ITARS 2022

Vol 2, No.3 (2022)

International TVET Academic and Research Symposium ITARS (2022)

Excellence in TVET and Entrepreneurship

Organiser:

PUSPANITA CAWANGAN KECIL JPPKK

Co-organiser and Publisher:

PERSATUAN KEDOKTORAN TEKNIKAL MALAYSIA

MALAYSIAN TECHNICAL DOCTORATE ASSOCIATION

e ISBN 978-967-18231-1-8

9 789671 823118

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ISBN 978-967-18231-1-8 (e-book)
Front cover image by PKTM
e-book design by PKTM

First e-book edition July 2020
Second e-book edition April 2022

Persatuan Kedoktoran Teknikal Malaysia (PKTM)
No 64, Persiaran Wira Jaya Barat 40,
Taman Ipoh Jaya Timur 1, 31350 Ipoh,
Perak.
http://www.pktm.org

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FINITE ELEMENT MODELLING AND ANALYSIS OF ANKLE FOOT ORTHOSIS WITH DIFFERENT THICKNESS

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Abstract
This study provides a new design for a revolutionary orthosis made of polyethylene, as well as simulation findings (CFRP). Ankle-foot orthoses (AFOs) are commonly used to help ambulatory human with neurological disorders like cerebral palsy or spina bifida to improve their gait function. Ankle foot orthoses (AFOs) also commonly used for those who had a stroke, or a spinal cord injury have problems in their lower limbs, which causes them to walk abnormally. Now day, most popular and faster manufacturing development in this area are using the cad design and analysis software such as ANSYS to suit. As a result, the development of a supporting device for the treatment of ankle abnormalities is required. The orthosis for ankle-foot is intended to enable in the recovery of patients suffering from foot drop. The backside of the calf is supported by the form of the orthosis. It aids in the proper functioning of the gait cycle. The purpose of this study to develop three different pattern design holes by using CATIA which is design 1, design 2 and design 3 to find out the structural characteristics by using polyethylene material. Besides, three different thickness which is 4.7mm, 5.2mm and 5.7mm was been used to analysis by using static analysis software ANSYS. In this research, two alternative AFO models, articulated and non-articulated, are compared. The findings for equivalent Von-Mises stress, total deformation and minimum safety factor based on the thickness are observed and analysed using the ANSYS software. Several design, as well as their mixtures, are used in the numerical analysis. This study presents ankle foot orthotic (AFO) design principles based on selected design to construct appropriate AFOs and the optimum value of analysis is design 3 with thickness 4.7mm which is the value of the maximum von misses stress is 462.63 MPa it mean this design 3 able to accommodate large forces and the total deformation value is 16.333 mm shows that design 3 is not easily cracked due to high durability and the safety factor value is 0.054039 that show that design 3 is safe to being used because it safe factor value is small.
Keywords: Ankle-foot orthosis, Thickness, Finite-element analysis, ANSYS, CATIA, Pattern design holes

1. Introduction
The orthosis is an artificial product that aids externally in supporting the limbs or spine and preventing the patient from making needless movements. The difference between an orthosis and a prosthesis is that a prosthesis entirely replaces a damaged or missing bodily component. On the other hand, the orthosis aids in the recovery of injured limbs and the strengthening of their correct functionality. However, in terms of distinct roles the orthosis and prosthesis have a lot in common. Both of the products are designed to support a specific body part in order to improve function and mobility. Furthermore, both have common design characteristics such as lightweight, high stiffness, high compressive and tensile strength is required to sustain shear stress to endure the high impact and cheap in term of cost. The ankle-foot orthosis is a device that is used to manage and support the ankle mobility during foot drop. Drop foot occurs when the force component of the bottom leg muscles is anatomically paralysed or weak. Foot drop refers to the inability to lift the front half of the leg, which causes discomfort while walking. Walking problems might endure for a short time or for a long period, depending on a variety of variables such as a spinal cord, nerve or muscle condition (Mary et al., 2018). The ankle-foot orthosis is a device that aids in the treatment of a disrupted cycle of gait caused by a foot drop.
The foot strike tends to happen whenever the foot first contacts the ground and then continues to leave the ground. Both of these events are part of the normal gait cycle, which leads to the swinging stage, once the foot moves forward and does not touch the ground for a period of time duration. Due to the foot's inability to hold the weight of the body throughout the transitions between periods, the foot will touch against the ground instead of just hitting the foot part during the foot striking cycle, putting extra pressure on the leg. In addition, the knee cannot bend dorsally because it will be excessively flexed throughout the swing phase. High stepping gait is the term for this type of movement. Foot drop occurs when the ankle joint fails to dorsiflex sufficiently, resulting in the foot not reaching the ground during the swing phase of the gait cycle. The main ankle dorsiflexor muscle is the tables anterior (TA), and weakness in this muscle can cause the foot to snag on the ground. The TA has been discovered to enhance appropriate foot placement during heel strike during normal human locomotion, and it will be the major muscle that the exposit in this analysis aims to assist. Muscle weakness can occur as a result of nerve

damage, stroke, muscular atrophy or disease. A common type of rehabilitation is gait training, which targets to recover a natural gait cycle. However, it is believed that approximately 20% of persons undergoing gait therapy suffer from foot drop, which can make it difficult to regain a normal gait (Schifino et al., 2021).

