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Numerical Simulation of Slip Resistance of Shoe Sole Tread Patterns Using Finite Element Method

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ABSTRACT
Multiple factors can cause slips and falls, leading to long-term musculoskeletal injuries. Slip resistance can be achieved mainly by wearing footwear soles with better gripping materials and tread patterns. However, it is necessary to analyze the impact of a complex tread pattern design on slip resistance compared with a simpler outsole tread design. This study aims to assess the slip resistance of shoe outsoles with varied tread patterns and materials on soil and steel surfaces through finite element analysis. In this study, detailed geometric models of six tread patterns were developed using SolidWorks software. Ethylene-vinyl acetate (EVA), polyurethane (PU), thermoplastic rubber (TPR), and polyvinyl chloride (PVC) were used as the outsole materials, and the soil and steel surfaces were considered as ground surfaces. The simulations were performed using Ansys software by applying realistic boundary conditions to analyze the slip resistance performance of the outsoles through displacement analysis. The modeling and simulation process investigated the influence of tread patterns, material properties, and surface characteristics on slip resistance. The simulation results showed that complex tread patterns have higher slip resistance than simpler designs. In the case of soling materials, EVA outperformed PU, PVC, and TPR on both steel and soil surfaces, suggesting that it is the most effective material for slip resistance. PVC had the lowest slip resistance, while PU and TPR had almost the same results. The simulation outcomes provide valuable insights into the parameters that influence slip resistance, allowing designers and engineers to optimize the outsole designs for improved performance and safety.

Keywords: Finite Element Analysis, Footwear outsole, Tread pattern, Slip resistance, Soling material

1. Introduction

Slips, stumbles, and falls are among the most common causes of injuries reported annually. A study found that falls are the leading cause of accidental death in older adults, with pedestrian accidents accounting for second only to motor accidents [1]. In addition, slips and trips account for 67% and 32% of all falls among the elderly and young people, respectively [2]. Slip-and-fall-associated back pain or muscular strains are often not diagnosed as connected to slips; hence, the severity of the problem is likely more significant than that reflected by the aforementioned statistics [3]. Slipping and falling risks are related to footwear and floor materials, contamination state, and sole geometry [4]. Slip resistance is the relative force preventing a shoe or foot from sliding down a pathway surface. It is determined by a number of elements, including the walkway surface, footwear bottom, and the presence of foreign objects between them. An outsole with a strong slip resistance can effectively avoid slippage and improve stability when walking, thereby ensuring personal safety. Therefore, slip-resistant footwear can reduce the likelihood of a slip [5].

The frictional performance of slip-resistant footwear has been the subject of extensive experimental investigation [4]. The previous studies focused on how specific tread design parameters influence friction on contaminated surfaces using custom tread patterns [6]. Previous studies have indicated that treads oriented perpendicular or oblique to the direction of slip yield a higher dynamic friction coefficient than those aligned parallel to the slip direction, and proper footwear traction can improve performance and reduce the chance of injury [5]. Slip testers typically evaluate traction using the coefficient of friction between the shoe and the floor. Some studies have discovered that the slip resistance of outsoles can be measured using static and dynamic coefficients of friction [7]. Several studies have investigated the influence of various materials [8] and outsole patterns [9], whereas others have explored the impact of outsole pattern depth [4] and tread gap on slip resistance [10].

Although prior research has investigated the slip resistance of outsoles extensively, they were limited to real-world experiments with few samples on limited surfaces. Experimental tests are time-consuming and costly, and a limited number of samples with material variations can be evaluated using this process. However, through finite element analysis, various samples can be tested more efficiently and cost-effectively [11].

Previous studies created a finite element model to predict the friction coefficients between shoes and floors [12], but the rear part of the outsole had a more straightforward design. A recent study investigated the influence of different tread patterns on the traction forces and slip resistance of military boot outsoles during gait [13]. Although the study considered tread patterns, the models were simplified and lacked the complex curvature of the actual outsoles. Therefore, it is necessary to conduct research that compares the slip resistance

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of different shoe soling materials with various simple and complex tread patterns on different ground surfaces.

This study aimed to evaluate the slip resistance of shoe sole tread patterns made from widely used PVC, EVA, PU, and TPR soling materials on soil and steel surfaces using finite element analysis. The novelties of this study are manifold. Firstly, the slip resistance performance of both basic and complex designs was significantly contrasted in this study, whereas prior research examined only simple or complex tread patterns separately. Secondly, the soil and steel as ground surfaces were considered to compare the slip resistance of different tread patterns. Finally, a comparison was made among commonly used footwear soling materials to determine the best-suited soling material for slip resistance. The findings are expected to provide insights into the design and selection of anti-slip shoe sole tread patterns and materials.

