Applied Science and Innovative Research
ISSN 2474-4972 (Print) ISSN 2474-4980 (Online)
Vol. 9, No. 1, 2025
www.scholink.org/ojs/index.php/asir

Original Paper

Modeling and Statics Analysis of Outsole Structure of Men's Shoes Based on Finite Element Method

Pengbo Wan[1], Yu Wu[1*] & Xue Tian[2]

[1] College of Art and Design, Shaanxi University of Science & Technology, Xi'an 710021, China

[2] Xi'an Medical University, Xi'an 710021, China

[*] Corresponding author: Yu Wu, E-mail: 2795561526@qq.com

Received: November 9, 2024 Accepted: December 18, 2024 Online Published: December 24, 2024

doi:10.22158/asir.v9n1p24 URL: http://doi.org/10.22158/asir.v9n1p24

Abstract

In order to explore the influence of the heel structure of men's shoes on the deformation of the outsole, and simulate the stress distribution and deformation of the outsole in different human states, taking the existing leisure men's shoes outsole as the research object, the "sole-ground" coupling finite element model was established through reverse engineering, and the instantaneous stress of the sole was simulated and statically analyzed. The stress and strain areas of the model under different working conditions are consistent with those under the real test, mainly in the area where the transverse stiffener at the heel meets the inner edge. This paper applies finite element analysis to the static analysis of soles, which can provide new ideas for the design of regional structure of outsole heel of men's shoes, and improve the utilization rate of sole materials and sole performance.

Keywords

sole structure, reverse engineering, finite element analysis, static analysis

1. Introduction

As the terminal link of lower limbs, the foot has the functions of supporting stability, buffering shock and absorbing energy. Sole is the carrier of human feet contacting with the ground, which is composed of insole, midsole and outsole, in which outsole usually refers to the bottom of shoes contacting with the ground, which can effectively reduce the ground reaction force and is an important part in the research and development of shoes and boots.

At present, the research and design of sole structure in footwear manufacturing industry mostly relies on traditional design experience and subjective comfort feedback of the wearer, lacking scientific theoretical basis. Moreover, in the sole mold opening and production process, the adjustment of mold parameters will change the function and comfort of shoes and boots, which is prone to the problems of high research and development cost and long development cycle. In the performance testing stage of sole structure, physical experiments or sports biomechanics methods are usually relied on, and the sole data can't be adjusted and updated in time, which will lead to problems such as relatively lagging optimization of sole structure. In recent years, Finite Element Analysis (FEA), as an important means of simulation in modern engineering field, has been widely used in architecture, medical treatment, design and many other fields, which can provide support for human biomechanics and sole structure analysis. Ling Jingxiu et al. designed two kinds of sole schemes with rhombus and regular hexagon structure on the basis of existing soles, and analyzed the static performance of different soles by finite element method, and finally obtained the optimal sole structure scheme. Zhou Qixuan et al. established three kinds of foot contact simulation models by combining foot biomechanics and finite element method, designed the structure of running shoe midsole, and provided research ideas for the optimization of running shoe midsole structure.

The finite element analysis method is applied to the sole structure analysis, and the sole structure is divided into finite and regular continuous unit combinations. By establishing mathematical equilibrium equations and analyzing the mechanical properties of each unit, the approximate solution of the overall sole structure analysis can be obtained, which can provide guidance and reference for researchers, and cooperate with sports biomechanics research to analyze the sole structure, which can effectively supplement the sole R&D design method. In this paper, the outsole of men's shoes is taken as the research object. Through reverse engineering and finite element analysis, the existing outsole structure of men's shoes is modeled and statically analyzed, and the stress distribution and stress deformation changes of the outsole in different human motion States are simulated, so as to explore the feasibility of finite element analysis in the structural design optimization of men's shoes.

2. Materials and Methods

2.1 Research materials

The product number of this shoe is A2202AM1, and the outsole is made of rubber, with a shoe size of 42, as shown in Figure 1.

