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A Validation of Material, Design, and Physical Properties of Weightlifting Shoes Based on 3D Models

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This research paper explores the enhancement of weightlifting shoe (WLS) performance through a unique combination of physical analysis (PHA) and finite element analysis (FEA). While FEA is extensively employed in diverse design fields, its application to optimizing weightlifting shoes remains unprecedented. WLS underwent comprehensive physical testing, including evaluations of energy absorption, density determination, abrasion resistance, slip resistance, and compression, with subsequent calculation of mean values. Utilizing Creo software, 3D models of WLS soles were created and imported into the ANSYS workbench for detailed analysis. This analysis encompasses the assessment of critical parameters like total deformation, directional deformation, von mises stress, and von mises strain. The outcomes of this study offer a promising framework for enhancing the quality, design, and performance of weightlifting shoes, potentially benefiting both athletes and manufacturers in the field.

Keywords: Sports shoes, Finite element analysis, Weightlifting shoe, Footwear, Shoe Sole

1 Introduction

The footwear industry is an ever-growing sector with a constant need for new and improved models of footwear for a huge number of consumer base. So a constant demand for innovation of newer models especially in the sports footwear sector through its design and development of various R & D activities is needed. The analysis of sports shoes has been carried out since the 1930's albeit the methodologies were not very much upgraded like recent times. But since the year 1970's the studies on sports footwear have been expanded into various subsequent fields such as kinesiology, biomechanics and sports medicine. The foot forms the base of the human body and it functions as the primary supporting system while performing various activities[1]. Because of its complex structure, flexibility and robustness, it can endure severe stress[2]. All of the parts that make up the foot are capable of providing support, balance and movement to the body. For the development of any project involving the foot, it is vital to understand its movements and the areas that require more work[3]. Hence comes the necessity for the development of footwear.

Footwear is one of the most common interface between the foot and the floor, and it can help improve performance, avoid injury, or alleviate discomfort[2]. According to S. Lin *et.al*., [4], sports shoes, in particular, should be constructed with two goals in mind: (a) preventing excessive loads acting on the human body's structures, and (b) improving performance. Depending on the purpose of the footwear, the factors can be developed in a disjointed manner. The selection of materials used in the creation of footwear is a fascinating area of research. A tougher material is more secure and provides better protection and a soft mid-foot material induces (excessive) pronation of the foot and should be avoided[5]. A footwear which is constructed using Soft midsole materials is very much more likely to be unstable than the midsole which is made up of a hard material[6]. From this, the material properties-thickness relationship can be considered while designing a sole.

Shoe designing is a technical and innovative topic in ergonomics, particularly in sports science. Several technical reports on sports shoe design have been published. For example,[7] through observations in sports shoe biomechanics, the effects of several characteristics of shoe design such as cushioning, stability, friction and energetics were summarized[8] discussed the differences between athletic and casual footwear while describing numerous footwear features and components, particularly for athletic activities (running, cross-training, court

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sports, etc.). The outsole, midsole, insole, upper, and various reinforcements make up the majority of a sports shoe. Though, based on the playing conditions and main foot motions, its detailed design and structure differ for different sports shoes[9]. In this context, a unified shoe design concept is impossible, and shoe components must be designed to be compatible with the sport. Gender, physical condition, and the player's playing technique must also be considered[10]. A study of the literature on athletic shoes and biomechanics revealed that many effects are the indirect outcome of shoe-induced movement changes, i.e., a particular shoe characteristic elicits a kinematic adaptation, which in turn has secondary consequences on kinetics, injury, and performance[7]. Thus, the design of high-performance sports shoes is dependent on the accuracy with which the primary aspects necessary for each sport are evaluated.

In recent years due to the capacity to simulate structures with irregular geometry and complex material properties with sophisticated boundary and loading conditions, finite element analysis (FEA) has become widely applied in various fields and sectors. FEA contributes to an experimental strategy for modelling the distribution of loads on the foot or for other objects, including information such as internal forces and deformation[11]. Computer simulations can provide a complete and systematic examination of design variables to help guide by prescribing techniques for personalized footwear[12]. Finite element modelling accommodates geometry and experimental settings, allowing for the evaluation of the behavior of products under consideration[13].