2. Literature Review

Since many years, Ankle-Foot Orthoses (AFOs) have been widely utilised. Orthoses are increasingly being used as a substitute for casts. The creation of orthoses that combine the diverse functions improves ankle control during activities such as standing and walking. AFOs have been implemented to enhance walking speed, energy cost, weight bearing on the affected leg, posture and the double stance time in movement, as well as stability during balance (Kirtas et al., 2021). The orthosis device helps the process of anatomical reduction by ensuring that the fracture bone may heal by maintaining the position of the fracture bone via the installation of orthosis at the human's limb. However, the use of contemporary conventional casts frequently resulted within a few difficulties during the rehabilitation process. Micromovement integrity at the fracture site is one of the elements that could lead to quicker bone healing. Installing stable fixation devices could allow for optimal micromovement. As a result, the orthosis should be able to support walking action during the rehabilitation period, which primarily comprises of two stages in the gait cycle which is swing and stance(Amirul et al., 2021).

AFO manufacture is a complex procedure. AFO manufacture is a complex procedure. During the planning and engineering design process, there are several elements to consider (Kwan, 2021). The duration of the process is determined by the type of orthosis as well as the production method. There are two types of methods for producing AFOs such as by traditional production using imprints or moulage, thermoplastic polymer materials, and additive manufacturing by utilising 3D printing (Methodology, 2021). Specific design aspects and selection of materials were explored to reduce the impact of stresses on the structure while keeping the overall weight of the structure to the recommended minimum for an effective ankle support (Sustainability et al., 2021). Ankle-foot orthoses (AFOs) are product that offer ambulatory individuals with neurodegenerative disorders like cerebral palsy or spina bifida with angular motion control and joint stabilisation in the lower limb. Metal, leather, and plastics type such as polypropylene (PP), acrylic, polyethylene (PE) and nylon are used to make AFOs. Plastic AFOs are preferable since they are lighter, more aesthetically pleasing, and provide additional support to compensate for ankle weakness. Abnormal ankle plantar flex is greatly reduced by solid AFOs with a rigid body structure (Kemal & Ziya, 2021).

The strength study was carried out using the Finite Element Method, a computational method that allows complex design, time-consuming mathematical analysis, and difficulties without no analytical solutions to be solved. It is feasible to alter the ideal circumstances by performing FEM analysis early in the design process. Simulation tests are used to determine the proper material and create the ideal geometry. FEM may be used to determine the degree of stress, which can then be utilised to define the risk of failure. This reduces costs and time by avoiding the creation of orthotic prototype that aren't suited. As a consequence, the data of the FEM analysis can be quite useful in the design of AFOs (Peng et al., 2021). The mechanism was applied to a nonlinear computational analysis to evaluate the effect of stresses on the AFO structural components based on the maximum stress conditions occurring while normal walking related to kinetic forces energy on the ankle joint (Sustainability et al., 2021). This is can be achieved via discretization and the subsequent determination of differential or algebraic equations. In the negative Z and Y directions, the force is applied. The user's weight affects the force in the Z direction. During walking, there is a force in the Y direction (Liu & Gao, 2021).

During design of the 3D model, the thickness and trim edges were also factored. To analyse the influence on stress and deflection, the AFO was simulated having various materials and thicknesses. The mesh size is set at 2.0mm to guarantee that the simulation results are valid, and the number of elements and nodes is determined by the AFO thickness. As the thickness increases, the maximum tension and displacement decrease. With the exception of 5mm thickness, which has a 19% weight reduction, the thickness 3mm and 4mm experience a 26 percent weight decrease. The maximum stress is reduced by 8% in the 3mm thickness type. After geometry improvement, the 3mm and 4mm models are the optimal thicknesses (Tan, 2021). Furthermore, according to a prior study the AFO is composed of Polypropylene material with values of thicknesses of 3 mm give a better result in term of safety factor which is below than 3 and less deformation occur (Yadav, 2021). The static analysis revealed that the polypropylene AFO produced reduced stress, superior results, low deformation, and a high factor of safety (Kubasad et al., 2020).

