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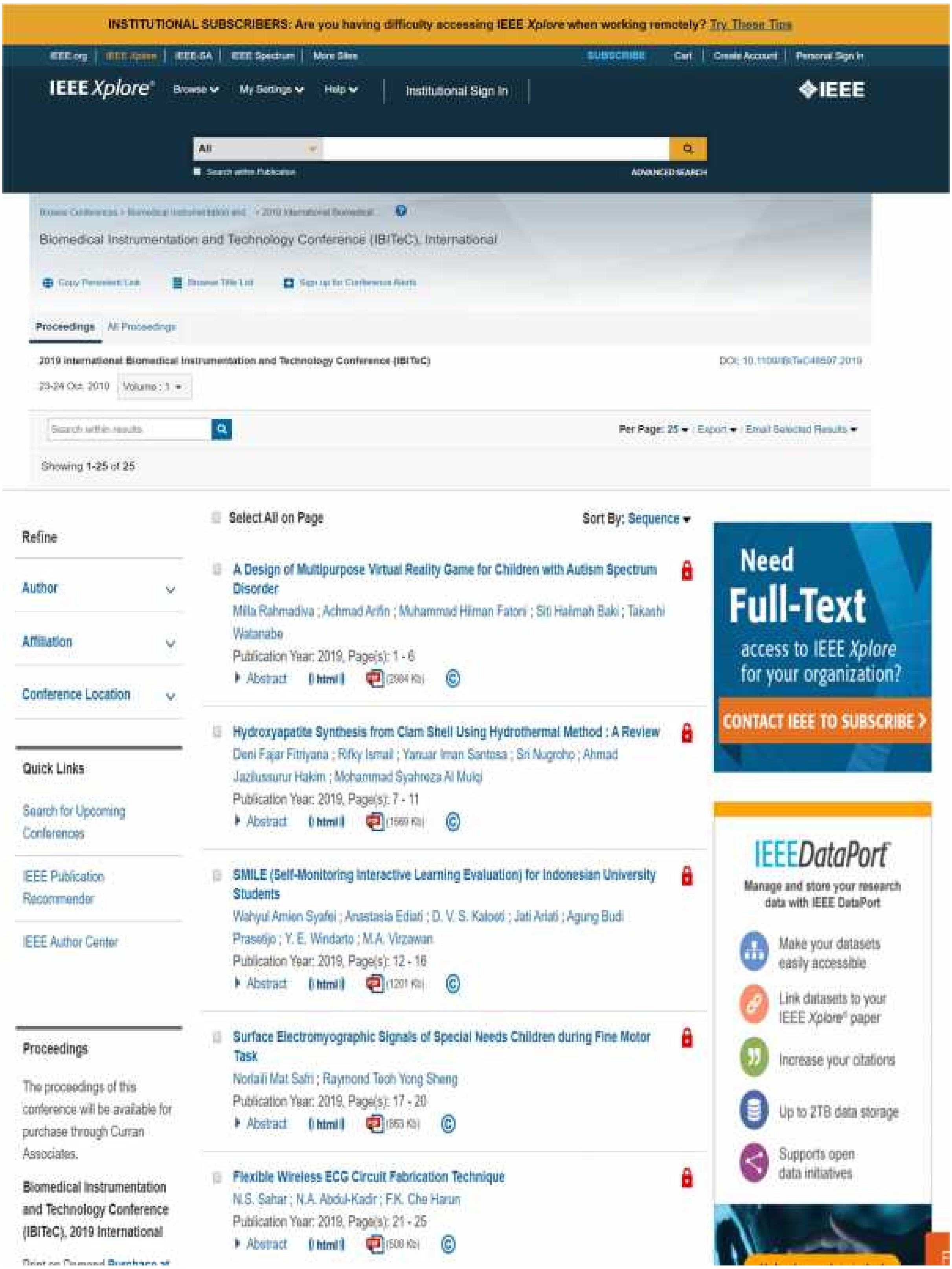
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Optimization of Mechanical Parameters on Outsole Shoes Orthotic Comfort Using Finite Element Analysis

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Abstract:
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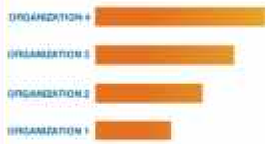