Without having to build the footwear, FEA allows for an efficient evaluation of numerous structural and material factors. The literature models demonstrate the promise of understanding the biomechanics of the foot and footwear. However, because most models have sophisticated geometry, it's difficult to simulate them precisely[14]. Because of its ability to model structures with irregular geometry and complex material properties, as well as the ease of simulating complicated boundary and loading conditions in both static and dynamic analyses, computational modelling, such as the FEA method, has become increasingly popular in many biomechanical investigations. The FEA method can be used in conjunction with an experimental methodology to estimate load distribution between the foot and various supports, providing additional information such as internal stress and strain in the ankle-foot complex. Without the need for constructed footwear or reproducing patient trials, FEA allows for rapid parametric evaluations of the results of shape alterations and other design factors of footwear[15].

FEA is a computer-based program for predicting the impact of environmental influences on different structures. The process starts with creating a geometric model and describing material attributes as well as boundary conditions. The model is then meshed, which divides it into smaller components that are joined at nodes. This makes it easier to approximate stress-strain correlations. The FEA package then inputs environmental parameters such as force, heat, and vibration as equations, which it solves simultaneously. Finally, charts and numerical results are generated to give engineers information about the model's behavior. Corporations all across the world utilize FEA to simulate testing that would otherwise be performed on prototypes of components and systems.

Engineers may test and analyze components and systems using FEA without having to make physical prototypes thereby saving time and money for the company. FEA's purpose is to accurately mimic testing and deliver data to engineers. For FEA to be most effective, simulations must almost exactly mirror the live testing done on the prototype. A minimum number of FEA should also be performed. To be an effective and efficient substitute for live tests, FEA must be able to imitate live testing with a small number of analyses. when the amount of time and money spent running the FEA is greater than or equal to the amount of time and money spent executing the live tests, then the FEA is not a desirable option in the manufacturing process. The precision of the test results is another advantage of FEA. This assertion, however, is only true if the simulation input is appropriate.

FEA has the potential to assist companies in the athletic shoe industry in creating, modelling, and analyzing shoes or their components. It would also allow them to change design, materials, or dynamics without having to create a new component by changing numerical inputs. FEA has already been included in the design and production processes of many other industries. In reality, FEA is critical to the success of many businesses and industries. However, only the WLS industries have yet to use FEA in their analysis.

The goal of this study is to perform the overall tests on the different design and material aspects of quantifying the WLS and determine the significance of the WLS used by weightlifters and other recreational users. In this context, the sequence of operation used in this paper starts from the usage of creo software to create a sole component geometry for designing a geometry of WLS sole and then use a popular FEA software to execute FEA, followed by analyzing the physical model of WLS and perform various physical tests and tabulate both the FEA test results and physical test results to identify and characterize the WLS as a reliable option for the activity of weightlifting and for various squats performed by the athletes. Total deformation, directional deformation towards the y-axis, von mises stress value, and von mises strain value are all important measurements to determine the functions of a WLS sole. Physical testing to determine the basic physical characteristics of the WLS followed by Computational technology to test the in-depth character of the WLS for their exclusive functions which make them a viable and superior footwear option for the activity of weightlifting. Implementing a numerical simulation could reduce the number of design iterations and enhance design quality, as well as make the product development process more efficient and less expensive.

2 Materials and Methods

The methodology used in this study included physical testing's as well as FEA, Data from the experimental analysis were collected and used to perform Finite element analysis. The sole was modelled with a heel thickness of 0.75 inches which is the heel height of the shoe taken into the study, and the following parameters were experimentally determined and calculated as young's modulus, density and Poisson's ratio from the CATERS testing facility which is available at CSIR-CLRI. the calculations were performed using the formula given

$$YoungsModulus(E) = (FL_0)/A(L_n - L_0)$$

Where

A – Cross sectional Area

F – Force

L_0 *– original Length*

L_n *– New Length*

During the contact and impact between the foot and the ground, the major kinetic changes occurring in the body around the performance improvement and stability will be the result of the primary Kinematic changes occurring through the shoe sole design structure and material variations[7]. Hence, for this reason, only the sole of the WLS has been designed and tested instead of testing the whole shoe which is more time consuming and not necessary for this analysis.

