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Research paper

Computational Analysis of Adjustable Ankle Foot Orthosis for Cerebral Palsy Children

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Abstract

Children with cerebral palsy may present several gait patterns, and the most common spastic deformity is foot equinus. One of the most effective methods of correcting foot deformity is orthotics, which involves the use of synthetic or mechanical devices worn on the feet to stabilize, heal, or prevent deformity to weak joints or bones. However, the ankle foot orthoses that is available in the market are usually fixed and not flexible. The main aim of this project was to design an adjustable ankle foot orthosis with adjustable ankle flexion and to investigate the effects of shell thickness of the foot and shank to promote optimum product. Proper engineering design process was developed in this project at several phases including the idea generation and conceptualization, evaluation of concept using Pugh Method, finite element model and analysis, and also the fabrication of the prototype using 3D printing technology. Variation of shell thickness of the foot and shank part was analyzed to predict the optimum thickness of the product. Results show that the model with .5 mm of shell thickness produces the best findings. The maximum value of von misses stress was predicted at 45.7 MPa and 4.7 MPa for the foot and shank part, respectively. Prototype model of the adjustable foot orthosis was successfully fabricated using 3D printing technology.

Keywords: *ankle flexion, ankle foot orthosis; cerebral palsy; 3D printing*

1. Introduction

Cerebral palsy is a well-known condition that occurs in the early stages of life, and usually persists through lifespan. The prevalence of cerebral palsy-affected children is found to be 2 per 1000 live births [1]. Cerebral palsy is neither progressive nor contagious. It will not produce further degeneration and will not spread through human contact. However, it is considered chronic because it is long term and the cure is not yet discovered.

Foot deformity is a very common symptom associated with cerebral palsy children. It is estimated that 93% of children with cerebral palsy have foot or ankle deformities [2]. They may also present with several gait patterns due to muscular spasticity [3]–[5]. The most common type of foot deformity in cerebral palsy is equinus [6], a condition where dorsiflexion of the foot at the ankle is equal to or less than 90 degrees. This occurs due to contracture at the gastrocnemius or the gastrocnemius-soleus muscle tendon complex [7].

Physical therapy is an essential component in the treatment of children with cerebral palsy. One of the most effective physical treatments is orthotics. Orthotics is believed to help correct abnormal gait by maintaining a neutral or slight dorsiflexion and a reduction of ankle plantar flexion during swing phase and prevent foot drop during swing [2].

There are various types of orthotics devices available in the market, such as hips orthoses and knee ankle foot orthoses. However, this project is focusing on children who experience deformity in the foot region, especially foot equinus. The most suitable device for these children is ankle foot orthosis. The dimensions in the design is made based on children who aged between 10 to 12 years old. This is the ideal age to implement orthotics. Children in younger age is more suitable to be prescribed with walkers.

While it is crucial to provide physical treatment for these children, including the use of suitable supporting devices, the available ankle foot orthoses in the market are usually complex and expensive. They are usually fixed at ninety degrees angle or composed of a dynamic dorsiflexion damper. This might provide discomfort or even pain for children who are in the beginner stage of orthotics treatment.

Meanwhile, researchers have found that one of the risk factors of cerebral palsy birth is low socioeconomic status [8]. Thus, it is important to design a simple yet effective device so that it is affordable for children who came from families with low socioeconomic status.