Figure 1. Outsole for Testing

2.2 Finite Element Model Reconstruction

In this study, reverse engineering (RE) was used to reconstruct the sole model. Reverse engineering is a reverse implementation of traditional forward engineering. By measuring the three-dimensional dimensions of existing product entities, using computer-aided design to model and digitally reproduce them, product redesign, innovation and manufacturing can be realized. The measurement principle of reverse engineering includes contact and non-contact. In this paper, the non-contact scanning method is used, and the outsole is scanned by MetraSCAN 3D scanning equipment to obtain the data information of the outsole of men's shoes. Combined with the supporting VXelements 3D scanning software, the collected point cloud data is viewed. The point cloud data of the outsole is imported into Geomagic Wrap software, and the point cloud data of the outsole is deleted and noise points are filtered, and the outsole data is transformed into triangular patches, and the unsealed area of the outsole is filled and repaired, and the data of the front and back sides of the sole are merged to generate a closed surface. The repaired sole surface is exported to STL format, which is imported into UG 3D modeling software. The basic coordinates of the outsole surface are adjusted and the benchmark is checked, and the missing details of the outsole model are repaired during 3D scanning. The midsole with a thickness of 1.5mm is drawn based on the edge of the inner surface of the sole, and the midsole is divided into 99 separate areas according to the distribution of 99 sensors of the sole pressure insole, so that the stress on the outsole is more in line with the actual situation. The model is exported to STP format. At the same time, a cuboid with a length of 40cm, a width of 20cm and a height of 1cm is drawn as a ground model. The solid models of ground, outsole and midsole are assembled into a three-dimensional coupling model, which is derived in STP format for subsequent finite element analysis. The coupling model of "sole-ground" is shown in Figure 2.

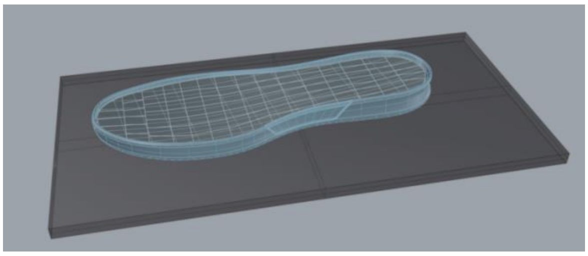


Figure 2. "Sole-Ground" Coupling Model

Finite element modeling and mesh generation are carried out by HyperMesh software. The outsole of men's shoes is meshed with tetrahedral elements. In order to ensure the accuracy of the analysis, the mesh size of the midsole is set to 1.5mm according to the thickness of the midsole. The outsole structure is complex, and the grid size is set to 3 mm; The grid size of the ground has little influence on the simulation accuracy, and the size is set to 10 mm. Four indexes, such as Jacobian, Aspect Ratio, Warpage and Skew angle, are selected to compare the grid quality. Setting the Jacobian value above 0.7, the length-width ratio value less than 5, the warping degree less than 5 and the torsion degree less than 60 meets the requirements. Finally, the "sole-ground" coupling finite element model has 50,842 nodes and 136,026 elements. The size and quantity of each unit are shown in Table 1.

Table 1. Dimensions and Quantity of Components and Units

Components	Unit Type	Unit Size (mm)	Number of Units (unit)
Middle bottom plate	Two-dimensional S4	1.5	15247
Outsole	Three-dimensional C3D4	3	116271
Ground	Three-dimensional C3D4	10	3934

2.3 Finite Element Model Material Properties

The density, elastic modulus and Poisson's ratio of sole materials were measured by precision electronic analytical balance, universal testing machine and static strain gauge respectively. The material parameters of the sole and ground are shown in Table 2.