The Testing component is divided into two studies. The first one is doing a physical test to determine the following properties such as energy absorption test, density determination test, abrasion resistance test, slip resistance test and compression test and compile these results. The second study is performed using FEA, using a popular FEA software such as ansys workbench 2020 R1, the following analysis such as the total deformation, directional deformation, von-mises stress & von-mises Strain are derived and compiled.

The physical tests that were performed are listed as energy absorption of the seat region, density of materials by volume displacement, abrasion resistance- rotating drum method, weight measurement- in house method, friction- slip resistance, compression set- constant stress method. The first test performed is the energy absorption of the seat region which comes under ISO 20344:2011 and the clause 6.2.4 of EN ISO 20345:2011 specifies the requirement for determining the energy absorption of the seat region. The SATRA STM 766 tensile tester with STM 766BP can be used to perform the test (a set of six back part punches made from standardized lasts). Clause 5.14.1.2 specifies several critical last punch measurements that apply to a wide variety of shoe sizes. The footwear sample is put on the lower jaw base plate of the tensile tester, and a back part punch is selected for the top jaw based on the footwear sample size as specified of EN ISO 20344:2011. The upper punch is lowered to only make touch with the inside of the footwear sample in the heel area. A compressive load is applied at a 10mm/min rate until a force of 5,000N is achieved. Up to the maximum force applied, a plot of load versus deflection is obtained (5,000N). The energy absorption is estimated by integrating the load-deflection curve between 50 and 5,000N, which is done by using tensile testing machine.

The density of materials were measured by volume displacement method which follows the test Method: SATRA TM134: 2010/ISO 2781:2018. The principle is that the test specimen is weighed in the air first and reweighed while completely submerged in water. The weight loss appears to be equivalent to the amount of water displaced. The density is estimated by dividing the volume displacement, which is equal to the volume of the test item, by the weight in the air.

$$\text{Density (d)} = \frac{\text{M}}{\text{v}}$$

Where

M – Mass

V – Volume

The abrasion resistance - rotating drum method and it follows the test Method: SATRA TM174:2016/ISO 20344(8.3) ISO4649:2017. The principle is that a circular test specimen is placed in contact with a rotating cylinder covered with a standard abrasive cloth under constant tension. The specimen is then moved around the cylinder's length, forming a helical contact path with abrasion. The volume loss is determined by measuring the amount of material reduced by measuring its thickness from the initial stage to the final stage.

$$Abrassion\ Resistance\ = \frac{200\times \text{Tn}}{\text{Density} * 0.5(\text{Cn} + \text{Cn} + 1)}$$

The next step is the weight measurement and it follows the in-house test procedure with the laboratory weighing instrument, the principle is that the strain gauge translates the force exerted by the load into an electrical signal when it is placed on the scale. The load cell reverts to its natural shape after the load is removed from the cell. The next test is the friction (slip resistance) of footwear and floorings which follows the test Method: SATRA TM144. The principle of this test method is that the footwear item and the test floor are brought into contact, and then moved horizontally relative to one another at a steady pace after being subjected to a prescribed vertical force for a short duration of static contact. The horizontal frictional force is measured at a specific point after movement begins, and the dynamic coefficient of friction is determined for the test's specific conditions. The compression test which follows the test Method: SATRA TM64. The principle of this test is stated as the test specimen's percentage change in thickness and it is calculated after it has been compressed for a predetermined amount of time and then allowed to recover for another predetermined amount of time. The second phase of the test is the FEA which is the most crucial operation for this research. The testing procedure for the aforementioned test is described below. The procedure for conducting this test can be divided into several steps: Creating the 3D model using the creo software, giving dimensions to the geometry precisely as per the WLS sole, importing this geometry file as STP format into the ANSYS workbench 2020 R1 software, implementing the boundary conditions to the imported geometry, applying forces, characterize the material properties, classifying element groups, specifying mesh density, generating a mesh, and executing the analysis.