Optimization of Mechanical Parameters on Outsole Shoes Orthotic Comfort Using Finite Element Analysis

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***Abstract*—The shoes selection as the right footwear is very related to the feet comfort, especially in the selection of shoe materials. The shoe consists of three parts: insole, outsole, and upper shoe. The right outsole material will affect the comfort of feet during activity. This paper demonstrates a mechanical testing method on optimization of outsole material based on computer aided engineering (CAE). The outsole design on milutes diabetic patients in previous studies used as the basic design for mechanical testing at CAE. Three types of mechanical testing on Abaqus software 2016: bending, torsion, and plantar plessure used in this paper to determine the optimal outsole material as outsole material shoe orthotik. The test results showed that the material EVA rubber type declared with optimum characteristics of the von mises stress 0.0013 MPa, maximum principal stress 0.0036 MPa and features shock absorption of 5.01562 mJ. This data can served as a basic reference for the process of manufacturing the outsole of shoe on CNC machines.**

Keywords—comfort, outsole shoe, CAE, FEA, Abaqus 2016

I. Introduction

Footwear has an important role to protect the feet, especially on bottom part, so that they are not injured when facing diverse environmental conditions. Footwear also functions as a supporting appearance to enhance the performance. The main factors that need to be considered in choosing footwear are comfort, where these factor are a combination of physical processes, physiological and psychological aspects [1-4].

Wrong choice of footwear is bad for our health, especially foot health. When someone uses wrong and not needed footwear (according to foot geometry and material), it can increases the risk of injury. In addition, it can also cause various kinds of diseases such as inflammation of the tissues in the lower legs, hardening of the skin, and even pain in the lower back. Therefore, it is highly recommended to choose footwear that suits the needs and shape of the user's feet.

Shoes and sandals have been made in several variants based on aspects of the needs and shape of human feet. Shoes consist of three parts, namely upper, insole and outsole [5, 6]. These parts have their respective function. The upper is a foot cover that protects it from outside danger. Insole has a function to maintain balance in body posture. While the outsole functions to grip the surface of the ground and prevent damage to the midsole as reported [7, 8]. Outsole or known as shoe sole, is the bottom of the shoe that is directly in contact with the ground. In order to function properly when used, outsole as explained [7, 8] is generally made of rubber material. This material type, generally has ability to grip properly, but has different characteristics. Polyurethane has better machineability but harder so the assembly process with upper will take longer [9, 10]. EVA rubber type also can be used as an outsole with softer characteristics which has an impact on the machineability is not good, but it easier to sew with the upper so it can be processed faster [6, 8].

The use of these two material types as an outsole in the orthotic shoe manufacturing process has been done by several researchers, but most only discussed is about materials manufacturing aspects in CNC machines and rarely discuss about aspects of outsole designs optimization in both materials [8, 9, 10]. In fact, according to previous research, the type of material and footwear's geometry is very influential on the characteristics of footwear deformation despite only discussing on the standard outsole form [11]. This means that these two factors are significant in choosing comfortable footwear.

Finite element analysis (FEA) is one of the numerical methods that often used by Computer Aided Engineering (CAE) engineers for multi-dimensional and asymmetric problem solving to estimate an optimal solution before the manufacturing process on CNC or 3D printing machines [9, 12, 13]. FEA tool also can be used to determine design optimization of a product or component at design or development stage of innovative designs, especially based on reverse innovative design (RID) such as developed [14, 15].

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The definition of comfort is clearly stated [1-3, 16] as "lack of pain" and "a happy feeling of health and well-being" needed by patient and this is situationally (against reactions made by patients) which consists of physiological, psychological and physical aspects. The skeleton parts of the foot defined in a simple form built from other softer tissues. Feet are parts of the human body that located at the far end and significantly accept all loads. Overloading on feet can be a cause of discomfort, pain and actual injury to human's body part. Interaction or direct mechanical contact between feet and soil can occur directly or use footwear consisting of one or more parts of footwear. Here, the bottom of the foot will receive a full or significant load through contact mechanics on the plantar side of the foot with the soil.

The definition of mechanical comfort [1, 17-19] can be divided into two, namely plantar and dorsal mechanical comfort. Plantar mechanics of standing and gait are very important for the rough mechanics of the body and are discussed in several works.