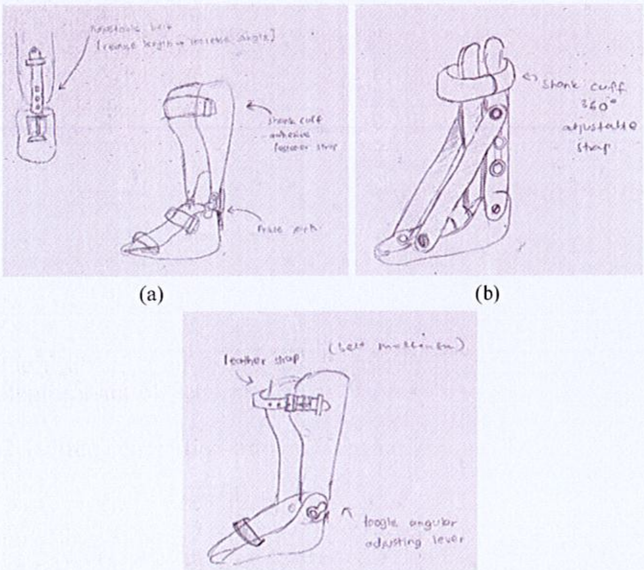
The objectives of this project are (i) to design an adjustable ankle foot orthosis for cerebral palsy children, (ii) to predict the optimum shell thickness of the model using finite element analysis, and (iii) to fabricate the prototype model using 3D printing technology.

2. Methodology

Engineering design is a demanding process, requiring both ingenuity and methodical approach to collecting, interpreting, and using information [9]. Three phases are carried out throughout this project to achieve the objectives. The first phase is idea generation and conceptualization, where sketches of design mechanisms are proposed and evaluated using Pugh Method to select the best concept for preliminary design. The second phase is the development of finite element model. The design is developed in computer aided drawing and static analysis is performed on each part. Lastly, the final design of the model is fabricated using 3D printer by implying suitable settings.

2.1. Idea generation and conceptualization

Based on the research made, three conceptual designs were generated for the ankle foot orthosis. All three concepts were made based on the idea that the device must be adjustable. The differences between all three concepts are focusing on the angle adjusting mechanism as well as the fit. To clearly visualize these concepts, three separate sketches have been made prior to concept selection process. Fig. 1 shows the sketches of all three concepts that are initially proposed in this project.



(a) (b) (c)

Fig. 1: Sketches of (a) Concept I, (b) Concept II and (c) Concept III

2.1.1. Evaluation of Concepts

In Concept I, the shank part and foot part are connected by using ankle joints. These joints enable the shank part and foot part to be rotated freely. To fix the angle, adjustable belt is attached to the back of the heels. This belt has three holes to enable the angle to be fixed at desired angles. This concept also uses adhesive straps as fasteners at three locations as shown in the sketch.

The advantage of this concept is that the ankle joints are elastic, thus, together with the adjustable belt, they are able to provide angle adjusting and fixing mechanism without causing too much uncomfortable tense to users. Furthermore, this concept can be easily installed because it uses simple yet effective fasteners that are easily available in the market. However, the adjustable belt must be elastic yet strong enough to keep the ankle fixed while walking.

Meanwhile, Concept II uses sliding bar as the angle adjusting mechanism. Two bars are attached to the sides of the foot base. Each bar has three slots to represent angle fix at 90, 110, and 130 degrees. Since side bars are used, adjustable straps need to be installed 360 degrees around the shank. Another strap is positioned around the ankle to provide better fit. The straps are also made of adhesive fasteners.

The advantage of this concept is that it is easy to be used. The adhesive fasteners are very convenient, even for cerebral palsy children who have muscle distortion. The disadvantage of this concept is that it uses side bars with sliders, where the mechanism is quite critical compared to others. These details must be considered properly to avoid defects and risk of dysfunctionality.

For Concept III, the shank part and foot part are made separately in this concept. They are attached together by a toggle lever which also acts as an angle changing mechanism. Users can adjust the angle of the orthosis to their desired position by pulling the toggle lever. This concept uses belt fastener mechanism as a strap at the shank. Another strap is located at the foot part to provide sufficient fit.

The advantage of this concept is the use of toggle lever as angle adjusting method. This is a very convenient way for users to adjust the angle according to their needs. However, this toggle might not be sufficient to provide pressure required for bracing purpose to treat foot equinus. Also, the belt mechanism for shank strap might be inconvenient because children with cerebral palsy might need help to fasten the straps.

2.1.2 Concept Selection

A quantitative assessment is carried out using Pugh Method in order to identify the best concept selection. The conceptual designs are evaluated based on the criteria needed for an adjustable ankle foot orthosis, which are the functionality, manufacturing cost, ease of installation, and simplicity of design.