3. Methodology

3.1 Materials and Methods

The ankle foot orthosis is fabricated using the vacuum moulding technique from a polypropylene with 3 mm thickness by an experienced orthoptist. In this method, the polypropylene sheet is cooked in an oven to its softening temperature. After that, the polypropylene sheet is wrapped around a positive mould that was created from a negative mould. Moulds were created in the study based on the lower limb of a patient with spina bifida, a neurological disorder caused by a spinal cord abnormality that can cause mild to severe physical and intellectual disability. The ankle foot orthosis was initially trimmed to remove the normal trimline border, resulting in a hard solid ankle foot orthosis. The ankle foot orthosis was then cut beyond the usual trimline to allow for flexibility when walking.

3.2 Geometrical Model

The ankle foot orthosis model was being generated in the CATIA to transform the mesh into certain boundary condition with three different designs but with same dimension. Since the model geometry is so complicated, we used a simplified geometry based on measurable data such foot support length and width, leg height and back curvature, ankle lateral and medial, curvatures and medial plantar arch. The model was extracted as the STEP file in the Solid Work and Inventor then imported into the Ansys Workbench for design analysis. The surface for the ankle foot orthosis can be improved by plotted some point on it. Then the thickness used by the three different design of the ankle foot orthosis was different which is used to compare the better result. The figure 1, 2 and figure 3 below show the three different design of the ankle foot orthosis with different hole design and shape at the back of the calf muscle strain that give the different result for the safety factor, total deformation and von-misses stress value.

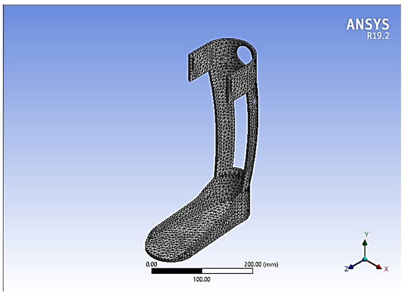


Figure 1: Model design 1

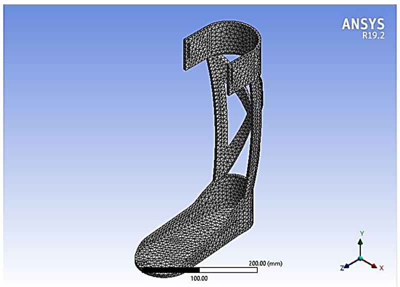


Figure 2: Model design 2

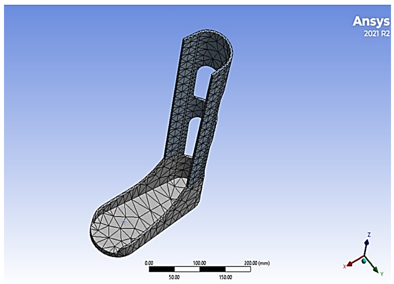


Figure 3: Model design 3

3.3 Material Properties

Based on the project used synthetic material such as polyethylene to test on the ankle foot orthosis model to get a suitable and the best material that can be applied to the ankle foot orthosis model. Table 1 shows polyethylene material properties that being applied on the ankle foot orthosis model with value of Tensile Yield Strength is 25 MPa, Tensile ultimate Strength is 33 MPa, Shear Modulus is 387.32 MPa, Poisson Ratio is 0.42, Bulk Modulus is 2291.7 MPa and Young's Modulus is 1100 MPa, Compressive Yield Strength and Compressive Ultimate Strength is 0 MPa.

Table 1: Polyethylene properties

Density	9.5e-007 kg $mm^{-3}mm^{-3}$
Coefficient of Thermal Expansion	2.3e-004$C^{-1}C^{-1}$
Specific Heat	2.3E+006 mJ $kg^{-1}C^{-1}kg^{-1}C^{-1}$
Thermal Conductivity	2.8e-004 W $mm^{-1}C^{-1}mm^{-1}C^{-1}$
Tensile Yield Strength	25 MPa
Tensile Ultimate Strength	33 MPa
Young's Modulus	1100 MPa
Poisson's Ratio	0.42
Bulk Modulus	2291.7 MPa
Shear Modulus	387.32 MPa

3.4 Element Type

Meshing is an essential part in the Finite Element Analysis process to make the model less complex and it uses an automated meshing technique to make it easier to observe model structure without having look at the pre-stress at the object model. Based on this project, the process to do the meshing is an automated meshing process to observe the stress that distributed on the surface object model. This process can improve the analysis based on the material used and easier to get the data and it more save in many terms such as times to do the analysis. The Figure 4 below show the ankle foot orthosis model that already been meshed, and the Table 2 was show the result for the nodes and element exist in the ankle foot orthosis and Table 3 shows the element quality.