In detail of previous research [2, 19, 20], has already stated that the most important problem in the plantar mechanics is the ground reaction force to the action of the weight as shown in Fig. 1. On this picture, it looks that normal vector (the influence of force that occurs against the surface of the foot plantar) of this force is greater than the vector of transverse and lengthwise.

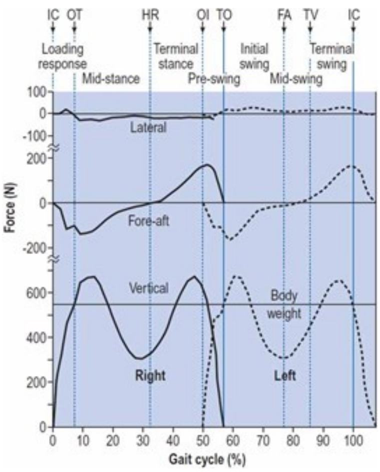

Fig. 1. Force during gait (IC = Initial Contact, OT = Opposite Toe Off, HR = Heel Rise, OI = Opposite Initial Contact, TO = Toe off, FA = Feet Adjacent, TV = Tibia vertical) [1]

The use of FEA modeling and extensive to do the actual measurement, calculation or estimation of normal plantar force has also been done by some researchers [1, 9, 12, 21, 22, 24]. The effects of normal plantar force happen at the level of discomfort, pain and injury are significant when sliding force vector quantity resulting from mechanical contact is limited. Even though in the end this will cause to happen tissue damage in the feet.

This paper discusses the application of FEA to evaluate performance in terms of comfort outsole mechanics based on simulation testing of bending, torsion, and plantar pressure (contact mechanics between the legs with the outsole). The simulation stage is based on FEA with the help of CAE software from the shoe structure which is treated according to their performance restrictions and combined with a simpler human foot detail Biomodel.

II. MATERIAL AND METHODOLOGY

One DM patient is defined in this paper for the manufacture process of insole and outsole using the RID method [8]. 3D outsole design obtained from the insole of high risk scale diabetic patient foot on Fig. 2 [10], actually still needs to be simplified on the rocker arm [24, 25]. This simplification is being done by researchers according to needs and without compromising the essence of design [12]. The simplification results can be presented in Fig. 3.

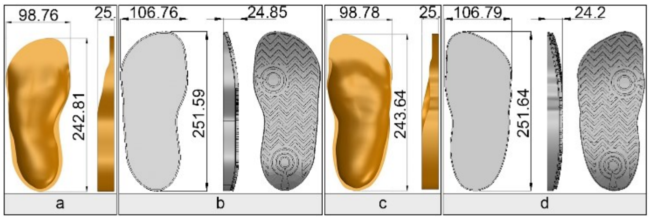

Fig. 2. The 3D (a) left insole, (b) left outsole, (c) right insole, (d) right outsole [8]

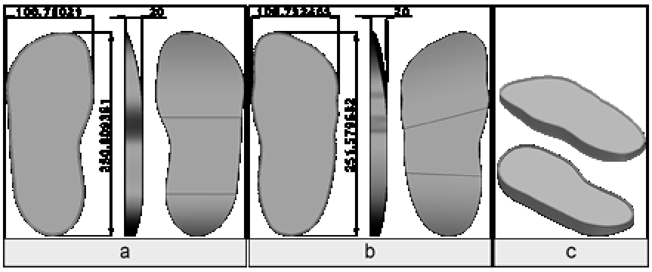

Fig. 3. Revised 3D outsole shoes orthotic for diabetic patients: (a) right foot; (b) left foot; (c) isometric view [27]

FEA process with the CAE software (Abaqus 2016) in this paper is done with three types of testing (bending, torsion, and plantar pressure) based on six types of material data (PU, EVA A, EVA D, EVA E, ABS, and PVC). Outsole material data that will be performed contact mechanics can be presented in Table I. Based on previous research [1, 11], testing can take one of the right or left leg samples as it is essentially for material analysis to require only basic shapes. The stage of contact mechanics testing with Abaqus 2016 is based on the order of modules in the software and presented in Fig. 4. The parameters of the three types of tests are set to resemble previous research [1] But some adjustments were made to face the new test conditions.