Based on the Table 1, it can be decided that Concept I scores the highest weightage in the assessment using Pugh Method. Therefore, concept I is selected as the best design and will be proceeded to preliminary design.

Table 1: Concept selection using Pugh method

Criteria	Weightage	Concept		
		I	II	III
Functionality	0.35	3	1	2
Manufacturing Cost	0.25	2	3	1
Ease of Installation	0.25	2	1	3
Simplicity of Design	0.15	1	2	3
Total	1.00	2.20	1.65	2.15

2.2. Development of Finite Element Model

In this project, static analysis is conducted using commercial design software. Prior to loading definition, the material of the model is specified as Polylactic Acid (PLA). The material properties are identified by referring to Karl et. al. [10] and are summarized in Table 2.

Table 2: Material properties of PLA

Density	1240 kg/m^3
Elastic modulus	3500 MPa
Shear modulus	1287 MPa
Poisson's ratio	0.36
Yield strength	70 MPa
Ultimate tensile strength	73 MPa

Fixed geometry is defined on the supports, and loading is applied at the inner surfaces as shown in Fig.2. The green indicators represent fixtures supports while the purple arrows indicate load direction on the surface applied. The force applied is 150 N, this value is based on the maximum weight of children that is specified in the scope of project, which is 30 kg.

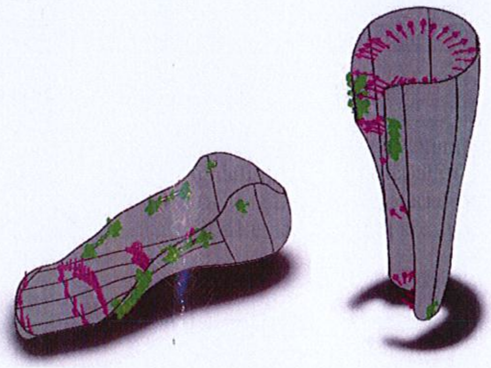
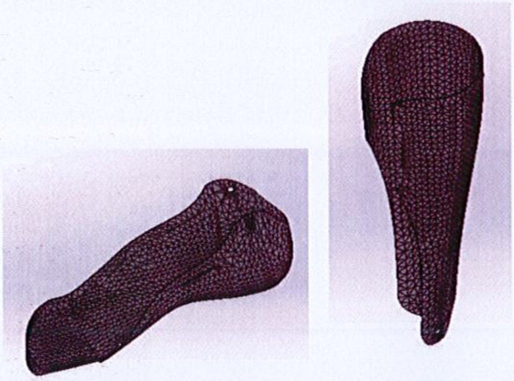


Fig. 2: Fixtures and Loads Applied on the Model

To complete the analysis, mesh is created on the foot part with element size of 4.7 mm, which results in a total node of 18699 and a total element of 9318. For the shank part, the mesh size is 5.9 mm. The total node and total element are 16813 and 8235, respectively. The meshing of both parts is shown in Fig.3.



(a) (b)

Fig. 3: Meshing of (a) Foot Part and (b) Shank Part

2.3. Fabrication of Model Using 3D Printer

The model that has passed required analysis is constructed using 3D printing technology. From the 3D CAD model, the design is saved as an STL file and opened using the 3D printer support software, which is Qidi Tech V4.2.12, as shown in Fig. 4. The settings are defined as in Table 3 according to suitable condition.

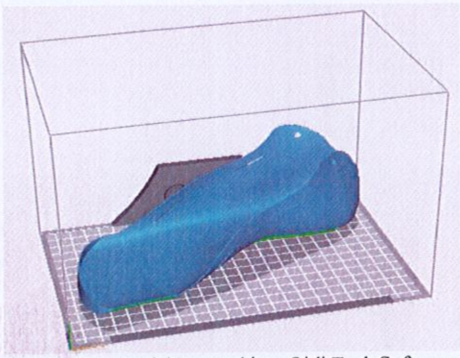


Fig. 4: STL Model Inserted into Qidi Tech Software

Table 3: Settings Defined in the Software

Layer height	0.18 mm
Printing temperature	220°C
Build plate temperature	45°C
Print speed	50 mm/s
Support placement	Touching build plate
Support pattern	Concentric
Build plate adhesion type	Skirt

Slicing operation is then performed on the model as shown in Fig. 5. This enables users to observe the construction of the 3D model in layer mode, which displays the travels, helpers, shell and infill that will be extruded by the printer.