The first step under the FEA is to create a 3D model of the sole geometry. This is performed by using the creo software. A sole pattern of the WLS sole is taken manually and then using these measurements the geometry is designed and developed using the creo software precisely. The next step is to import this geometry into the ansys workbench 2020 R1 in STP format. Then verify whether the imported geometry's structure is perfect and it does not have any errors or incorrect measurements. The model's boundary conditions are the next step in the analysis. Using boundary conditions, the user can determine the range of motion for any point, line, face, or body defined within the model. To test the sole component, all movement, including rotation, is forbidden on the bottom face of each subcomponent because these faces are practically attached to the floor. The rest of the sole is free to react to its forces. To simulate the floor where the shoe sole makes contact, an analytically stiff surface is used.

External forces must be applied once the boundaries have been defined. These forces can be entered as a function of an independent variable, like time, or as a single value. The force is given to the full top surface of the sole to simplify the test. This simplification is permissible since the entire surface or a portion of it is directly operated upon and does not affect the outcome. The force is exerted along the z-axis from top to bottom direction and the value of force provided to act on the sole is 5250 N. The next phase in the model analysis is to define the model's material properties. Young's modulus, poisson's ratio, and other important properties of a linear material be started with a single quantity. However, input equations are required for performance to specify the material response under various circumstances for the more intricate, non-linear materials employed by the athletic shoe business. so for determining the material properties of EVA which is found in the selected WLS sole, the soles have been tested using various physical analyses and from them, young's modulus, poisson's ratio & density has been calculated. The element groups are defined when the material attributes are specified. Each element of the model is defined during this step. A subcomponent is referred to as an element, and the sole has two of them. Before meshing the model, these subcomponents were defined as discrete entities. Each subcomponent was meshed independently and considered as a separate object due to this. The top sole block, which makes up the majority of the WLS sole is made of Ethylene Acetate (EVA), and the bottom sole surface part, which is a thin layer of Rubber that offers the essential slip resistance and grip, is the two subcomponents of the sole. A mesh density for each element group is defined after the element groups are defined. As the mesh density grows, the accuracy of the analysis will improve.

The mesh is constructed after the mesh density has been set. Each subcomponent is no longer a single entity when it is created. Each element is separated into multiple nearby pieces by meshing the model. Cutting up the model into differential parts and then reassembling the model by linking the corners, or points, of each differential is the equivalent of meshing. The final stage in preparing the analysis model is to create the mesh. The analysis is carried out following the model's and environment's earlier specifications. Once the analysis is complete, the findings for the conditions such as total displacement, directional displacement, von-mises stress, and von-mises strain are been found. The entire process took six hours, from designing the shape to analyzing the data. This period is spent understanding the procedures of analysis, putting the analysis into practice, and fine-tuning the mesh to obtain more refined data. Following the completion of the FEA tests, the data is correlated and tabulated along with the test results of the physical analysis. The outcomes are tallied. All the steps and sequences are mentioned in Fig. 1

3 Results and Discussion

3.1 Physical testing's

This study is the first to determine the test evidence which provides a shred of quantifiable evidence for stating that the WLS significantly improves athletes or the person who trains wearing WLS shoes.

Observation in the physical analysis provided a consistent result in all the testing phases. For the energy absorption test, the load provided on the WLS sole is in the range of 5000.06 N to 5000.46 N and the test punch size used is in the diameter of 265 mm for all the tests. The extension acquired were in the range of 14.46 mm and 15.15 mm with a mean value of 14.8 mm. The energy dissipation values acquired are 23.96 J and 23.90 J with a mean value of 23.93. these values are significantly higher than the regular shoes or other athletic shoes which were studied in the literature[16].