Bending testing on this research using 2 boundary conditions, there are the front bottom of 3D outsole is set as fixed area along 26% of the total length of the outsole, then the back is bent upward until it makes a maximum angle of 55°. As for the torsion testing, the heel area of the 3D outsole is twisted by 15 ° and fixed the same area on the bending test. Furthermore, the testing of plantar pressure, all over the bottom surface of the 3D outsole is used as a fix area by providing a load 340 kN with 3D model foot form. The size of 3D outsole mesh in this study is 7 which more thorough than the previous research is 10, while the 3D mesh size of the foot model is 2. Because of the difference in the mesh size, when the assembly process uses the dependent instance type.

The results of three tests from this research in the form of fringe diagrams presented in Fig. 5 - Fig. 7. The data from the chart included in Table II - Table IV for easy benchmarking of material characteristics. In addition, testing bending and torsion also produces stress-strain curve, whereas the testing of plantar pressure generating reaction force - displacement, reaction force - pressure stress, and strain energy pertime period curves.

TABLE I. MATERIAL DATA FOR TEST

Material	Young's Modulus (GPa)	Poisson's Ratio	Mass Density (kg/m3)	Description
EVA A	0.0094	0.49	80.8310	
EVA D	0.01464	0.49	138.3024	
EVA E	0.01035859	0.49	181.9600	
PU	2.07	0.3	1240	
ABS	2.9	0.40	1015	
PVC	4.14	0.42	1400	
Foot	937	0	1.15	Indenter
Stainless Steel	200	0.27	7800	Indenter