The estimated time of fabrication and also length of filament that is to be used are also displayed. For the foot part, the estimated time of fabrication is 6 hours 23 minutes and the length of filament used is approximately 31 metres. The model is then saved as X3G file. The 3D printer recognizes this type of file and model is printed out directly.

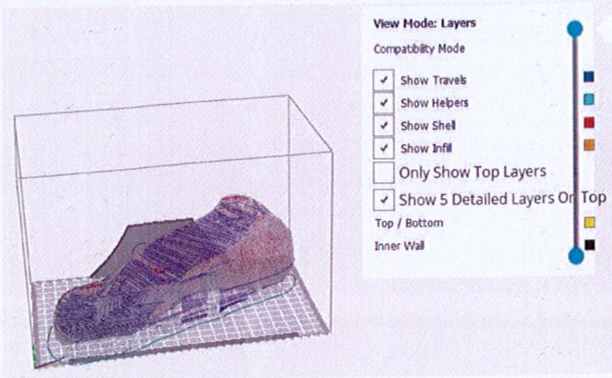


Fig. 5: Layers View Mode

3. Result and discussion

3.1. Design Development

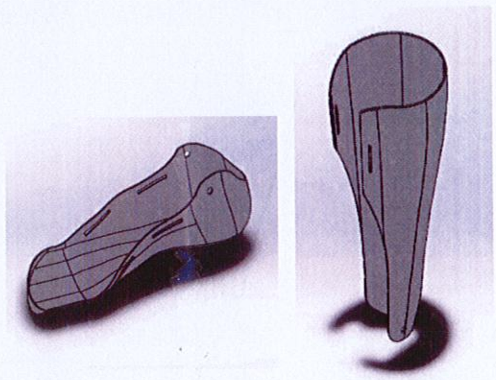
3.1.1. Preliminary Design

The sketch of selected concept which is Concept I is transformed into three dimensional model for better visualization, as illustrated in Fig. 6. In this project, all design processes are conducted using commercial CAD software.

Fig. 6: Preliminary Design of the Device

3.1.2. Finalized Design

The main body of the ankle foot orthosis is composed of two pieces of braces, namely foot part and shank part as shown in Fig. 7. These parts are to be fabricated using 3D printer, while the ankle joints, belts, and straps are to be purchased.



(a) (b)

Fig. 7: Final Design of (a) Foot Part and (b) Shank Part

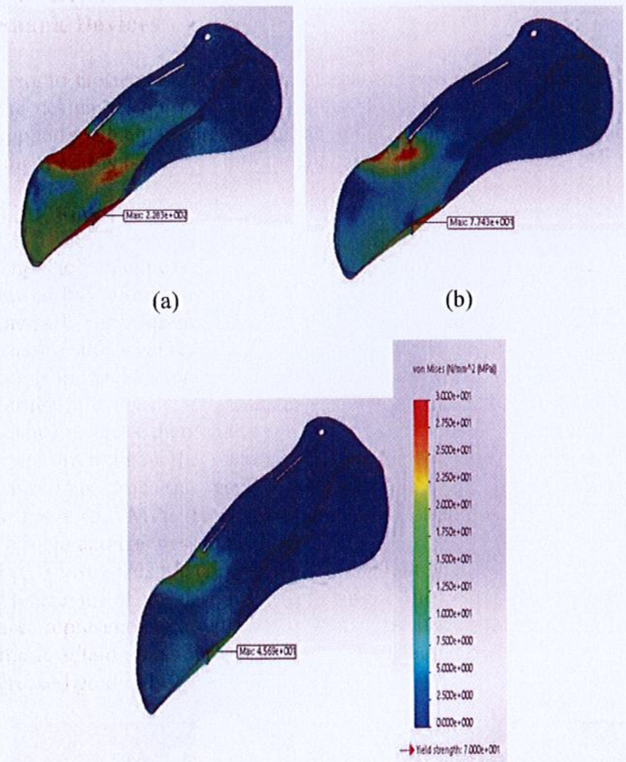
3.2. Effects of Shell Thickness Variable in Foot and Shank Devices