The density determination test is performed by two methods, the first method is by analyzing the density of the whole WLS sole and the next method is by analyzing each individual component. The mean density value of the whole WLS sole is 0.7452g/cc

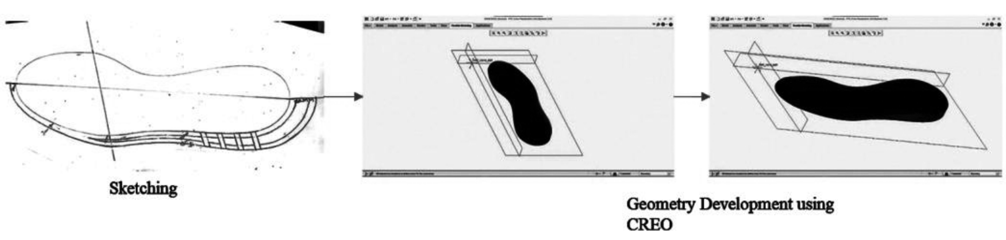

Fig. 1 — Creation of geometry using CREO.

Table 1 — Energy Absorption of seat region (ISO 20344:2011)

S.no	Load at maximum compressive load	Extension(mm)	Test punch size(mm)	Extension at maximum compressive load(mm)	Energy at 5000 N(J)	Energy at preset point (compressive load 5000 N(J)
1	5000.06	14.46	265	14.45	23.96	23.96
2	5000.46	15.15	265	15.14	23.90	23.90
Mean	5000.26	14.8		14.79	23.93	23.93

Table 2 — Density of materials by volume displacement (SATRA TM134:2010/ISO 2781:2018)

Parameters	Whole Unit		As Individual Layers		
	Specimen 1	Specimen 2	EVA Topsole	EVA Midsole	Rubber Outsole
A. Weight of the sample, g	2.3±0.07	1.9±0.02	1.42±0.02	3.21±0.08	3.71±0.01
B. Weight of sinker in water, g	11.1±0.07	11.1±0.07	11.1±0.02	11.1±0.02	11.1±0.02
C. Weight of sample + sinker in water, g	10.15±0.02	10.5±0.1	9.93±0.08	7.12±0.08	11.7±0.06
D. Weight of sample in water, g (C-B)	0.9±0.06	0.59±0.1	1.17±0.02	3.9±0.02	0.6±0.02
E. Vol of water displaced, (A-D)	3.3±0.06	2.5±0.1	2.5±0.06	7.2±0.06	3.09±0.02
F. Density, g/cc=A/E	0.7±0.01	0.76±0.03	0.54±0.01	0.44±0.01	1.1±0.01
Mean	0.73±0.02 g/cc		0.54±0.01	0.44±0.01	1.1±0.01

Table 3 — Abrasion resistance (SATRA TM174:2016/ISO 20344(8.3) ISO 4649:2017)

Standard										
Weight, g	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10
Initial	2.12	1.84	2.14	1.94	1.74	1.55	1.35	1.15	2.12	1.84
Final	1.92	1.64	1.94	1.74	1.55	1.351	1.15	0.96	1.92	1.64
Difference	0.19	0.199	0.20	0.19	0.19	0.199	0.2	0.19	0.19	0.199
Test										
Weight, g	T1	T2	T3	T4	T5	T6	T7	T8	T9	T10
Initial	1.25	2.54	1.24	1.34	1.46	1.21	1.42	2.12	1.82	1.24
Final	0.62	1.88	0.6	0.74	0.77	0.48	0.75	1.33	1.23	0.6
Difference	0.63	0.66	0.64	0.6	0.69	0.73	0.67	0.79	0.59	0.64
Abrassion Resistance	427.29	444.05	435.50	427.29	444.05	435.5	427.29	444.05	435.5	427.29

and the mean density value of the top sole layer component is 0.5452g/cc, the middle sole layer component is 0.4464g/cc and the bottom sole layer component is 1.1893g/cc. When the density characteristics of the WLS soles were compared with the other types of athletic shoe soles used in training, it is observed that the density of the WLS sole component is generally higher than the other types of athletic shoes which have been previously tested before[2].