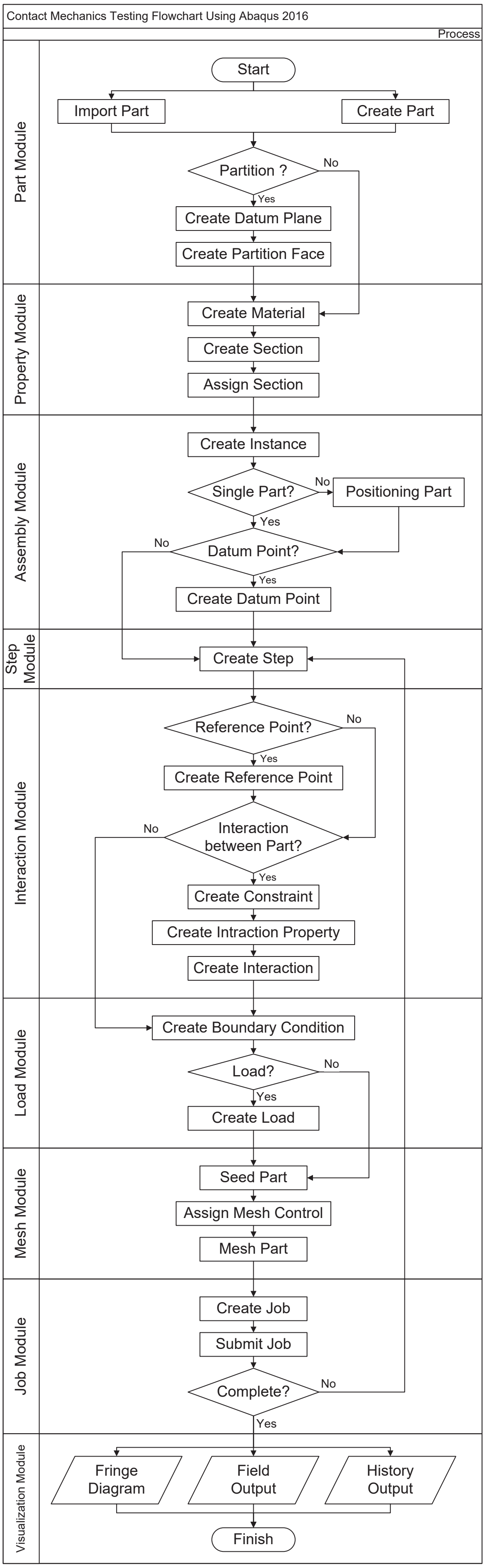

Fig. 4. Contact Mechanics Testing Using Abaqus 2016

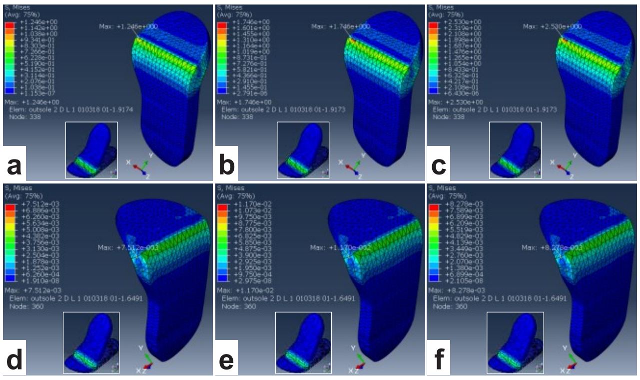

Fig. 5. Fringe diagrams of von mises stress for: (a) PU, (b) ABS, (c) PVC, (d) EVA A, (e) EVA D, (f) EVA E on bending test [27]

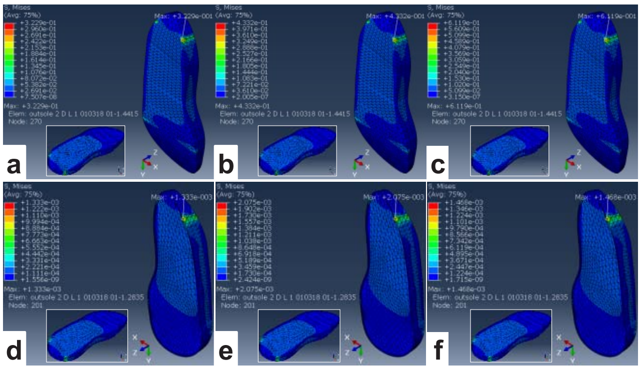

Fig. 6. Fringe diagrams of von mises stress for: (a) PU, (b) ABS, (c) PVC, (d) EVA A, (e) EVA D, (f) EVA E on torsion test [27]

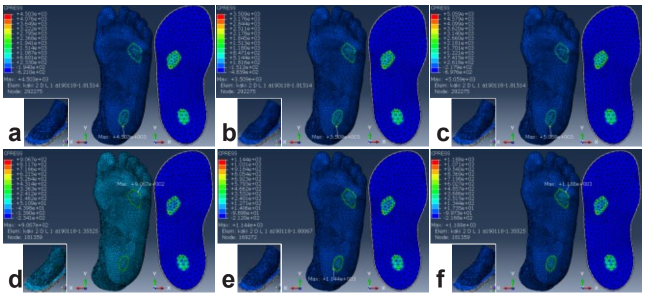

Fig. 7. Distribution of plantar contact pressure for: (a) PU, (b) ABS, (c) PVC, (d) EVA A, (e) EVA D, (f) EVA E [27]

TABLE II. STRAIN-STRESS FROM BENDING TEST

Material	Stress		Logarithmic Strain
	Von Mises (MPa)	*Max. Prin. Abs. (MPa)*	*Max. Prin. Abs.*
PU	1.24552	1.13783	0.455304
EVA A	0.00751238	0.0120893	0.426745
EVA D	0.0117001	0.0188285	0.426745
EVA E	0.00827848	0.0133222	0.426745
ABS	1.74625	1.84954	0.442026
PVC	2.53001	2.80579	0.442145

TABLE III. STRAIN-STRESS FROM TORSION TEST

Material	Stress		Logarithmic Strain
	Von Mises (MPa)	*Max. Prin. Abs. (MPa)*	*Max. Prin. Abs.*
PU	0.322894	0.355109	0.202296
EVA A	0.00133259	0.00366398	0.164172
EVA D	0.00207545	0.00570646	0.164172
EVA E	0.00146849	0.00403763	0.164172
ABS	0.433237	0.711036	0.196587
PVC	0.611856	1.06547	0.193729

TABLE IV. PLANTAR CONTACT PRESSURE, REACTION FORCE, AND STRAIN ENERGY FROM PLANTAR PRESSURE TEST

Material	Plantar Contact Pressure (MPa)	Reaction Force (x10^{-8}kN)	Strain Energy
PU	4503.39	1.2489	45.7867
EVA A	906.725	0.995418	5.01562
EVA D	1144.48	1.11817	8.76533
EVA E	1188.1	0.602554	10.4532
ABS	3509.23	4.94235	47.3498
PVC	5058.73	5.85597	54.0731