Prior to fabrication, finite element analysis is conducted to observe the design feasibility under loading. Fixtures are applied on the supports, which are presenting the nut holes and strap holes. Loading of 150 N is exerted into the model.

3.2.1. Foot Part

The shell thickness of the model is initially set as 0.5 mm, followed by 1.0mm and 1.5mm to predict the optimum thickness of the part. For 0.5mm thickness case, this results show in a high von misses stress value, which is 228.3 MPa. This significantly exceeds the yield strength of PLA which is 70 MPa, which indicates failure in structure. The thickness is then increased to 1.0 mm. The resultant stress then changes to 77.4 MPa. This also exceeds the yield strength of the material. Lastly, the thickness is set as 1.5 mm. This time, the result shows that the value of von Misses stress is 45.7 MPa. Thus, the thickness of 1.5 mm is considered as feasible and has passed analysis.

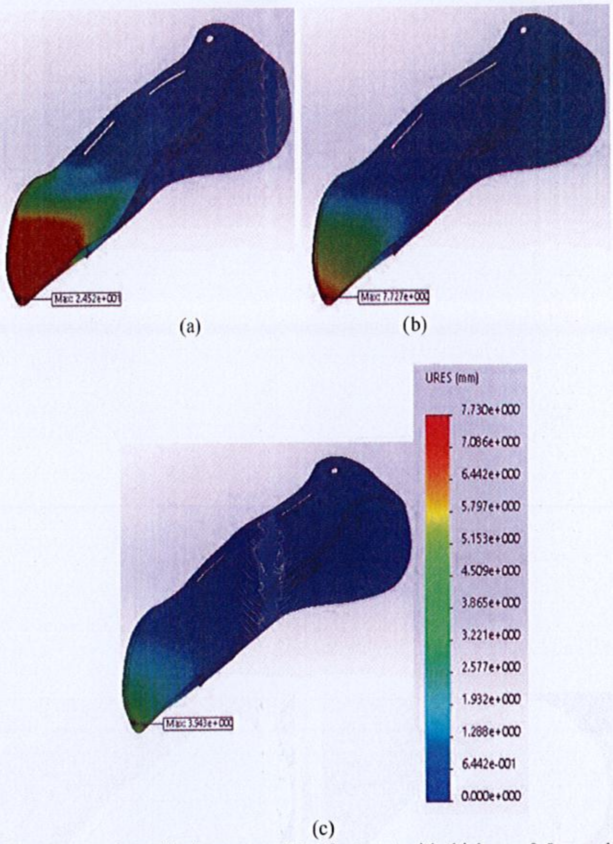
Fig. 8 visualizes the comparison of resultant stresses of the various thicknesses of the design. By referring to the colour scale, the red area represents area with maximum stress. It can be observed that the resultant stress in this design is minimized as thickness is increased gradually.



(a) (b) (c)

Fig. 8: Resultant Von Misses Stress of the foot part with thickness of (a) 0.5 mm, (b) 1.0 mm, and (c) 1.5 mm

In term of displacement, the similar approach is applied, where thickness is gradually increased and changes in displacement is observed. The resultant displacements for thickness 0.5 mm, 1.0 mm and 1.5 mm are 24.5 mm, 7.7 mm, and 3.9 mm respectively. Based on Fig. 9, it can be observed that the critical area in term of displacement is the edge of frontal foot section. This is because maximum force is focused on that area especially when the user is walking. This complies with a study by Nandikolla et. al., which suggests that maximum forces act on the toe area during locomotion [11]. Fig.10 demonstrates the increase in pressure intensity from light blue to red colour in the 2D plantar.



