.

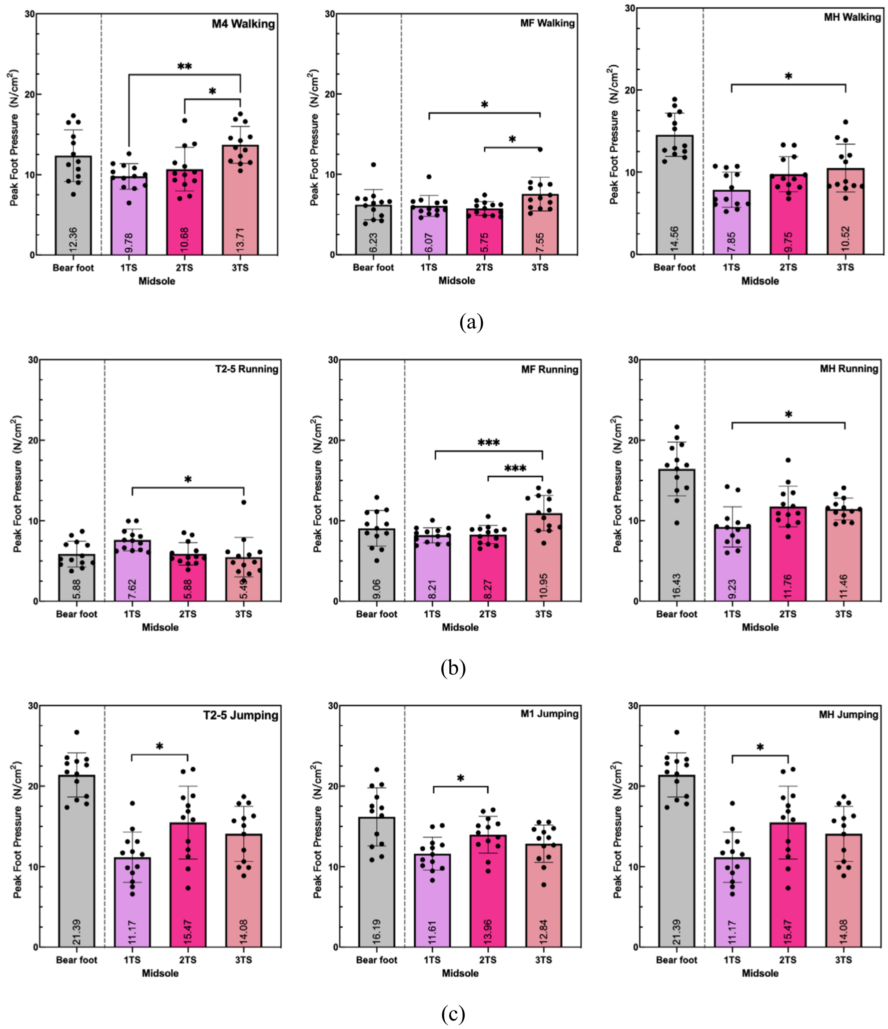


Fig. 7 The statistical graph of peak plantar pressure of three types of dynamic motion ((**a**) walking, (**b**) running, and (**c**) jumping) with various zones

Statistical analysis of peak plantar pressure with three types of dynamic motions

The peak plantar pressure was statistically analyzed to compare the significant differences in foot pressure among dynamic motions of walking, running, and jumping under different density of three midsole. Figure 7 shows the peak plantar pressure of peak plantar pressure of three types of dynamic motion with various zones. By statistically analyzing the significant differences of 1TS, 2TS, and 3TS in the three motions, we can explore the foot pressure feedback for different midsole densities during motions. Thus, Hypothesis 2 was used to compare the significant differences in foot pressure among different dynamic motions in the same midsoles.

During walking, significant differences were found in the M4, MF, and MH zones. While running, significant differences were observed in the T2-5, MF, and MH zones. During jumping, significant differences were noted in the T2-5, M1, and MH zones. A significance level of P less than 0.05 validates Hypothesis 2.