The abrasion test is carried out to check the WLS soles abrasion to determine their material loss on usage over a period of time by carrying out three test samples and the results of the tests are 427.29 mm^3, 444.05 mm^3 and 435.50 mm^3 with a mean value of 435.59 mm^3. There is no significant material loss when compared to the other materials used as shoe soles[17].

The friction test values signify that the WLS sole provides an optimum amount of slip resistance and it is well above the worldwide minimum slip resistance of <0.3. The rubber outsole of the WLS provides excellent adhesion to the floor and hence it resisted much slip.

The compression test clarifies the potential of the WLS sole component to resist deformation on applying load, so the compression test is carried out by engaging a load of 5000N on the sole and the result is in the range of 2.5mm max to 0.54mm min. The results suggest that the WLS sole can potentially be stable till the weight is below the range of 500 kilograms according to the experimental analysis which was carried out.

Table 4 — Slip resistance of footwear and floorings (SATRA TM144 Friction)

Material	Dry	Wet
Unit sole/Whole footwear		
Forward heel slip	0.98	0.46
Backward forepart slip	0.95	0.45
Forward flat slip	0.93	0.47

3.2 Finite element analysis

In this study, the creo software developed a three-dimensional model of the WLS sole. The developed model took into consideration all the geometrical measurements exactly as the shoe model which had been taken for physical analysis and then imported into the ansys workbench 2020 R1 software for the FEA analysis. The WLS sole is comprised of different materials in its construction that are unique to its sports performances, the material properties have to be determined by analyzing using physical tests to quantify young's modulus, poisson's ratio and density. The mesh is generated in WLS sole geometry in order to increase the accuracy of the analysis and the mesh is generated with a tetrahedral geometry and provided

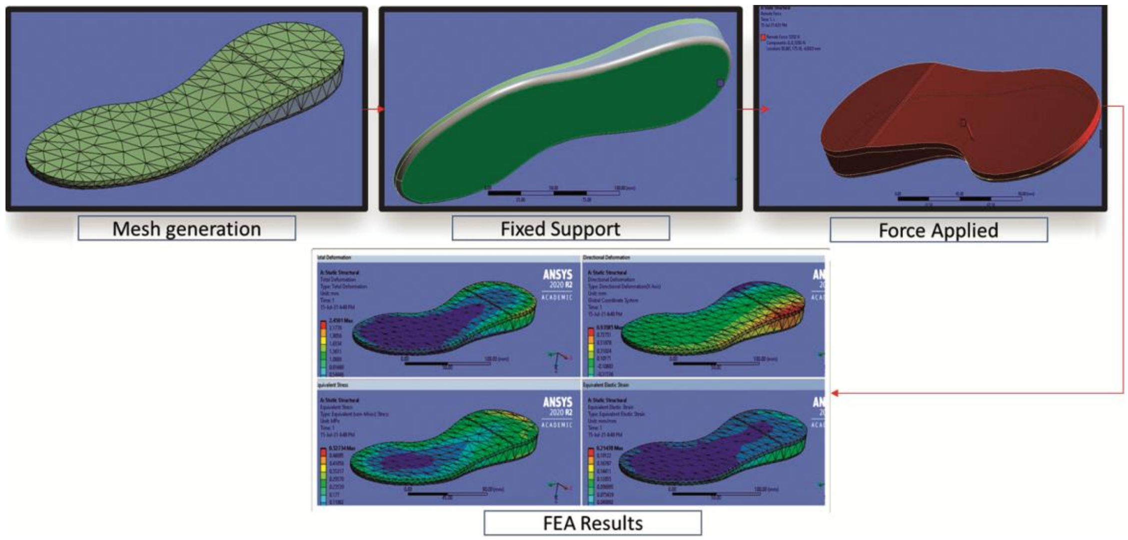

Fig. 2 — FEA results through ANSYS.

a span angle of coarse and its defeature size is kept as default.