(a) (b) (c)

Fig. 9: Resultant displacement of the foot part with thickness 0.5 mm, 1.0 mm, and 1.5 mm

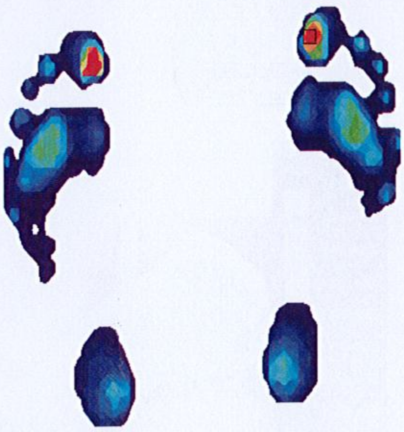
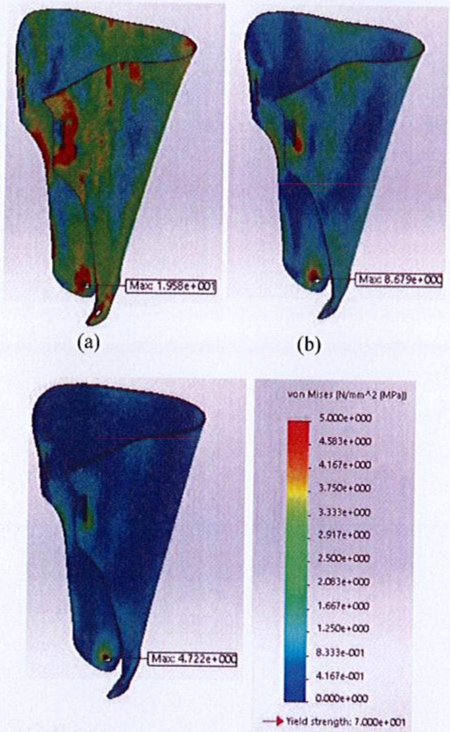


Fig. 60: 2D plantar pressure distribution [11]

3.2.2. Shank Part

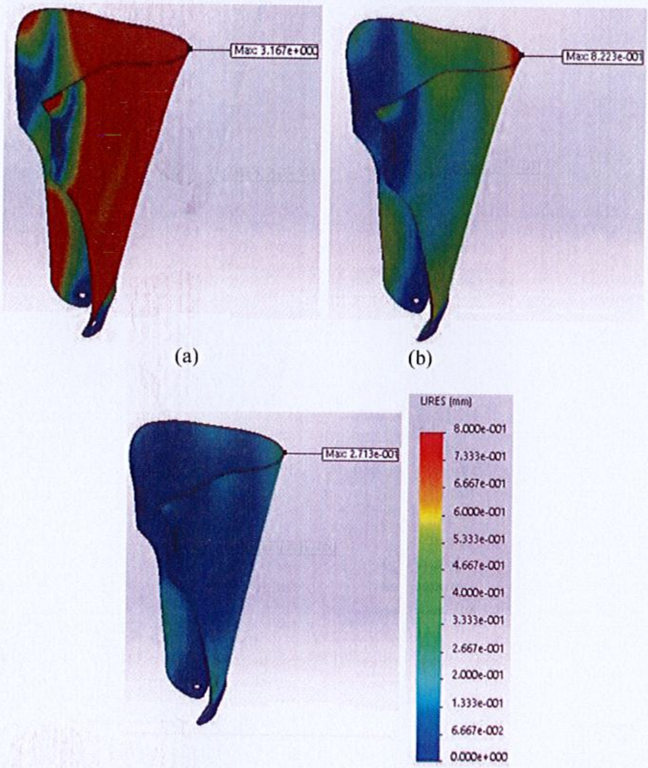
For the shank part, different thicknesses are also introduced to the model to analyse the resultant stress. When thickness of 0.5 mm is applied to the model, a resultant Von Misses Stress of 19.6 MPa is obtained. Meanwhile, for thickness 1.0 mm and 1.5 mm, the resultant Von Misses Stresses are 8.7 MPa and 4.7 MPa respectively. Fig. 11 shows that as the shell thickness is increased, the maximum stress is minimized gradually.