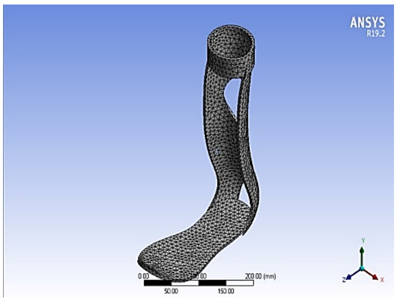


Figure a: Model design 1

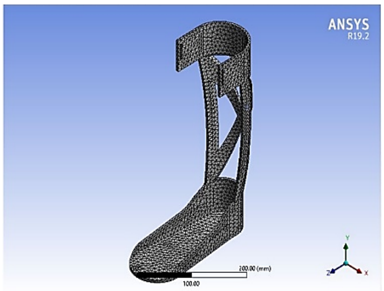


Figure b: Model design 2

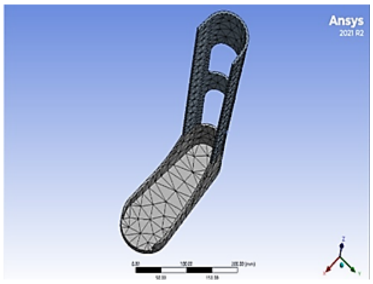


Figure c: Model design 3

Figure 4: Meshed ankle foot orthosis model

The result from the ankle foot orthosis after meshed show the model contains 20663 nodes and 9973 elements for model design 1 design. The number of nodes is 19418 and elements number is 9234 is the result for model design 2 . Lastly, the result meshed for nodes and element number by model design 3 is 5299 for nodes number and 2333 for elements number.

Table 2: Nodes and elements results for ankle foot orthosis

Design	Nodes	Elements
Design 1	20663	9973
Design 2	19418	9234
Design 3	5299	2333

The Table 3 below shows the value minimum and maximum for the element quality for model design 3. In Figure 5 after meshing process done. The minimum value for the element quality model is 0.1094 while the maximum value is 0.8584. Next, the average value is summation of minimum and maximum value by dividing two values with 2 to get the standard deviation value. The average value for this model is 0.42466 while the standard deviation value for this model in Figure 5 is 0.11415.

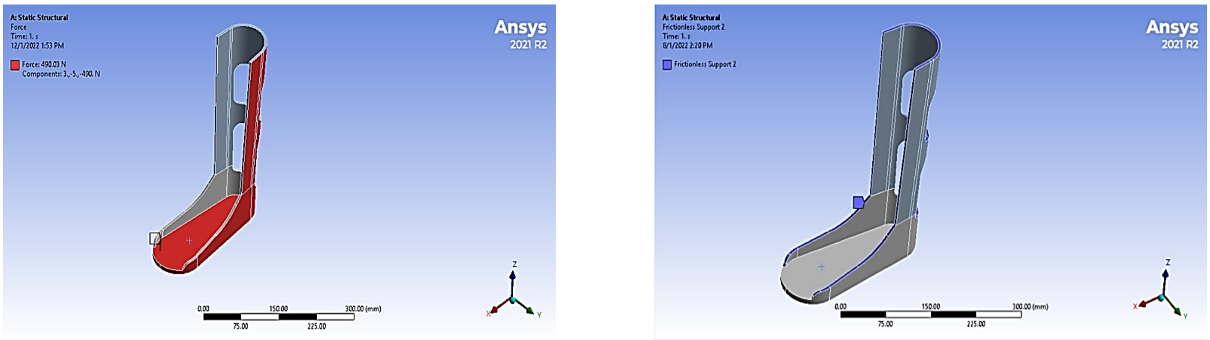
Table 3: Element Quality

Min	0.1094
Max	0.8584
Average	0.42466
Standard Deviation	0.11415

3.5 Boundary Condition and Loading Method

The ankle foot orthosis body contain force on the lower span of ankle foot orthosis model. While for the fix support was applied at each edge surface of the ankle foot orthosis model. The forced has been applied at the certain surface part which is the inner surface of the footprint and the outer surface of the foot limb of spina bifida of the ankle foot orthosis model with value of 490.03 N. The applied force values are 3 N in X-direction, 5 N in negative Y-direction, and 490 N in negative Z-direction follow as the paper stated. Figure 5, show the force that have been applied at the lower spans view of foot orthosis and the fixed support was applied at edge for the ankle model.

Figure 5: The force and fixed support applied



4. Finding and Analysis

4.1 FEM Verification

The ankle foot orthosis FE model was verified by comparing total deformation and equivalent (von-mises) stress to previous finite element analysis for ankle-foot orthosis research. The percentage difference in average total deformation and equivalent (von –mises) stress between the current and previous studies was 97 and 61 percent, respectively due of the design and materials used because there is a significant difference between this study and previous studies. According to prior study, 61 % say they would be more willing to wear their orthotics if they had more shoe alternatives, while 82% say choosing shoes that suit orthotics is difficult (Gegen et al., 2020).