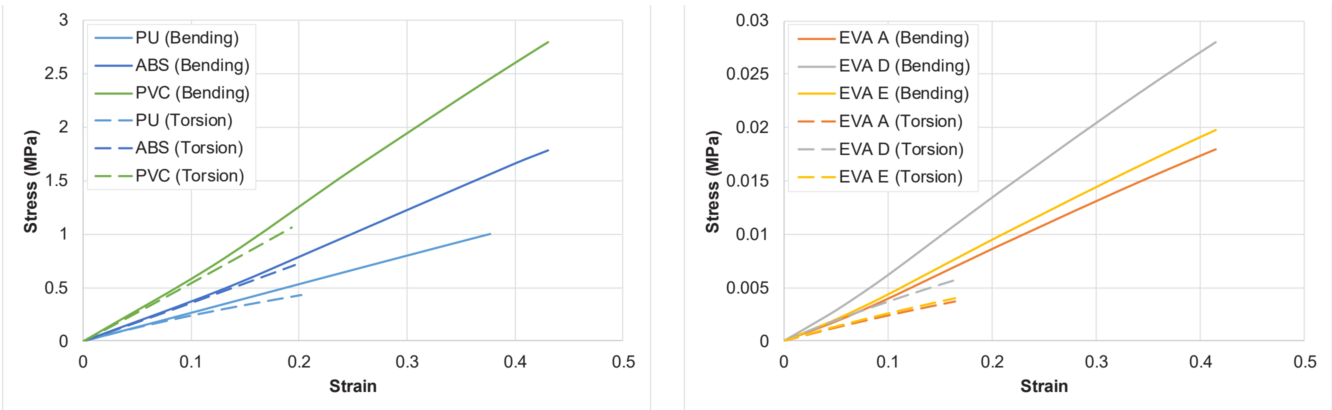

Fig. 8. Stress-Strain Curve from Bending and Torsion Test, Material : PU, ABS, and PVC; Type A, D, and E, EVA rubber [27]

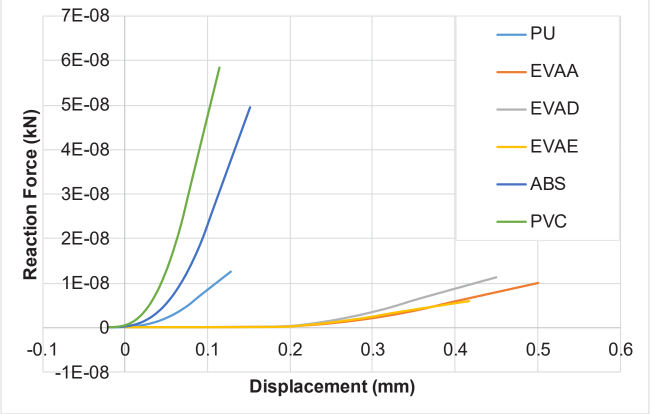

Fig. 9. Reaction Force – Displacement curve from plantar pressure test [27]

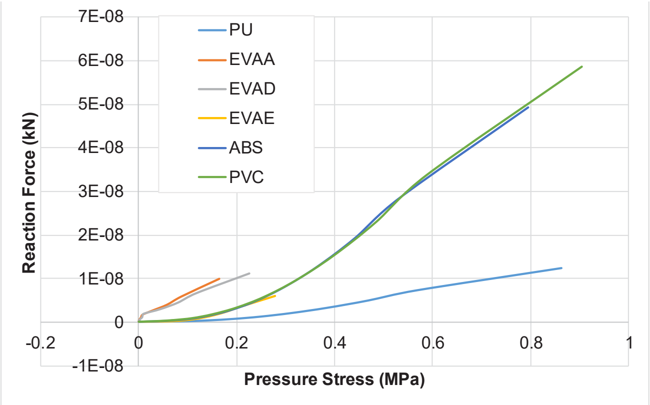

Fig. 10. Reaction Force – Pressure Stress curve from plantar pressure test [27]