As shown in Fig. 7, during walking, the 1TS significantly reduced foot pressure in the M4 zone compared to the 3TS, with 2TS also showing a notable decrease. In the M4 area, 1TS reduced foot pressure by 3.92 N/cm^2 compared to 3TS, with $F=10.95$ and $P=0.0002$, indicating high statistical significance. In the MF zone, As the printing density increased, the foot pressure in 3TS increased by 1.31 N/cm^2 compared to BF. The 2TS offered better cushioning in the MF. In the MH zone, Compared to 3TS, 1TS significantly reduced foot pressure by 2.66 N/cm^2, with $F=4.18$ and $P=0.02$. This indicates that lower-density TPU in the heel area provides better cushioning. During running, in the T2-5 zone, decreased with increasing midsole density. 3TS is significantly lower than 1TS by 2.12 N/cm^2, with $F=5.10$ and $P=0.01$, indicating a notable difference. In the MF zone, 3TS pressure values exceeded barefoot values, 1TS and 2TS reduced foot pressure by 2.74 N/cm^2 and 2.67 N/cm^2, respectively, compared to 3TS, with $F=13.77$ and $P=0.0001$, indicating very high significance. The force during running is primarily concentrated in the MF area. During jumping, similar trends were observed. Foot pressure in the T2-5 zone decreased with increased midsole density, with the 3TS showing significantly lower pressure than the BF. In the M1 area, 1TS significantly reduced pressure by 2.19 N/cm^2 compared to 2TS. Lower density materials demonstrated better damping performance against shear forces in both running and jumping motions (Noghondar & Yazdi, 2017). During walking, the 1TS provided better cushioning in the M4 and MH zones, while the 2TS also performed well in the M4 zone. The 3TS midsole had poor performance in the MF zone. During running, the 3TS showed lower foot pressure in the T2-5 zone, suitable for high-intensity activities, while the 1TS and 2TS had better cushioning in the MF zone. For jumping, the 1TS showed higher midfoot pressure, the 2TS performed best in the MF zone, and the 3TS had lower pressure in the T2-5 zone. Different densities of 3D printed midsoles optimized plantar pressure distribution and reduced peak pressure. The 1TS was best for walking and running, the 2TS excelled in high-intensity activities, and the 3TS needed further optimization. Significant differences were observed in foot pressure during various motions and among different midsole densities.

Statistical analysis of peak plantar pressure per 10 zones of plantar pressure area

To compare the differences in zones of plantar pressure area, the percentage reduction in plantar pressure for each zone with different densities of 3D printed midsoles was calculated. This was used to analyze and compare the mean and standard deviation of peak plantar pressure across various zones and types of motion. Based on the five zones that showed significant values, the data was analyzed. Table 3 represents the analysis for the M2/M3 zones as the meta area, MF area, and HM/HL zones as the heel area.

As the meta areas (M2 and M3), the 1TS reduced pressure by 32.82% and 30.12% during walking, and by 39.28% and 39.57% during running, compared to BF. For jumping, the 3TS showed reductions of 39.57% and 39.48% in M2 and M3, while BF had higher pressure values of 22.16% and 21.96% compared to running. Jumping generated greater vertical force, indicating that harder midsoles are necessary for adequate cushioning during jumping. Softer midsoles effectively decreased pressure during walking and running, while harder midsoles absorbed vertical forces during jumping, reducing injury risk (Baltich et al., 2015; Yu et al., 2021; Zhu et al., 2023).

About MF zone, compared to being BF, peak plantar pressure in the MF zone increased significantly by 21.22% and 20.86% during walking and running, respectively, indicating potential pressure accumulation with dense midsoles. Conversely, 1TS and 2TS exhibited lower foot pressure without significant differences observed. However, 3TS showed an increase of 21.22%, 20.86%, and 3.35% in the three motions compared with BF, emphasizing the challenge of rigid midsoles. The flexibility of the midsole structure plays a critical role in the MF zone. Softer structures mimic barefoot dynamics, reducing pressure buildup, whereas harder structures can potentially increase pressure and energy consumption. Overall, midsole density significantly impacts foot pressure distribution, underscoring the importance of selecting appropriate density to optimize comfort and performance (Uddin et al., 2024).

In terms of HM and HL zones, all 3D printed midsoles significantly reduced maximum pressure in a variety of motions compared to the BF control group, with reductions ranging from 27.67% to 47.77%. Particularly, the 1TS showed the most effective reduction in pressure during walking, running, and jumping, with reductions of 46.04%, 43.82%, and 47.77%, respectively. Additionally, when analyzing plantar pressure at the heel, it was observed that during walking, BF conditions showed higher pressure on the inner side and lower pressure on the outer side. During running motion, higher pressure was observed on the outer side compared to the inner side. During jumping motion, pressure tended to balance between both sides. Furthermore, it indicated that the 1TS performed better internally at the heel, whereas the 2TS performed better externally. Regarding LH zone, it was found that 2TS decreased in walking, running, and jumping by 34.98%, 31.13%, and 39.31%, respectively. However, the overall effect was similar to that of the 1TS, possibly due to differences in the hardness of the two samples.