The bottom of the sole geometry has been restricted from any movement and is considered as fixed support, the rest of the sole geometry is made to react freely to any forces that can be made acting on it. An analytically stiff surface is used to simulate the floor conditions. The force is allowed to act on the WLS sole geometry from top to bottom direction along the z-axis with a magnitude of 5000N. The analysis is carried out to determine the quantities such as total deformation, directional deformation, equivalent von mises stress and equivalent von mises elastic strain.

For the total deformation test, the maximum value that is derived is 2.45mm max and the minimum value derived is 0.544mm min. The deformation is caused when the sole geometry is subjected to a load of 5000N considerably less and it occurs only in the corner areas of the heel which are susceptible to a mild and gradual deformation on prolonged use under high stress. The majority of the inner surfaces of the sole which will be used to perform the activity of weightlifting don't undertake any deformation. For the directional deformation, the maximum value that has been derived is 0.93mm max and the minimum value derived is -0.31 mm. The directional deformation is caused along the x-axis and is in a medium range along the mid-region of the sole and the deformation is significantly greater along the lateral side of the heel portion when the load is given in the range of 5000 N.

One of the most important features of the proposed model is the ability to predict stress and strain distributions. Figure 2 shows the von mises stress plots with a maximum stress value of 0.52MPa and a minimum stress value of 0.11MPa. At the commencement of the testing, an axial load is exerted on the material surface causing an area of high compressive stress in the WLS sole. With the increase in load, the material progressively softens. The stress intensity developed varies all across the material surface, although it varies the overall von mises stress value all across the material surface which falls in between the maximum and minimum value but the heel area provides a significantly higher von mises stress value compared to the toe regions. Von Mises strain gives out a maximum value of 0.21 mm/mm max and a minimum value of 0.49 mm and is concentrated along the toe region of the geometric model. The strain exerted on the geometric model is fairly less when compared with other parameters when given the same load.

The result of the FEA analysis suggests that the WLS design is just optimal for the activity of weightlifting but there can be room for improvements along the heel region of the shoe which is more susceptible to deformations over a prolonged period of usage.

The potential limitations of this research should be noted. Firstly, for the surface condition, the roughness of the surface is not tested. an analytically stiff surface is applied in the FEA model. Secondly, the loading conditions exerted on the FEA model are the uniform force acting on the top surface of the sole but in reality, more forces will be acting on top of the sole in one or more directions. Further analysis by using the whole unit of a WLS should be performed to validate the numerical outcomes in the future.

4 Conclusion

In the production of WLS, physical analysis followed by FEA is advised. The addition of FEA is a much more desirable way to fabricate a WLS than the conventional procedure. The use of FEA permits the shoe designer and manufacturer to test the ability of their shoe design in a new dimension, such as the advantage of changing the materials instantly to test the desirability of new material on a component and also testing the shoe with new non-conventional testing methods which will lead to the quantification of the shoe design in an overall aspect. It would be most helpful to use the FEA process on a macroscopic level, testing the entire WLS. However, several human elements influence the rating of an entire shoe, including the athlete's age, years of lifting expertise, gender, and Body Mass Index (BMI). There are a variety of FEA packages available for purchase. In general, each FEA brand provides software for performing a variety of tests. Currently, the WLS market does not require a total FEA package. As a result, the commercial ansys workbench can be used to evaluate the WLS as a professional FEA software. The WLS business will experience a variety of repercussions as a result of incorporating this new method of utilizing FEA in conjunction with physical testing in the manufacturing process. Currently, the athletic shoe manufacturer employs several Computer Aided Designing (CAD) packages, none of which are compatible with suppliers or one another. All of the models and testing will be performed in one package using FEA. Another advantage of using FEA is data storage. Each FEA's findings will be recorded and made accessible in the future. Another result of incorporating sophisticated technologies into the shoe component manufacturing process is an increase in the number of shoes manufactured each year. With more shoes being created, a WLS business that uses this method will have a better chance of gaining market share. The company will earn market share as a result of its ability to quickly reproduce concepts from other companies and share in the specific market for that particular shoe. Finally, when users gain experience with utilizing this method to create WLS, their knowledge will grow, and a way for testing the complete shoe more precisely may emerge in the future.

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