Next, based on this project some methods needed to use for verification of the finite element model of the ankle foot orthosis. There are two methods can be used for verification which is error plot method and mesh convergence test. The verification of the finite element model of the ankle foot orthosis socket can be identified by using the checking error plot method because error plot would verify for stress continuity so there should be no sudden stress alteration among the surrounding mesh. Figure 6 the ankle foot orthosis which is approximately 12.028 mJ for maximum while for minimum is 6.098-13 mJ. This result showed the stress for design 3 of the ankle foot orthosis are continuous. In addition, mesh convergence test also can be used to validate the finite element simulation findings. When the mesh density is increased the results must be more precise.

Since we refined the mesh so the results must then converge to a single value. To run this test had three important step that need to follow to get the result which is the setting convergence requirements need to be set correctly and need to check the outcomes and error plot to verify the finite element model. The results of mesh convergence would be displayed in Figure 7 and Table 4. Based on Figure 7 and Table 4, the mesh convergence analysis indicated that the maximum for equivalent stress (Von Misses) stress located at the orthosis for 4.7 mm thickness was approximately 13554 MPa. The global element size for 4.7 mm thickness can directly lead the value of 2389 MPa.

Figure 6: the ankle foot orthosis after convergence mesh

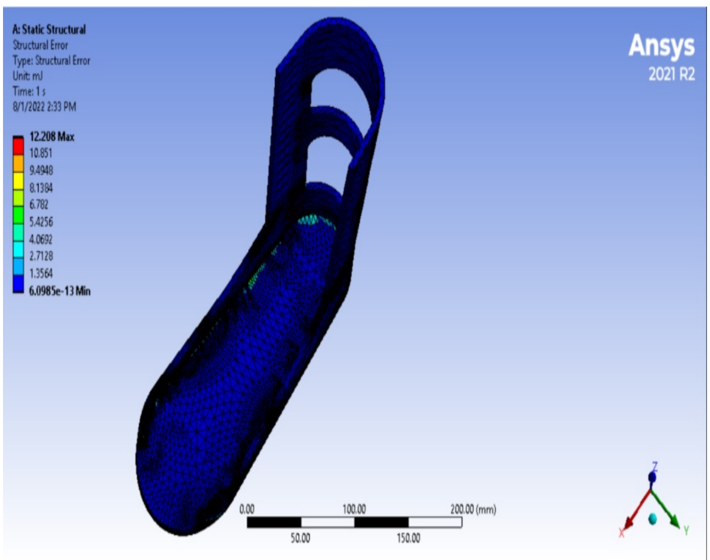


Figure 7: Graph of mesh convergence for design 3 of the ankle foot orthosis

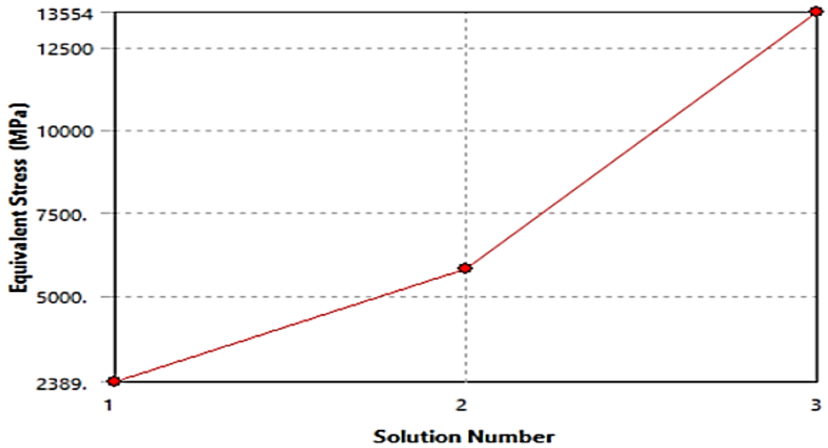
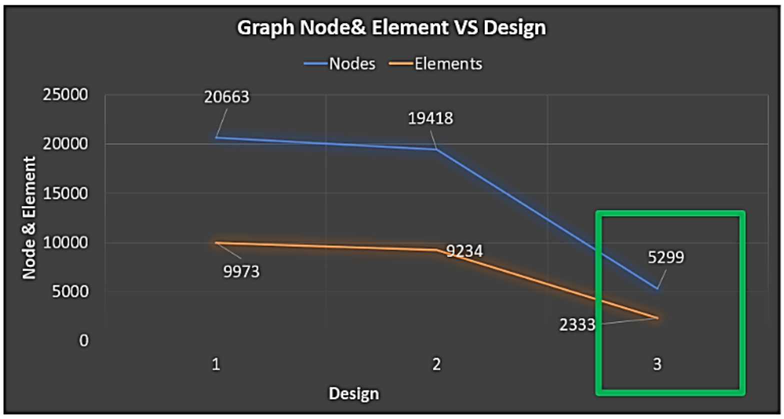


Table 4: Result of mesh convergence for 4.7 mm thickness of the ankle foot orthosis