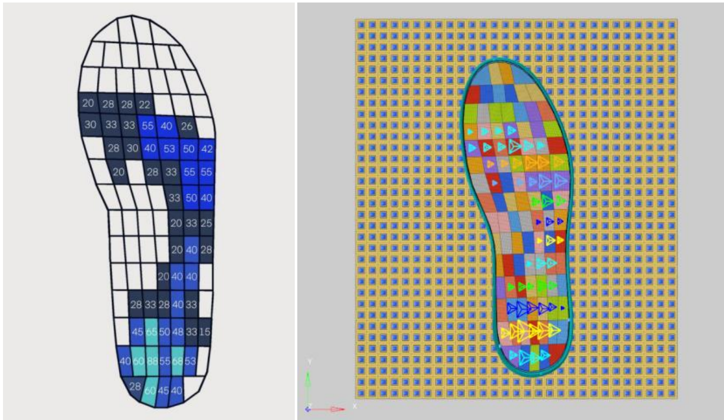
Table 2. Sole Material Parameters

Sole Material Parameters	Material Type	Density (g/cm^3)	Elastic Modulus (MPa)	Poisson's Ratio
Outsole	Rubber	1.149	1.47.26	0.454
Middle bottom plate	Cork	0.647	1100.00	0.339
Ground	Wood Composite Floor	0.733	1000.00	0.352

2.4 Finite Element Model Loading and Boundary Conditions

The research subject is a male college student (age 24, height 180cm, weight 73.6kg, shoe size 42), whose main stress foot is his right foot, with the habit of running and fitness every week. His arches are healthy, and there is no foot disease or related injury. The informed consent form was signed before the test. FootScan flat sole pressure system was used to measure the data of sole pressure when the subjects were standing still with shoes on, and Novel Pedar insole sole pressure testing system was used to measure the stress on the feet of the subjects in four movements: standing still, walking at a constant speed of 1.2 m/s, jogging at a speed of 2.4 m/s and actively jumping at a height of 40 cm. The test frequency is set to 100 Hz.

The finite element model of "sole-ground" is imported into Abaqus software and the boundary conditions are set. The midsole and the outsole are binding constraints, and the ground and the outsole are ordinary friction, so the ground is fixed constraints. According to the plantar pressure data when the subject stands still, they are respectively applied to the middle sole plate, and the direction is vertical downward, as shown in Figure 3.



(a) Distribution and data of sole pressure under standing condition (b) Plantar pressure loading

Figure 3. Distribution and Loading of Plantar Pressure under Static Standing Condition

2.5 Finite Element Model Verification

The measured pressure distribution values of the sole and sole of the subjects standing in static state are compared with the pressure nephogram obtained by finite element simulation, which verifies the effectiveness of the above-mentioned "sole-ground" coupling finite element model. Among them, the information of sole structure, sole material parameters, human load and constraint conditions are consistent with the actual situation, and the consistency of static standing conditions is maintained. The ground reaction force and contact area parameters are selected to calculate the average pressure between the outsole of men's shoes and the ground.

2.6 Static Simulation

In order to explore the stress difference and distribution of soles under different motion postures, this study selected three human motion conditions, namely, uniform walking, jogging and active jumping. Based on the above settings of loading constraints on the model under static standing conditions, Abaqus software was used to analyze the stress magnitude and distribution of soles under different working conditions. The dynamic equation of the system for linear statics analysis can be expressed by Formula 1.

$$M\ddot{X} + C\dot{X} + KX = F(t) \tag{1}$$

Where: m-mass matrix;

C-damping matrix;

K-system stiffness matrix;

F-external force;

$\ddot{X}$, $\dot{X}$, X represent the system acceleration, velocity and displacement.

According to the definition of linear statics, the load is constant and the speed and acceleration of the system are both zero, so based on Hooke's law, the static analysis equation can be expressed by Formula 2.

$$F = \mathbf{k}X \tag{2}$$

Where: k-material properties, model size and constraints, etc.