2. Methodology

In this study, six new shoe outsole tread patterns (STP1, STP2, STP3, STP4, STP5, and STP6) were designed using SolidWorks Software version 2016. Realistic boundary conditions, including constraints, applied loads, and frictional contact parameters, were implemented in Ansys version 2016. Detailed modeling and simulation techniques were employed to examine the influence of tread pattern designs, material properties, and surface characteristics on slip resistance.

2.1 3D modeling

Six different tread patterns for the outsole were modeled for a single-unit sole-based shoe using the SolidWorks software version 2016, and the tread patterns were developed based on the boot last of Paris Point size 41. Based on traditional observed outsole tread designs, simple tread patterns STP1, STP2, and STP3 were modeled using SolidWorks software. In contrast, STP4, STP5, and STP6 models were modeled using the software to investigate the slip resistance of complex patterns.

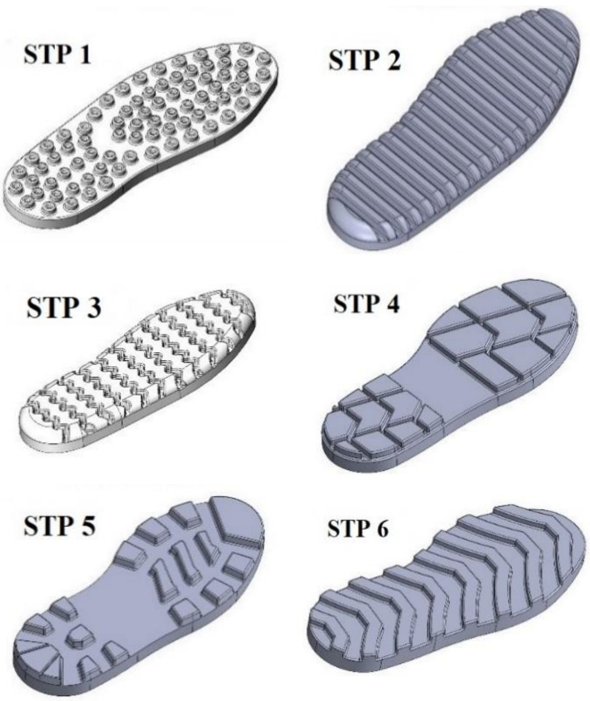

Fig.1 Tread pattern models of the shoe outsole.

The tread height of all patterns was 5 mm [14], and the overall thickness of the outsoles was 12 mm. The tread height and overall thickness of the outsole models were kept constant for proper comparison of the slip resistance of the outsoles. The simple and complex tread patterns developed are shown in Fig.1.

2.2 Assigning material properties

In this study, ethylene vinyl acetate (EVA), polyurethane (PU), thermoplastic rubber (TPR), and polyvinyl chloride (PVC) were used as outsole materials, which are widely used shoe sole materials. According to statistics from 2011, among 21 billion pairs of world footwear production, leather was 8%, PVC was 20%, rubber was 40%, TPR was 14%, EVA was 9%, and PU was 8% being used as shoe outsole material [15]. The mechanical properties of the different soling materials used in the simulations are listed in Table 1.

Table 1 Mechanical properties of different soling materials.

Soling Materials	Young's Modulus (MPa)	Density (Kg m^{-3})	Poisson's ratio	Ref.
EVA	25	965	0.48	[16]
PU	3400	1180	0.49	[17]
PVC	3100	1400	0.42	[18]
TPR	120	1060	0.49	[19]

Moreover, the simulations considered soil and steel as the walking surfaces. Because soil is the typical natural walking surface, and steel is commonly used as a walking surface in construction and industrial sites [20]. The mechanical properties of steel and soil as ground materials are shown in Table 2.

Table 2 Mechanical properties of ground materials.

Components	Young's Modulus (MPa)	Density (Kg m^{-3})	Poisson's ratio	Ref.
Soil	23.6	2180	0.26	[21]
Steel	200000	7850	0.3	[22]

2.3 Meshing

Tetrahedral elements were used to mesh the ground surface and shoe sole as they can adapt to complex surfaces more easily than hexahedrons, allowing for a more accurate representation of geometry without excessive mesh refinement [19]. 32000 to 35000 nodes and 18000 to 21000 elements were used to mesh different patterns. The meshing of an outsole is shown in Fig.2.