No	Equivalent Stress (MPa)	change (%)	Nodes	Elements
1	2389	-	129866	86089
2	57.98.5	82.2886	271282	183528
3	13554	80.148	471987	323961

The error plot results of the ankle foot orthosis after convergence mesh is completed. These results showed the error plot of the ankle foot orthosis model will be reached 12.208 mJ. These results showed the error plot of the ankle foot orthosis decreased after the convergence mesh completed from 279.51 mJ to 12.208 mJ for the maximum value for structural error. Hence, this design of the prosthetic socket can be verified because the stress would not suddenly be changed among the surrounding mesh. Figure 8 shown the stress and strain result analysis static structural under good condition and safe to apply the load or weight 490.03 Newton. Figure 8, shows the design 3 is the best design due to the result of meshing by ANSYS analysis which is the number of nodes is 5299 and number of elements is 2333 less compare to the others which can made the product more rigid and long lasting.

Figure 8: Graph selection best design of the ankle foot orthosis



4.2 *Different Design*

The best design to be selected was design 3 because from figure 9 shown the graph of design against total deformation shown that the value for total deformation of design 3 is very lowest compared to other two design which is it shown that the design 3 is not easily to be crack and fracture because it related with the size of element and node of the meshing result that is bigger mesh so it not easily cracks and fracture. Next, figure 10 also shown that the design 3 is the best selected design because the value of the equivalent (Von Misses) stress is bigger to overcome and force or weight that have been used on it compared to other two design and it shown that design 3 is not easily to crack and fracture.

Table 5: Analysis results for the different design of the ankle foot orthosis model

Design	Maximum Von Mises Stress (MPa)	Deformation (mm)	Minimum Safety
1	148.74	123	0.16811
2	83.399	122.82	0.28281
3	462.63	16.333	0.054039

The figure 9 and figure 10 shows a comparison of total deformation and equivalent(von-mises) with the previous study.

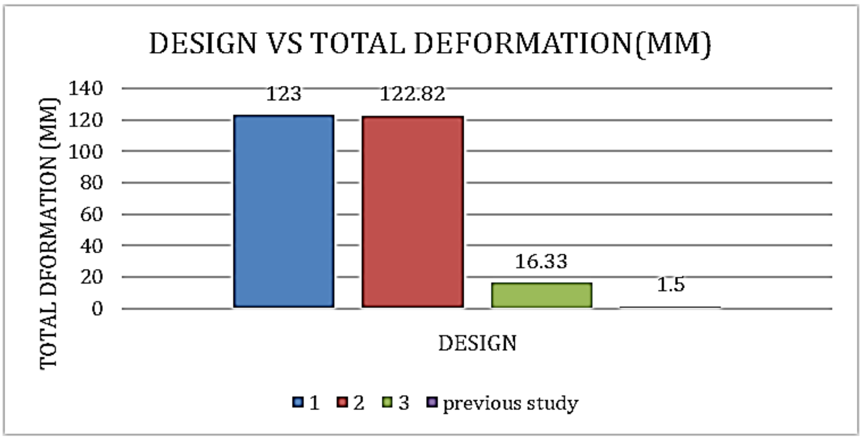


Figure 9: The bar graph of the Design Vs Total Deformation

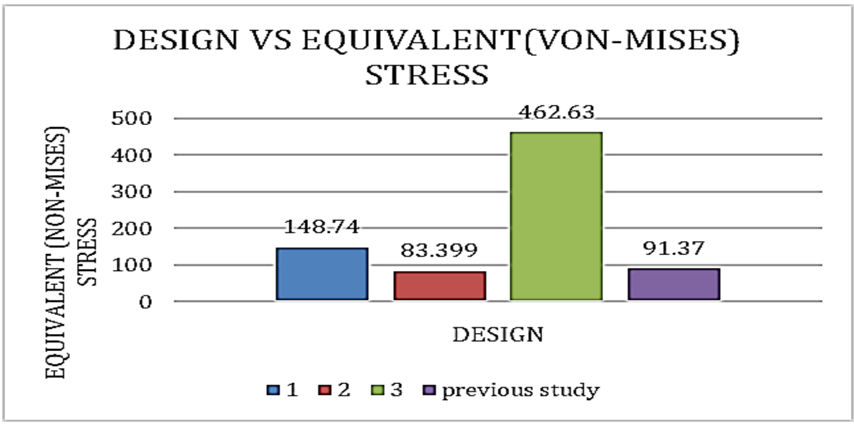


Figure 10: The bar graph of the Design Vs Equivalent (Von Mises)

4.3 Different Thickness

Table 6 shows the detail about the analysis result for different thickness of AFO's product for design 3. From this figure 11 and figure 12 shown that the thickness 5.7 mm is the optimum thickness value because can see that the value of the safety factor and total deformation for thickness 5.7 mm is very high value compared to the other thickness which is 4.7 mm and 5.2 mm. Next, even though the value for safety factor of the thickness for 5.7 mm is higher value and indicates it is safe to use.