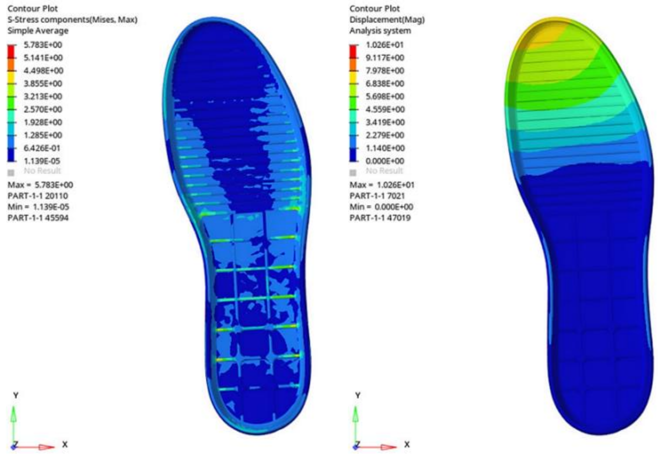
F-external force;

X-displacement;

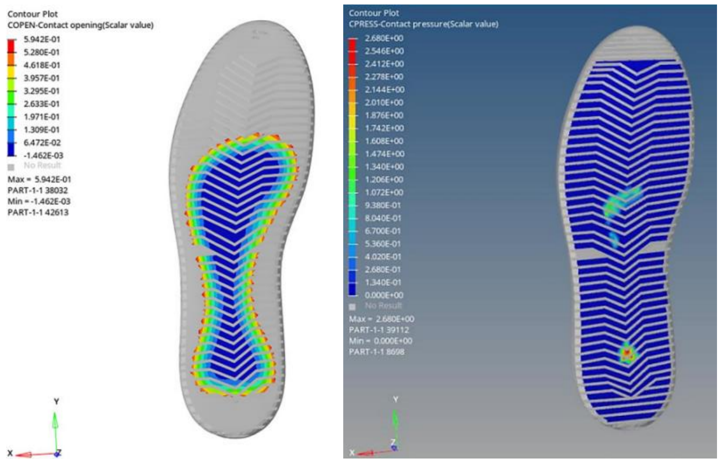
3. Research Result

3.1 Model Verification Results

The stress and strain between the outsole of men's shoes and the ground are shown in Figures 4-a and 4-b, that is, the stress distribution of the sole is relatively uniform under the static standing condition, and the maximum stress value is 5.783 Mpa. The largest deformation area is the forefoot area of the outsole, and the maximum deformation is 10.26 mm from the front tip to the back, the stress and deformation gradually decrease. As can be seen from Figure 4-c, the contact area between the outsole and the ground is mainly from the forefoot to the heel area, with a contact area of 83.6 cm^2 and a ground reaction force of 386.2 N. As can be seen from Figure 4-d, the peak pressure of the outsole is the red area in the center of the heel, and the maximum peak pressure is 2.680 Mpa.



(a) Stress distribution of outsole (b) Strain diagram of outsole



(c) The contact area between the outsole and the ground (d) The peak pressure of the outsole

Figure 4. Simulation Results under Static Standing Condition

Comparing the data measured by FootScan with the finite element simulation results of the outsole model, the results are consistent, the error is less than 10%, and the model is effective, as shown in Table 3.

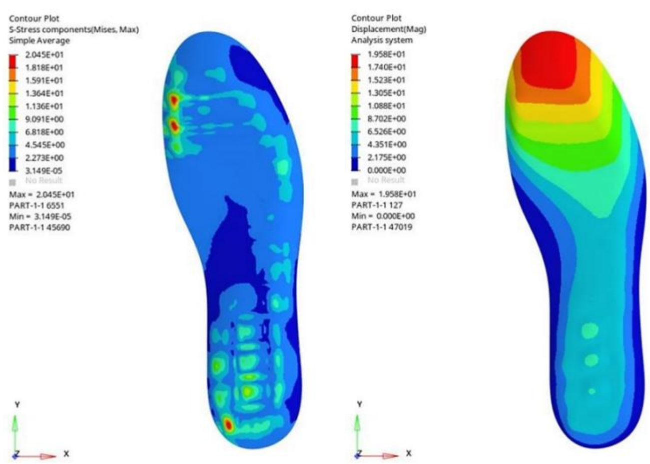
Table 3. Comparison of Simulation and Actual Measurement Results