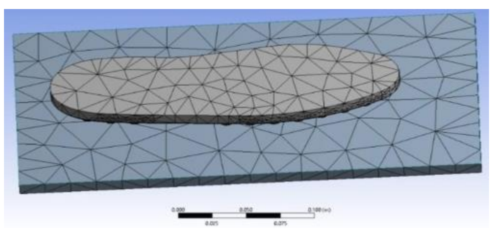

Fig.2 Meshing of footwear outsole in ANSYS Software.

2.4 Load and boundary conditions

Load and boundary conditions were applied in the Ansys (2016) software to simulate a real-life environment. Boundary conditions include the application of forces and/or constraints. A hyper-mesh uses load collectors to store the boundary conditions. A force of 70,000 Pa was applied to the sole models, representing the average pressure generated by a person while walking [23]. The frictional contact behavior was defined to simulate the interaction between the cleats and the ground, with a friction coefficient of 0.4 [4]. The ground was defined as a fixed support.

2.5 Data analysis

Six shoe outsole tread patterns (STP1, STP2, STP3, STP4, STP5, and STP6) were simulated using four material types on the soil and steel surfaces. After obtaining numerical simulations of the six tread patterns, the slip resistance was evaluated by displacement analysis. The displacement is the amount by which a shoe outsole having tread patterns moves from its original position when subjected to forces that mimic real-world walking pressure on different surfaces. Displacement is a key metric because it directly correlates with slip resistance; the less displacement observed, the more resistant the tread pattern is to slip. Therefore, the slip resistance was compared among four shoe soling materials and six trade patterns on the soil and steel surfaces based on the horizontal displacement value.

3. Results & discussion

The displacement data provided insight into the performance of the six tread patterns. Horizontal displacement was measured over time, comparing the ability of each tread pattern to maintain stability and resist slipping within different soling materials and surfaces. The displacement data for each pattern revealed its traction effectiveness over time, where lower displacements correlated with a higher traction force, indicating a higher slip resistance. The simulation of a shoe outsole displacement is shown in Fig.3.

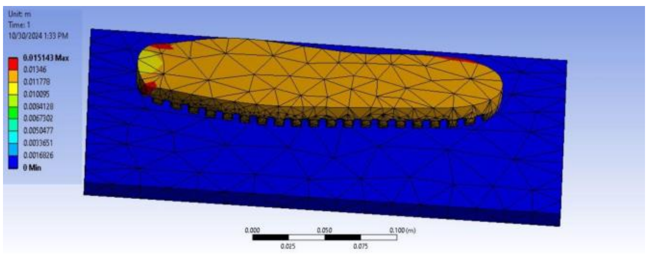

Fig.3 Simulation of displacement analysis.

3.1 Soil as the movement surface

The displacement of the six tread patterns under four types of soling materials with respect to time on a soil surface is shown in Fig.4. Across all the patterns, the displacement increased over time, reaching a peak at 1.0 seconds. STP5 exhibited the lowest displacement across the EVA, PU, and TPR soling materials, followed by STP6. STP5 recorded displacements of 14.019 mm for EVA, 14.372 mm for PU, 14.352 mm for PVC, and 14.597 mm for TPR. In comparison, STP6 exhibited displacements of 14.078 mm for EVA, 14.143 mm for PU, 14.452 mm for PVC, and 14.425 mm for TPR. STP3 and STP4 showed moderate displacements across all soling materials. However, STP4 of the EVA soling material showed slightly higher displacement, particularly at the 0.75-second mark, indicating reduced traction. STP1 and STP2 exhibited the highest displacements for all the materials. STP1 showed displacements of 14.468 mm for EVA, 15.156 mm for PU, 15.250 mm for PVC, and 14.949 mm for TPR, and STP2 had displacements of 14.875 mm for EVA, 15.484 mm for PU, 15.230 mm for PVC, and 15.065 mm for TPR.