Table 6: Analysis results for the different thickness of the ankle foot orthosis model design 3

Thickness (mm)	Maximum Von Mises Stress (Mpa)	Deformation (mm)	Minimum Safety
4.7	462.63	16.333	0.054039
5.2	143.39	11.154	0.17434
5.7	124.99	9.4477	0.20001

Figure 11: The graph of the Thickness Vs Total Deformation

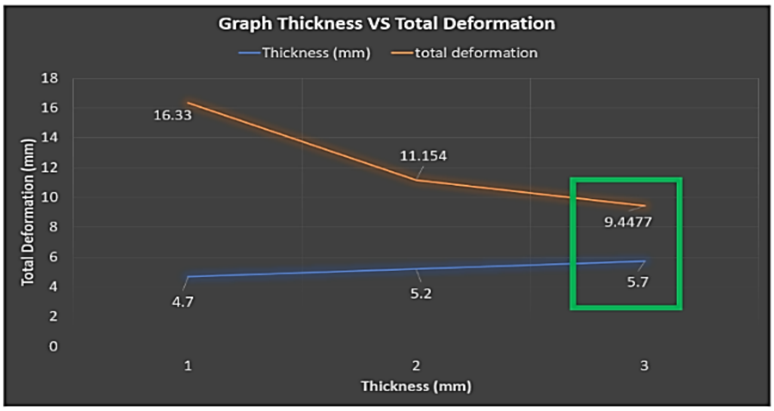


Figure 12: The graph of the Thickness Vs Von Misses Stress

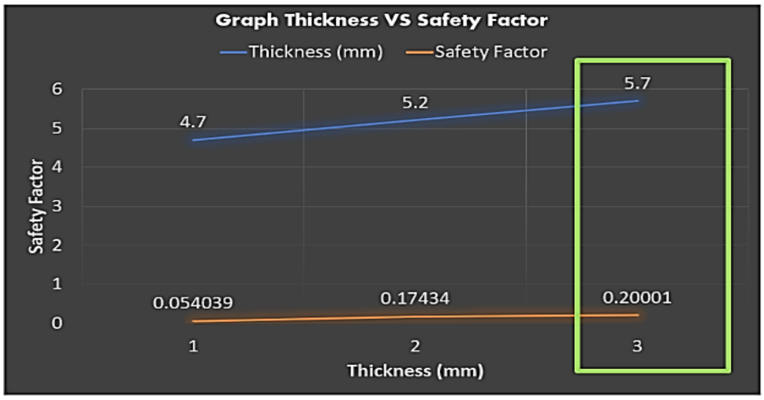
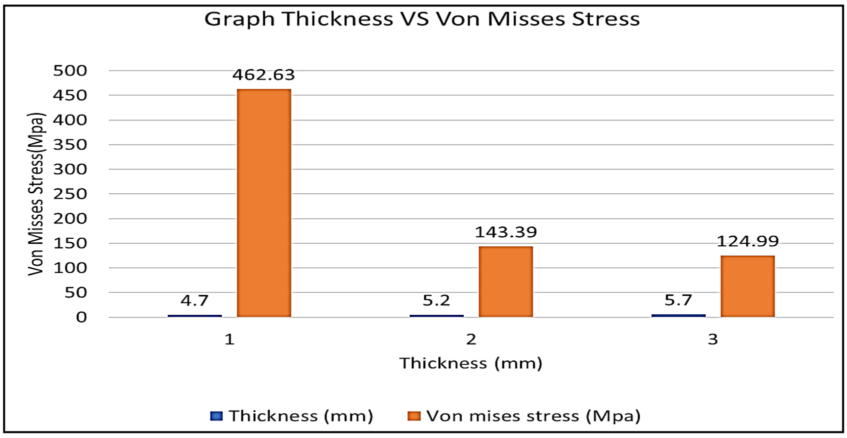


Figure 13: The graph of the Thickness Vs Von Misses Stress



4.4 Discussion

Based on the data in Table 5, it is critical to note that different design variations affect the evaluation of outcomes such as Von Mises stress, total deformation, and minimum safety factor. The result of equivalent stress (Von Mises Stress) at the surface of the ankle foot orthosis model for the different design. Since force impact on the footprint surface of the ankle foot orthosis then the maximum equivalent stress (Von Mises Stress) shows the result which is the highest equivalent stress (Von Mises Stress) will be reached 462.63 MPa for design 3, 148.74 MPa for design 1 and 83.399 MPa for design 2. The minimum safety factor for the design 3 of the ankle foot orthosis model is the lowest compared to other varieties of design. The lowest safety factor is 0.054039 desirable to resist the strong stress of daily activities. Design 3 showed it can resistance more stress compared to other