Index	Simulation	Actual Measurement	Error (%)
Ground reaction force (N)	386.2	379.2	1.8
Average pressure (N/cm^2)	4.6	4.2	9

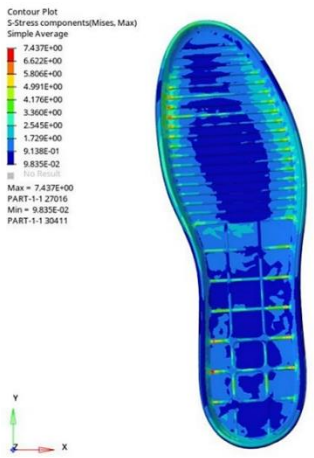
3.2 Static Simulation Analysis Results

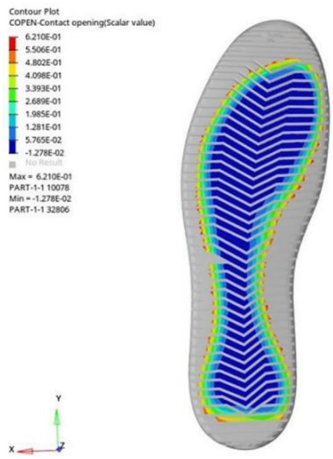
(1) Walking Condition

After solving the uniform walking condition of 1.2 m/s by Abaqus, the instantaneous calculation result of sole touching the ground is shown in Figure 5.



(a) Stress distribution of middle bottom plate (b) Deformation of bottom plate





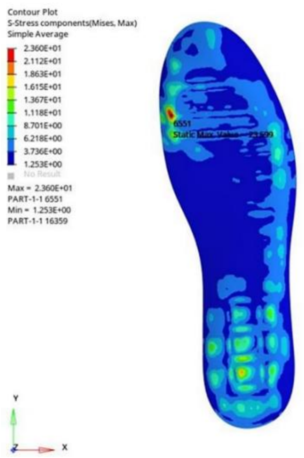
(c) Stress distribution of outsole (d) Contact area between outsole and ground

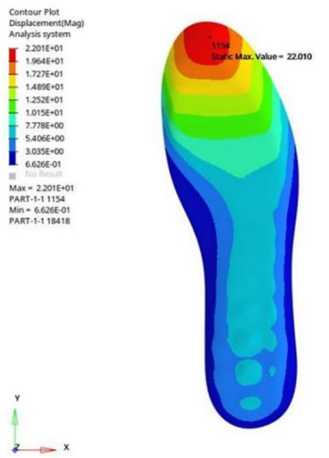
Figure 5. Simulation Results under Walking Conditions

From the simulation results, it can be seen that the stress of the midsole is mainly distributed in the forefoot region and the heel region of the outsole, and the stress in the region contacting with the reinforcing ribs of the outsole groove is obviously small, and the maximum stress value is 20.45 Mpa, which occurs in the forefoot region. The maximum deformation of the middle bottom plate is 19.58 mm, which appears in the front tip area. The stress of the outsole is mainly distributed in the edge area of the inner side of the outsole. The closer to the middle area of the outsole, the smaller the stress is, and the maximum stress value is 7.437 Mpa, which occurs in the area where the heel rib meets the inner side edge. The stress and deformation of the outsole of men's shoes are basically consistent with the distribution of the midsole, and the maximum deformation is 19.58 mm.