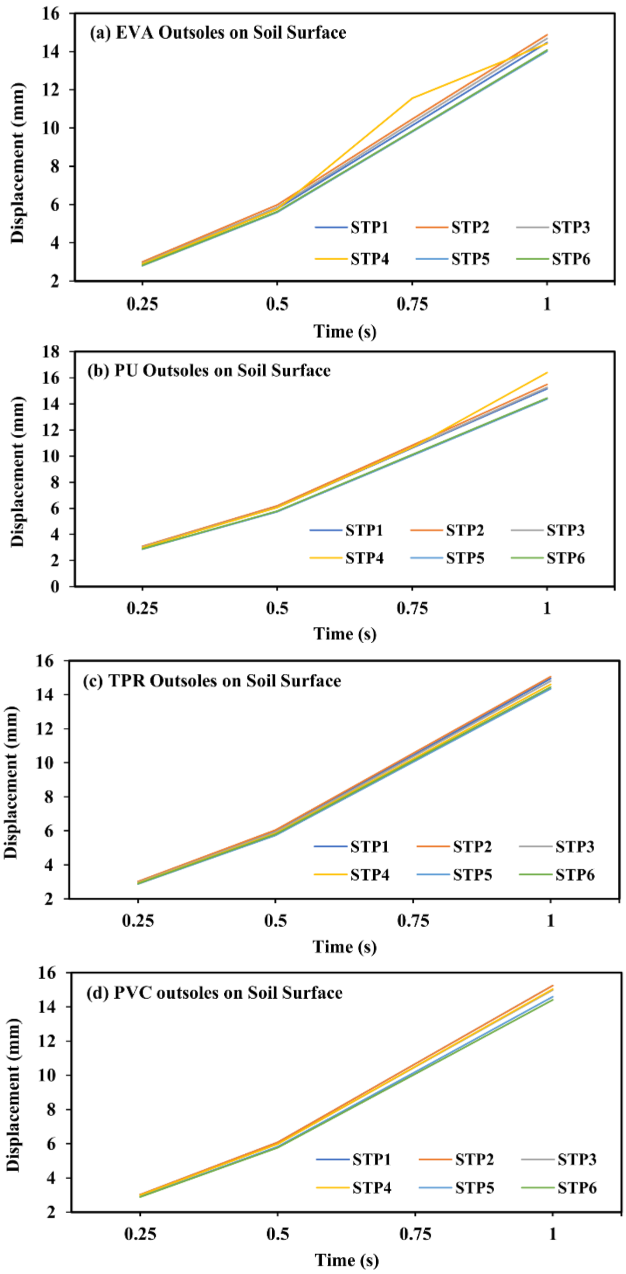

Fig.4 Displacement of outsoles on soil: (a) EVA, (b) PU, (c) TPR, (d) PVC.

The STP5 and STP6 models generally maintained lower displacements across all materials, suggesting that these designs offer better slip resistance on soil surfaces. Fig 5 illustrates the comparison of all soling materials on the soil surface for STP5 and STP6. It was found that EVA had the least displacement among the other materials, whereas PVC had the highest displacement. The PU and TPR materials exhibited almost the same displacement. These findings suggest that STP5 is the most effective for slip resistance, particularly with the EVA soling material.

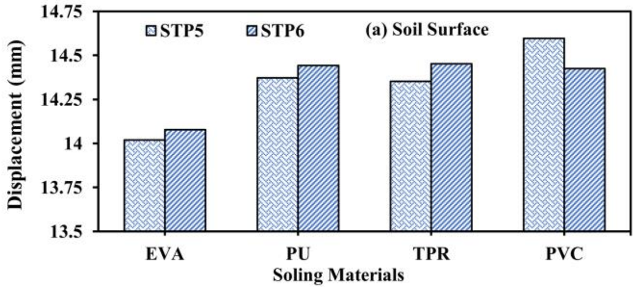

Fig.5 Displacements of soling materials on soil surface.

3.2 Steel as the movement surface

The displacements of the tread patterns on the steel surface over time are illustrated in Fig.6. Each soling material exhibited unique displacement characteristics when subjected to a steel surface. The displacement increased over time for all the patterns, peaking at 1.0 seconds.