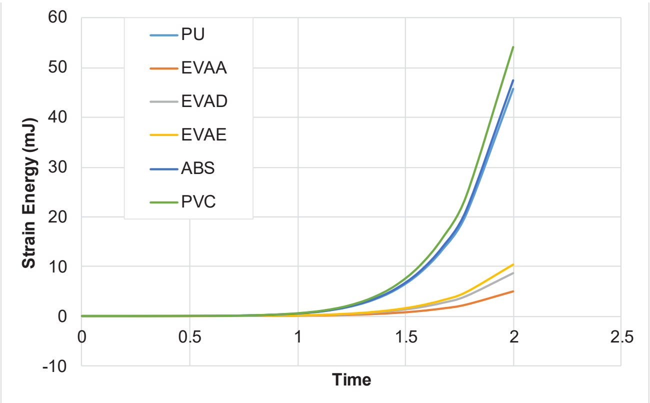

Fig. 11. Strain Energy pertime periode curve from plantar pressure test [27]

III. Result and Discussion

Simplification and improvements can be made in 3D design (Fig. 2 – Fig. 3) according to the requirement and without compromising its essence [12]. This is done because of the required regularity of mesh in 3D design so that it can be solved by FEA. Mesh size variation that is too large and not neat will affect simulated result data is less valid. It is because the calculation on each mesh is uneven. On the other hand, it will cause the analysis process longer and make excessive burden on the hardware.

As an initial step in testing, 3D outsole design that is fixed exported with STEP (STandard for the Exchange of Product) format and then imported into the Abaqus 2016 through part module. The same thing is done on the 3D model patient foot who already scanned in plantar pressure testing. The STEP format is selected because it is a high-profile replacement for format IGES (Initial Graphics Exchange Specification) that can be imported into all programs CAD, CAM, and CAE globally [26].

Fringe diagram of von mises stress (Fig. 5 – Fig. 6) shows the area of the occurrence of the failure that is marked with the color code. Red color indicates the critical area. According to von mises stress value in Table II and Table III, the failure rate is the largest PVC material with 2.53001 MPa on testing bending and torsion test at 0.611856 MPa. Meanwhile, EVA rubber type A has the smallest value with 0.00751238 MPa on testing bending and torsion test at 0.00133259 MPa. Stress-strain curve in Fig. 8, on all types of materials have a constant ride pattern, which means the bigger the change form the great force of working. From the curve can be seen that the PVC material is stated as the most rigid while the EVA rubber type with the most flexible. Flexibility indicates the ability to follow foot movements during activities.

Interaction in the case of contact mechanics between legs with 3D outsole is displayed in the distribution of plantar contact pressure (Fig. 7) with the red color code indicating the largest pressure area. According to Table IV, it is known that the combination of the foot with PVC material has the highest plantar contact pressure value of 5058.73 MPa or 5.6 times greater than EVA rubber type A material that only 906,725 MPa. Displacement of the legs will cause a reaction force on the outsole depicted in Fig. 9. Then, the reaction force is again causing pressure stress on the legs that are seen in Fig. 10. Outsole with PVC material has the biggest reaction force that is 5.85597×10^{-8} kN at displacement foot 0.114947 mm and resulted in a pressure stress of 0.903628 MPa. It can be interpreted that PVC material will be difficult to follow the contour of the foot because it has a strong tendency to return to the initial form when stepped on. In contrast, the EVA rubber type A material is easier to follow the contour of the foot because of its smallest reaction force of 9.95418×10^{-9} kN at displacement foot 0.50137 mm and resulted in pressure stress of 0.164489 MPa on the foot.

The curve of strain energy as a parameter to represent the shock absorption that is the ability of the material to absorb energy shock when the standing position [1]. The greater the energy that occurs may imply that worse shock absorption. Based on this research, EVA rubber type is declared to have be the best shock absorption because it has smallest energy strain that is 5.01562 mJ.

IV. Conclusion

Based on the analysis results, it is concluded that the comfort of foot mechanics can be reviewed by testing bending, torsion, and plantar pressure on the design of 3D outsole to obtain mechanical characteristics of each material such as stress, strain, and Shock absorption. Material EVA Rubber Type A is expressed as material that has the characteristics of qualified to be expressed optimally in the comfort of mechanical. It is able to follow the movement of the foot when worn and have the best shock absorption.

Factors affecting the mechanical comfort based on Finite Element Analysis (FEA) are stress, strain, and shock absorption. Initial data in the form of the basic properties of the material as the mass density, poisson's ratio, and young's modulus is required to get these factors. The optimal 3D outsole design also affects FEA because of the calculated value of mechanical comfort factor based on the element and the point in the design.

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