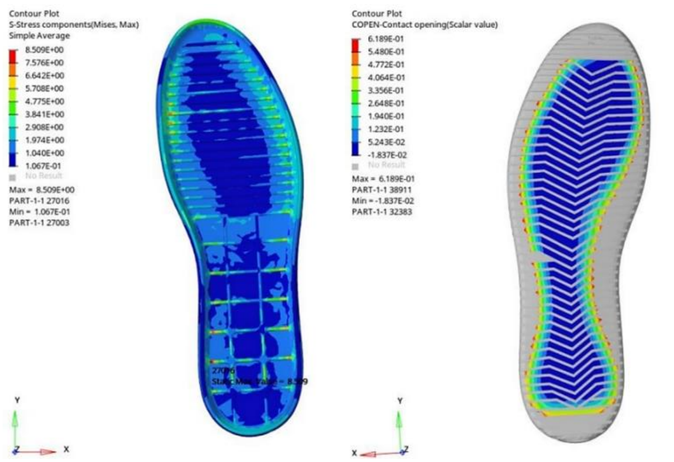
(2) Jogging Condition

The jogging condition of 2.4m/s at a constant speed is solved by Abaqus, and the instantaneous calculation result of the sole touching the ground is shown in Figure 6.





(a) Stress distribution of middle bottom plate (b) Deformation of bottom plate



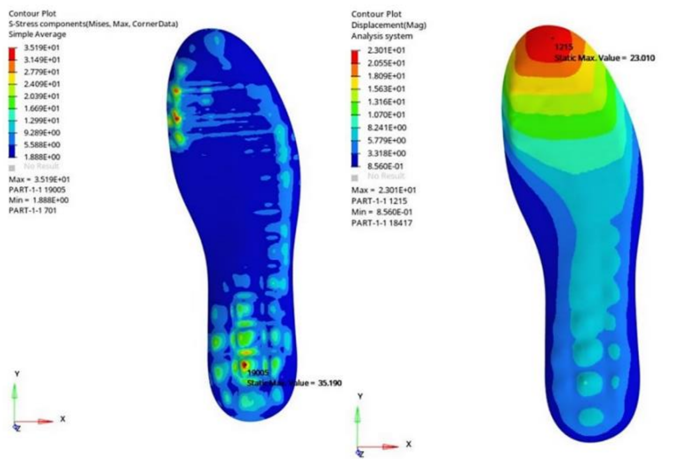
(c) Stress distribution of outsole (d) Contact area between outsole and ground

Figure 6. Simulation Results under Jogging Conditions

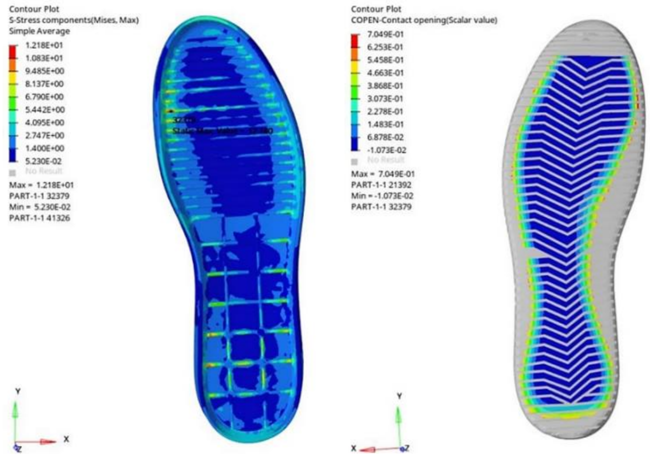
From the analysis results, it can be seen that the stress and strain distribution areas and forms of uniform jogging and walking tend to be consistent, and the maximum stress and deformation of the middle floor are 23.60 Mpa and 22.01 mm respectively. The maximum stress of the outsole is 8.509 Mpa and the maximum deformation is 21.43 mm.

(3) Active Jump Condition

After Abaqus solves the active jumping condition with a height of 40 cm, the instantaneous calculation result of the sole touching the ground is shown in Figure 7.