Therefore, in the meta areas, the 1TS significantly reduced pressure during walking and performed best during running motion. For jumping, the 3TS performed better by reducing pressure from high vertical forces. In the MF zone, the 3TS with high-density increased pressure during walking and running, whereas the 1TS and 2TS showed lower pressure, underscoring the benefit of a softer structure to minimize pressure accumulation. In the heel areas, all midsoles significantly reduced peak plantar pressure, with the 1TS performing best during walking, running, and jumping. Specifically, the 1TS exceled on the MH, while the 2TS performed better on the LH. Furthermore, there were issues with foot pressure balance, especially in the MH and LH zones, which varied across different motions. These findings indicated the necessity for further research into the stability index of shoe midsole designs, particularly in reducing instances of internal rotation and outward flipping.

Conclusions

This study investigated the impact on plantar pressure of 3D-printed running shoe midsoles applied biomimetic structures with different densities during different motions. To identify the most suitable midsole, a plantar pressure experiment was conducted and the values were compared and analyzed statistically. As results, for static motion, all midsole densities enhanced pressure distribution and reduced peak pressure compared to barefoot conditions, with the 1TS midsole being the most effective. During

Table 3 Peak plantar pressure with dynamic motion wearing different densities of 3D printed midsoles

Area	Zone	Motion	State	Mean (N/cm^2)	TS-BF (N/cm^2)	Change (%)	*P*-value
Meta	M2	Walking	BF	17.67 ± 3.57	0	n/a	n/a
			1TS	11.87 ± 2.29	−5.80 ± 0.77	−32.82%	< 0.001
			2TS	13.05 ± 2.21	−4.62 ± 0.68	−26.14%	< 0.001
			3TS	12.77 ± 1.70	−4.90 ± 0.78	−27.73%	< 0.001
		Running	BF	21.69 ± 5.03	0	n/a	n/a
			1TS	13.17 ± 2.77	−8.52 ± 0.89	−39.28%	< 0.001
			2TS	15.79 ± 4.13	−5.90 ± 0.65	−27.20%	< 0.001
			3TS	13.24 ± 2.75	−8.45 ± 0.90	−38.95%	< 0.001
		Jumping	BF	22.16 ± 5.63	0	n/a	n/a
			1TS	14.10 ± 2.18	−8.06 ± 1.17	−36.37%	< 0.001
			2TS	15.46 ± 3.01	−6.69 ± 1.01	−30.23%	< 0.001
			3TS	13.39 ± 2.52	−8.77 ± 1.24	−39.57%	< 0.001
	M3	Walking	BF	17.56 ± 2.48	0	n/a	n/a
			1TS	12.27 ± 2.24	−5.29 ± 0.52	−30.12%	< 0.001
			2TS	12.81 ± 1.83	−4.75 ± 0.49	−27.05%	< 0.001
			3TS	13.33 ± 2.52	−4.22 ± 0.45	−24.08%	< 0.001
		Running	BF	20.61 ± 4.89	0	n/a	n/a
			1TS	14.06 ± 3.34	−6.54 ± 0.44	−31.78%	< 0.001
			2TS	15.38 ± 4.17	−5.22 ± 0.42	−25.37%	< 0.001
			3TS	14.03 ± 2.80	−6.58 ± 0.44	−31.92%	< 0.001
		Jumping	BF	21.96 ± 4.79	0	n/a	n/a
			1TS	14.03 ± 2.99	−7.92 ± 0.76	−36.11%	< 0.001
			2TS	14.12 ± 2.76	−7.83 ± 0.73	−35.70%	< 0.001
			3TS	13.29 ± 2.48	−8.66 ± 1.04	−39.48%	< 0.001
Midfoot	MF	Walking	BF	6.22 ± 1.88	0	n/a	n/a
			1TS	6.06 ± 1.29	−0.16 ± 0.52	−2.57%	1.0
			2TS	5.75 ± 0.85	−0.47 ± 0.41	−7.55%	1.0
			3TS	7.54 ± 2.11	+ 1.31 ± 0.22	21.22%	< 0.001
		Running	BF	9.06 ± 2.22	0	n/a	n/a
			1TS	8.20 ± 0.94	−0.85 ± 0.44	−9.49%	0.46
			2TS	8.27 ± 1.13	−0.78 ± 0.42	−8.71%	0.54
			3TS	10.95 ± 2.18	1.89 ± 0.44	20.86%	< 0.007
		Jumping	BF	11.32 ± 0.74	0	n/a	n/a
			1TS	10.41 ± 0.38	−0.90 ± 0.48	−8.03%	1.0
			2TS	10.49 ± 0.51	−0.82 ± 0.72	−7.33%	0.63
			3TS	11.70 ± 0.94	+ 0.37 ± 1.09	+ 3.35%	1.0