Meanwhile, displacement of the shank part under similar loading is also analyzed. Three different thicknesses are also applied to this model. The resultant displacements of shank part with thicknesses of 0.5 mm, 1.0 mm, and 1.5 mm are 3.2 mm, 0.8 mm, and 0.3 mm respectively. This once again proves that greater thickness produces smaller displacement, which results in better and more reliable design in term of static deformation. As shown in Fig. 12, the critical area of deformation for this part is the back of the shank.



(a) (b) (c)

Fig. 7: Resultant von Misses Stress of the shank part with thickness of (a) 0.5 mm, (b) 1.0 mm, and (c) 1.5 mm



(a) (b) (c)

Fig. 12: Resultant displacement of the shank part with thickness 0.5 mm, 1.0 mm, and 1.5 mm

3.3. Fabrication of Adjustable Ankle Foot Orthosis

3D Printer is used to construct the ankle foot orthosis. In this project, PLA is chosen as the material because it is a well-known and widely used biodegradable polymer. Researchers also agreed that PLA is an ideal material to be used in biomedical field, as it is biocompatible with environmental concerns [12].

Ankle joints are purchased to assemble the two braces. The joints are made from rubber and are specially intended to be used for prosthetics. Straps, belts, and shoe insole are also purchased as finishing to the product as shown in Fig. 13.

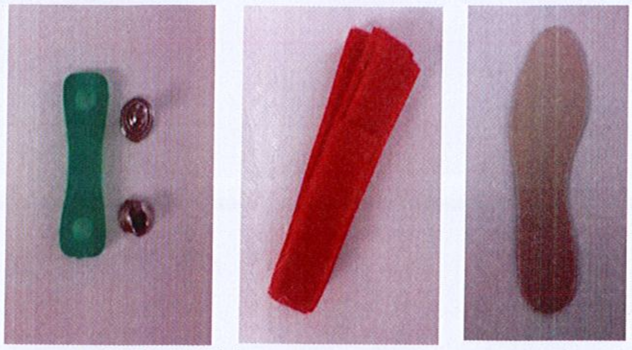


Fig. 13: Ankle joints, adhesive straps and shoe insole

The foot part and shank part are extruded separately. For the shank part, the height of the entire model is 310 mm while the maximum model height that can be constructed using the 3D printer is only 200 mm. therefore, the shank part is split into two parts in order to fit the model into the 3D printer. The extruded parts and purchased parts are then assembled together in the final product as shown in Fig. 14.

This project is believed to be a significant potential to help cerebral palsy children because this condition is considered chronic and the cure is not yet discovered. The effects of having equinus foot, especially abnormal walking gait can persist through lifetime if left untreated. Efficient and effective walking is an important treatment goal for children with cerebral palsy because mobility is associated with functional independence and participation of the child in society. Therefore, physical therapy is an essential component in the treatment of these children.

Fig. 8: Side view and front view of final product

4. Conclusion

This project is revolving around three main objectives, which are designing an adjustable ankle foot orthosis for cerebral palsy children, performing computational analysis on the design, and also constructing the model using 3D printing technology. The design is made by proper conceptual evaluation. Based on the three initial ideas, one is selected by using Pugh Method. Then, analysis is performed on the conceptual design. The model with thickness of 1.5 mm produces the best result, as compared to thinner model. The maximum value of von misses Stress under this condition for foot part is 45.7 MPa, while the maximum displacement is 3.9 mm. Meanwhile for the shank part, the maximum resultant values of Von Misses Stress and displacement are 4.7 MPa and 0.3 mm respectively. These values indicate that the design is feasible. Lastly, the model is fabricated using 3D printing technology. Specific procedures and settings are conducted to achieve the best outcome.

Acknowledgment

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