design of the socket although the lifespan of the design 3 is short because it Maximum von Mises Stress that it can be hold back is biggest among the three different designs. Based on this project design 2 has the highest safety factor compared to the design 3 but it not selected because the Maximum von Mises that being imposed on it only 83.399 MPa. According to the magnitude of deformation seems to be the biggest mostly on the footprint surface for the three different designs, but it also focusses on the left and right sides of the orthosis model for design 1 and design 2. Furthermore, the Von Mises stress is equal to or greater than the stress of uniaxial failure then the distortion energy concept is commonly employed to estimate ductile material failure, and this prove that design 3 with the thickness 4.7mm is the best design among three model of the design because it has the biggest Maximum Von Mises Stress which is 462.63MPa that mean the design is able to accommodate the big stress that being imposed on it even though it life span life is short because the safety factor for design 3 is 0.054039 which is very small compared with two other design. Some reasons that cause the accuracy data compared to the results of the ankle foot orthosis model in real life cannot be achieved because the liner or strap doesn’t apply toward the FE modelling design in this project. The liners add on maybe appear to spread the pain more uniformly and can allow the ankle foot orthosis is not easily pulled out on the limb and the footprint because it can improve the probability of good application of the orthosis model.
Other than that, the results also will be affected the inner surface model interface because the disparity in structure between the inner surface of the model and the footprint raises some problems in touch simulation. Simplification was generally done under the footprint and the pre-stress are being neglected and may contribute to layout inaccuracy. Next, based on the thickness results for design 3, the thicker the thickness of the model the high safety factor for the model and it mean the 5.7 mm thickness design model is not easily fractured but the Maximum von Mises Stress that it can imposed is lowest which is 124.99 MPa demonstrated the model with thickness 5.7 mm increase in the stiffness which mean it not easily to fracture but the slack is it decrease in the amount of stress that the orthosis model can handle. While for thickness 4.7 mm for the orthosis model that allow the orthosis model can be charged is biggest compared to the other two thickness of the orthosis model which is 5.2 mm and 5.7 mm thickness but the main slack is the safety factor for the orthosis model with 4.7 mm thickness is smallest compared the two other thickness which is 0.054039 which mean the life span for this thickness 4.7 mm is short because it easily gets fracture on the dorsiflexion surface. The cause might be due to a mismatch in thickness between the neck and the base of the skull which thickens the neck locally and causes stress concentration. Thus, better avoid the sudden change between small areas to larger areas because if this is not being avoided then the area change around the neck should be smoothed to moderate the stress for the remarkable area. Furthermore, if the design model is too thick it is heavy and uncomfortable for the patient to wear. As a result, this project does not recommend the thickness 5.7 mm for design model because it not very efficient. According to Table 6 results, 4.7 mm thickness of the orthosis model is the best thickness that can be choose because even though the minimum safety factor is lowest compared to other two thickness minimum factor safety which is 0.054039 but this thickness can resist more stress which is 462.63 MPa compared to other thickness orthosis. Due to nearly the suitable safety factor, the low magnitude of deformation and lightweight which required fewer materials to be produced then the 4.7 mm thickness is the suitable thickness for the ankle foot orthosis model. Based on the previous research the best thickness for the orthosis design product is between 3mm to 4mm due to the maximum stress decrease 22% by foot flat, 20% by heel rise and 27% by heel strike (Tan, 2021).

5. Conclusion

In conclusion, FE analysis is the most effective approach to investigate stress distribution and other outcomes for simulation using simulation or by comparing to past case studies. The ANSYS simulation programme was used. This study and simulation discovered the maximum overall deformation for each of the three designs and thickness. The minimum safety factor for the design 3 of the ankle foot orthosis model is the lowest compared to other varieties of design. The lowest safety factor is 0.054039 desirable to resist the strong stress of daily activities. Design 3 showed it can resistance more stress compared to other design of the socket although the lifespan of the design 3 is short because it Maximum von Miss Stress that it can be hold back is biggest among the three different designs. The magnitude of deformation seems to be the biggest mostly on the footprint surface for the three different designs, but it also focusses on the left and right sides of the orthosis model for design 1 and design 2. The causes are the accuracy data compared to the results of the ankle foot orthosis model in real life cannot be achieved because the liner or strap doesn't apply toward the FE modelling design in this project. The best thickness that can be selected from this simulation and study is 4.7 mm thickness because it has greater Maximum von Mises Stress which is 462.63 MPa compared to other varieties thickness which is 5.2 mm and 5.7 mm. Next, the lowest safety factor is 4.7 mm thickness compared to other two thickness which is 0.054039.

Acknowledgment

The authors would like to appreciate the contribution of madam Zalaida Talib from Politeknik Banting Selangor regarding in term of knowledge about the Technical Design for Finite Element Analysis and encouragement to done this project.

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