Table 3 (continued)

Area	Zone	Motion	State	Mean (N/cm^2)	TS-BF (N/cm^2)	Change (%)	*P*-value
Heel	MH	Walking	BF	14.55 ± 2.63	0	n/a	n/a
			1TS	7.85 ± 2.13	−6.71 ± 0.36	−46.04%	< 0.001
			2TS	9.75 ± 2.12	−4.80 ± 0.51	−32.98%	< 0.001
			3TS	10.52 ± 2.91	−4.04 ± 0.42	−27.69%	< 0.001
		Running	BF	16.43 ± 3.34	0	n/a	n/a
			1TS	9.23 ± 2.49	−7.19 ± 0.67	−43.82%	< 0.001
			2TS	11.75 ± 2.52	−4.67 ± 0.73	−28.48%	< 0.001
			3TS	11.45 ± 1.36	−4.97 ± 0.83	−30.31%	< 0.001
		Jumping	BF	21.39 ± 2.73	0	n/a	n/a
			1TS	11.17 ± 3.11	−10.2 ± 0.48	−47.77%	< 0.001
			2TS	15.47 ± 4.52	−5.91 ± 0.72	−27.67%	< 0.001
			3TS	14.07 ± 3.41	−7.31 ± 0.66	−34.22%	< 0.001
	LH	Walking	BF	13.75 ± 2.66	0	n/a	n/a
			1TS	10.04 ± 2.32	−3.71 ± 0.82	−26.98%	< 0.001
			2TS	8.94 ± 1.70	−4.81 ± 0.43	−34.98%	< 0.001
			3TS	9.75 ± 2.91	−4.00 ± 0.95	−29.09%	< 0.001
		Running	BF	17.41 ± 4.08	0	n/a	n/a
			1TS	12.49 ± 2.75	−4.90 ± 1.06	−28.25%	< 0.004
			2TS	11.99 ± 2.99	−5.41 ± 0.58	−31.13%	< 0.001
			3TS	13.62 ± 3.38	−3.78 ± 0.92	−21.76%	< 0.009
		Jumping	BF	21.47 ± 4.03	0	n/a	n/a
			1TS	13.63 ± 3.50	−7.83 ± 0.92	−36.51%	< 0.001
			2TS	13.03 ± 3.53	−8.43 ± 0.92	−39.31%	< 0.001
			3TS	15.64 ± 5.03	−5.82 ± 1.35	−27.15%	< 0.006

[*] $P < 0.05$, **$P < 0.01$, ***$P < 0.001$

dynamic motions, the 1TS and 2TS midsoles effectively distributed plantar pressure in the midfoot and heel areas, while the 3TS midsole provided better support and stability under high-intensity activities like jumping. Statistical analysis revealed that the 1TS midsole provided comfort and flexibility but lacked support, the 2TS midsole balanced support and cushioning across activities, and the 3TS midsole offered superior support and stability but reduced elasticity during jumps. During walking, 1TS offered comfort but less support, 2TS balanced comfort and support, and 3TS provided strong support with less comfort. In running, 1TS caused instability, 2TS reduced impact, and 3TS offered the best support. For jumping, 1TS prioritized flexibility, 2TS balanced flexibility and support, and 3TS provided optimal support but could feel heavy. Significant differences in pressure distribution across various zones (M1, MF, MH, and LH) highlighted the impact of midsole design and density. Overall, 1TS and 2TS demonstrated advantages in reducing pressure accumulation in the meta and midfoot zones. Therefore, this research provides valuable insights into the influence of 3D printed midsole densities on plantar pressure distribution. And this study underscores the importance of selecting appropriate midsole densities to optimize comfort and performance across different activities. Future studies should continue exploring the optimization of midsole materials and structures to enhance athletic footwear performance and comfort, ultimately aiding in injury prevention and improving user experience. These findings emphasize the critical role of midsole design in tailoring support and cushioning to meet the specific demands of various activities.

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Author contributions
SL, JL conceived the work and JL, IJ prepared the samples and performed the experiments. All authors are participated in the sequence alignment and drafted the manuscript. And all authors read and approved the final manuscript.

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Availability of data and materials
The data sets used and analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate
This research was conducted under the approval and supervision of Dong-A University Institutional Review Board (IRB Approval No: 2–1040709-AB-N-01–202311-HR-048–03) regarding ethical issues including consent to participate.

Competing interests
The authors declare that they have no competing interests.

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