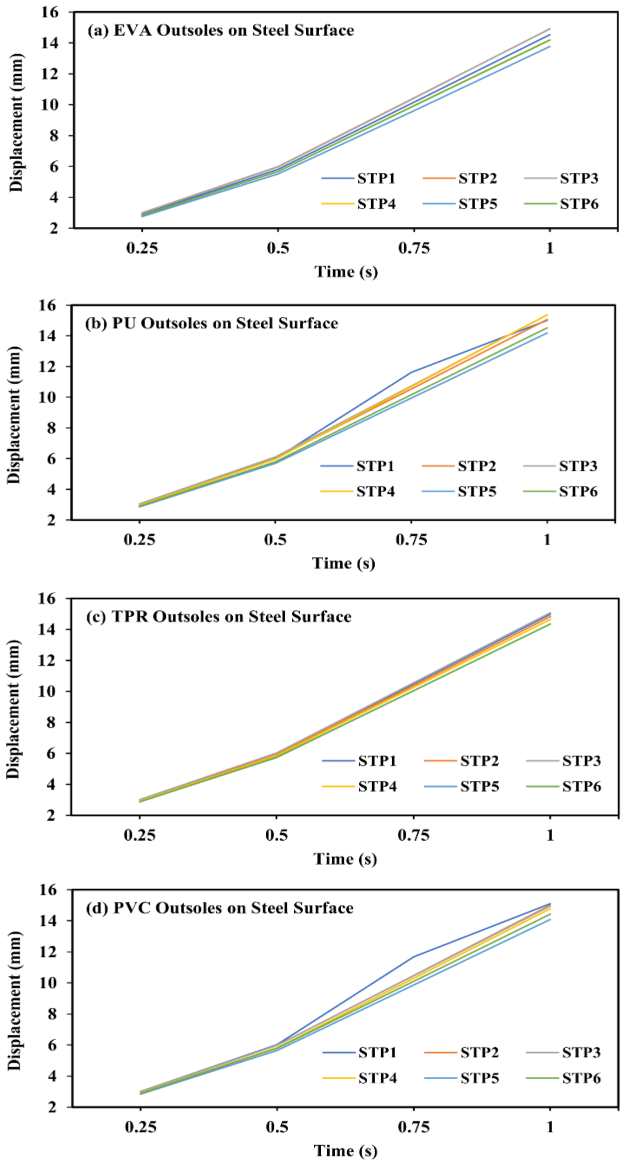

Fig.6 Displacement of outsoles on steel: (a) EVA, (b) PU, (c) TPR, (d) PVC.

Across all soling materials, STP5 had the least displacement, followed by STP6, which came in second. STP5 recorded displacements of 13.768 mm for EVA, 14.188 mm for PU, 14.352 mm for PVC, and 14.085 mm for TPR. In comparison, STP6 exhibited displacements of 14.187 mm for EVA, 14.524 mm for PU, 14.359 mm for PVC, and 14.425 mm for TPR. STP1 and STP2 consistently resulted in lower displacement values across all the soling materials. STP1 showed displacements of 14.532 mm for EVA, 15.010 mm for PU, 15.101 mm for PVC, and 14.985 mm for TPR, and STP2 exhibited displacements of 14.904 mm for EVA, 15.064 mm for PU, 15.005 mm for PVC, and 14.830 mm for TPR.

Fig.7 compares the displacement of all soling materials on the steel surface for STP5 and STP6, as these two models showed better results than the other models. Among the materials tested, EVA exhibited the highest slip resistance, followed by TPR, PVC, and PU, demonstrating the lowest slip resistance.

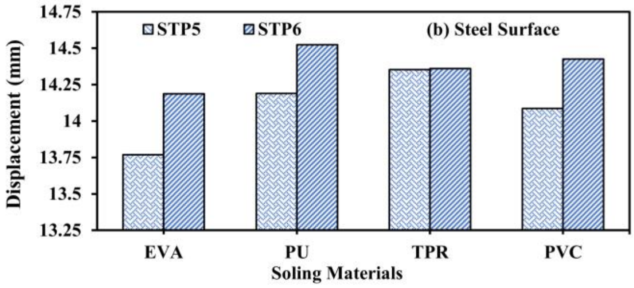

Fig.7 Displacement of soling materials on steel surface.

In all cases, complex tread patterns were observed to have less displacement than simpler patterns, possibly because of their enhanced ability to manage ground contact. Complex patterns often incorporate a multidirectional layout, which increases the shoe’s surface contact with the ground and allows for greater frictional engagement [24]. In addition, EVA outsoles demonstrate improved slip resistance compared to PVC, TPR, and PU soling materials on soil and ground surfaces because of their higher compressibility and energy-absorbing properties [25], which increase the contact surface area and help stabilize the foot under load [26].

This study had some limitations. First, the study used a standard outsole shape, although the results may differ depending on the shape, which can be considered a limitation. Moreover, this study did not consider wet or oil-contaminated surfaces, where slips usually occur. Future studies should consider various fluids among soling materials with different tread patterns on tiles as the ground surface to determine a better slip-resistant outsole.

4. Conclusion

The results of this study indicate that the STP5 sole model, made from ethylene vinyl acetate and featuring a complex structure, had the lowest displacement, making it the most slip-resistant outsole based on the tread design and material. The results demonstrated the importance of tread complexity and material choice for improving slip resistance. The study also highlighted the importance of computational analysis in footwear design optimization, offering a more efficient and precise method for testing and improving tread patterns. The findings can help guide future footwear innovations, especially in fields where slip resistance is crucial, such as healthcare, manufacturing, and sports.

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