(a) Stress distribution of middle bottom plate (b) Deformation of bottom plate



(c) Stress distribution of outsole (d) Contact area between outsole and ground

Figure 7. Simulation Results under Jumping Conditions

From the analysis results, it can be seen that the stress and strain distribution areas and forms of uniform jogging and walking tend to be consistent, and the maximum stress and deformation of the middle floor are 35.19 Mpa and 23.01 mm respectively. The maximum stress of the outsole is 12.18 Mpa and the maximum deformation is 22.36 mm.

According to the test of the validity of the finite element model under static standing conditions and the static analysis under three characteristic conditions, the stress and strain analysis results of the middle floor and the outsole are shown in Table 4 and Table 5 respectively.

Table 4. Stress and Strain Results of Bottom Plate under Different Working Conditions

Index	Maximum stress (MPa)	Maximum deformation (mm)	Maximum stress area
Stand still	0.74	10.26	Middle area of forefoot
Walking at a constant speed of 1.2m/s	20.45	19.58	Medial margin of forefoot
Jogging at a constant speed of 1.2m/s	23.60	22.01	Medial margin of forefoot
40cm active jump	35.19	23.01	Middle heel area

Table 5. Strain and Stress Results of Outsole under Different Working Conditions

Index	Maximum stress (MPa)	Maximum deformation (mm)	Maximum stress area
Stand still	5.783	10.26	Middle heel area
Walking at a constant speed of 1.2m/s	7.437	19.58	Edge of medial heel rib
Jogging at a constant speed of 1.2m/s	8.509	21.46	Edge of medial heel rib
40cm active jump	12.470	22.36	Edge of medial heel rib

According to the stress nephogram, maximum stress and strain results of the outsole of men's shoes under four different conditions, it can be seen that the maximum stress area in each condition is mainly concentrated in the heel area, and most of them are related to the position of the transverse stiffener, and the stress value in the rest of the heel area is relatively small.

4. Discussion and Analysis

In the study of sports shoes, every optimization of sole structure is inseparable from the study of sports biomechanics. The establishment of sole-ground finite element analysis model can effectively help to analyze the interaction between shoes and ground under various working conditions, and provide scientific basis for the performance test of sole materials, the optimization of sole structure and the production design of soles. Ke Sicheng et al. established the finite element simulation model of foot-sole-ground, simulated the stress of the foot in the state of shoes during landing, and predicted the shock absorption performance of the sole. Yu et al. established a three-dimensional coupled finite element model of foot-ankle-shoe, simulated the wearing contact process and walking process of foot and shoe by interface contact simulation method, studied the plantar pressure when walking in high heels, and proved the versatility and potential of the calculation method in biomechanical evaluation and optimization in virtual environment. Tian et al. established a three-dimensional finite element model of foot-boot coupling, and simulated and studied the biomechanical changes of paratroopers' foot contact with the ground during parachute landing and falling. Dimitris et al. established a dynamic finite element model of running shoes, taking into account the time-varying plantar pressure distribution and boundary conditions, and put forward suggestions for improving the material distribution of midsole. Based on the existing traditional outsole of men's shoes, this study established a finite element model of sole-ground coupling, combined with biomechanical tests to explore the stress and strain size and distribution of soles, and provided guidance and suggestions for the optimization of outsole of men's shoes, especially the lightweight design of sole ribs.

Model verification is one of the most important steps after the model is established. By comparing the simulated calculation value with the actual test value, the consistency of the two methods is analyzed, so as to realize the simulation as close as possible to the real motion characteristics. In this study, there is a difference between the simulation results of the finite element model of men's shoe outsole and the biomechanical test results, and the relative error is less than 10%, which may be caused by the reverse modeling of the sole or the accuracy of sensor acquisition during actual measurement. Although the simulation analysis results are not exactly the same as the actual measured values, the measured results show that the validity of the finite element model meets the expected requirements and can be used for subsequent analysis and guidance in the early stage of shoe design and development. By comparing the stress and strain analysis of each area of the outsole of men's shoes under three working conditions, it is found that the area where the outsole of men's shoes has the largest deformation is the forefoot under the static standing condition. This is because in the actual production of shoes and boots, the front tip of the shoes will be designed with a certain degree of warping, which is generally called front stilts to meet the requirements of human comfort. The stress distribution area of the outsole of men's shoes is mainly in the edge area of the inner side of the outsole, and the closer it is to the middle area of the outsole, the smaller the stress is, because the midsole needs to be bonded with the inner edge of the outsole, and the inner edge of the outsole will be stressed more.

5. Conclusion

Based on an existing casual men's shoe outsole, this study constructs a "sole-ground" coupling finite element model by combining reverse and forward modeling methods, and the model is verified to be effective and reliable. By measuring the sole load under three common human movements, namely walking, jogging and active jumping, the stress, strain and distribution of the outsole of men's shoes under different working conditions are solved, and it is concluded that the stress and strain of the outsole of men's shoes are in the front stilt part of the shoes and the area where the lateral rib of the heel meets the inner edge, which can provide research ideas and data support for the structural design of the outsole of men's shoes.

References

Davia-Aracil, M., Jimeno-Morenilla, A., & Salas, F. (2016). A new methodological approach for shoe sole design and validation. *The International Journal of Advanced Manufacturing Technology*, *86*(9-12), 3495-3516. https://doi.org/10.1007/s00170-016-8427-5

Dimitris, D., Evagelos, K., & Maria, P. (2018). Gait-Specific Optimization of Composite Footwear Midsole Systems, Facilitated through Dynamic Finite Element Modelling. *Applied bionics and biomechanics*, 20186520314. https://doi.org/10.1155/2018/6520314

E. D. L., Madhusudhan, V., & A. W. W. (2010). Foot strike patterns and collision forces in habitually barefoot versus shod runners. *Nature*, *463*(7280), 531-5. https://doi.org/10.1038/nature08723

Hu Mingyu, Song Ying, & Wen Yong. (2019). Feasibility Study on Predicting the Deflection of Female Soles by Finite Element Method. *Leather Science and Engineering*, *29*(04), 54-57.

Ke Sicheng, Xie Hong, & Li Jiecong. (2020). Study on the Application of Finite Element Modeling Technology in Predicting the Shock Absorption Performance of Soles. *Leather Science and Engineering*, *30*(01), 68-73.

Li Jinglong, & Wen Guanning. (2021). Structural Optimization Design of Ming-style Round-backed Chair Based on Finite Element Method. *Industrial Design*, (06), 159-160.

Ling Jingxiu, Yang Xiaojing, & Wu Zhihong. (2019). Structural Performance Analysis of Multi-cell Sole and Influence of Cell Parameters. *Journal of Fujian University of Technology*, *17*(06), 560-564.

Qiu, T., Teo, E., & Yan, Y. (2011). Finite element modeling of a 3D coupled foot–boot model. *Medical Engineering and Physics*, *33*(10), 1228-1233. https://doi.org/10.1016/j.medengphy.2011.05.012

Yan Pei. (2017). The Influence of Sports Shoe Sole Design on Biomechanical Characteristics of Lower Limb. *China Leather*, *46*(04), 49-51+54.

Yang Yi. (2021). *Establishment and Verification of Static and Dynamic Finite Element Model of Foot-sports Shoes Based on Two Coupling Methods*. Beijing Sport University, Beijing.

Yu, J., Cheung, T. J., & Wong, W. D. (2013). Biomechanical simulation of high-heeled shoe donning and walking. *Journal of Biomechanics*, *46*(12), 2067-2074. https://doi.org/10.1016/j.jbiomech.2013.05.009

Zhou Qixuan, Gu Bingfei, & Lou Yi. (2024). Design and Analysis of Midsole Structure of Running Shoes Based on Finite Element Model of Foot. *Journal of Basic Science of Textile University*, *37*(01), 68-75.9.