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Development of Dynamic Ankle Foot Orthosis for Therapeutic Application

Azmi Patar[a]*, Norman Jamlus[b], Khushairy Makhtar[c], Jamaluddin Mahmud[d], Takashi Komeda[e]

[a,b,c,d] *Faculty of Mechanical Engineering, Universiti Teknologi MARA, Shah Alam, Selangor, Malaysia*
[e] *College of Systems Engineering and Science, Shibaura Institute of technology,Omiya, Japan*

Abstract

In a population of aging with low birth rate, many elderly become bedridden because of their suffering from injuries or diseases that require a long period to heal and rehab. We developed the lowest cost of production while provides the highest performance and reliable prototype. The selective 27 parts were identified and used in this project including the cabling assembly for wiring. The other selective 14 parts are using other polymer materials such Acrylontrile Butadine Styrene (ABS) and Polypropylene. The alpha prototype was produced using FDM (Fuse Deposition Modeling). The model is fabricated by using real scale of (1:1) for the chosen conceptual design. Engineering drawing is the last process in design stage, where the final prototype must be verified as according to requirement and the related problem rise have been solved. The effective cost reduction newly designed DAFO is presented in this study. The functional test was conducted in the laboratory and based on human testify. The performance was good even though the prototype using rapid prototype materials. The controller board also functions as it programmed. The DC motor was performed a job based on signal provide by two (2) limit switch at the bottom part of lower foot. As a conclusion, The development of cost-effective new mechanism of dynamic ankle-foot orthosis was successfully fabricated in this current study. Further evaluation need to be tested accordingly prior to use as important device in rehabilitation therapy.

Keywords: Rapid Protyping, Ankle Rehabilitation ,Gait cycle, Plantarflexion, Dorsiflexion

1. Introduction

An ankle-foot orthosis (AFO) is commonly used to help subjects with weakness of ankle dorsiflexor muscles due to peripheral or central nervous system disorders. Both of these disorders are due to the weakness of the tibialis anterior muscle, which results in lack of dorsiflexion assist movement. The deformity and muscle weakness of one joint in the lower extremity influences the stability of the adjacent joints, there by requiring compensatory adaptations. We present an innovative dynamic ankle-foot orthosis (DAFO) with new mechanism that was designed to allow one degree-of-freedom motion while serving to maintain proper foot position for subjects. The prototype DAFO would introduce greater functionality over currently marketed devices by means if its inversion-eversion degree-of-freedom in addition to flexion/extension. The flexion-extension is controlled with the help of an actuator and inversion-eversion with a spring and a damper.

The DAFO is widely used, particularly has several unique features. First, it allows graded foot motion within the orthosis so normal balance reactions involving proximal musculature can occur. Second, by providing support of the foot's natural arches, weight is more equally distributed throughout the foot. Thus, stimulation of foot reflexes better approximates normal

* Corresponding author. Tel.: +603-55436287; fax: +603-5543 5160
E-mail address: azmipatar@salam.uitm.edu.my

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function. Third, DAFOs provide secure medial-lateral stability and midline positioning, resulting in improved grading of ankle plantarflexion and dorsiflexion. This stabilization has proven so effective; many clinicians have noted a decrease in abnormal plantarflexion in patients wearing DAFOs.

Orthotic devices are invented to support the ankle, correct deformities, and prevent further occurrences. Orthotic treatment is also to assist the patient in achieving a measure of normal function. Ferris *et. al.* proposed an ankle-foot orthosis powered by artificial muscles. The orthosis has two pneumatic muscles to control the dorsiflexion and plantarflexion motion of the ankle. Yamamoto *et. al*. developed a dorsiflexion assist, controlled by a spring. Dorsiflexion correction is achieved via the compression force of a spring within the assist device. Blaya *et. al.* proposed an active ankle-foot orthosis with one degree-of-freedom. The active ankle foot orthosis comprises a force controllable series elastic actuator (SEA) capable of controlling orthotic joint stiffness and damping for plantar and dorsiflexion ankle motions. There are a number of commercial ankle foot orthosis manufactured. All these orthosis are single axis or are elastically deformable. The inversion-eversion motion in all of these orthosis is accommodated through the flexibility of the material, such as polypropelyene. The limitation in normal inversion-eversion adds to the discomfort and does not provide a natural motion to the ankle.

The ankle-foot orthosis with one degree of freedom is proposed. The two motions incorporated are dorsiflexion-plantarflexion and inversion-eversion motion. The dorsiflexion-plantarflexion motion is actively controlled by a DC servo motor. The inversion-eversion joint is passive with a torsion spring and a damper. The spring and the damper create a virtual wall and restrict the motion beyond a certain range by the application of the spring force. The device is aimed to be used in two different scenarios as a standalone measurement device to measure forces and torques at the joints like Kin Comand Bio Dex. The ankle foot orthosis also can be integral part of other rehabilitation device. The motion of the ankle can be controlled more accurately if the position of the leg in the gait cycle is available at all times.

Hence, this study was conducted to develop a cost effective DAFO for rehabilitation patients with ankle-foot problem. To date, the two-degree freedom of DAFO is used, however, in this present study; we were interested to develop one degree of freedom of DAFO for patients with ankle foot problem.

2. Methodology

2.1. Material Selection

Polymer material such as Polypropylene (PP) is used in this project**.**

2.2. Detailed Design

Pre final drawings were designed. The three dimensional data for rapid prototyping were prepared in STL and IGS format. The selective 27 parts were identified including the cabling assembly for wiring. The other selective 14 parts are using other polymer materials such Acrylontrile Butadine Styrene (ABS) and Polypropylene. In addition, five (5) of the parts are using metal such stainless steel, including screws and nuts. Only 2 parts were using EPDM rubber (Ethylene Propylene Diene Monomer).

2.3. Rapid Prototyping

The alpha prototype was produced using Fuse Deposition Modeling (FDM). The models is fabricated using real scale of (1:1) for the chosen conceptual design A plastic filament or metal wire is unwound from a coil and supplies material to an extrusion nozzle which can turn the flow on and off. The nozzle is heated to melt the material and can be moved in both horizontal and vertical directions by a numerically controlled mechanism, directly controlled by a computer-aided manufacturing (CAM) software package. The model or part is produced by extruding small beads of thermoplastic material to form layers as the material hardens immediately after extrusion from the nozzle. Stepper motors or servo motors are typically in use to move the extrusion head. The thermoplastics are liquefied and deposited by an extrusion head, which follows a tool-path defined by the CAD file. The materials are deposited in layers as fine as 0.04 mm (0.0016") thick, and the part is built from the bottom up – one layer at a time.

2.4. Engineering Drawing

Engineering drawing is the last process in design stage, where the final prototype must be verified as according to requirement and the related problem rise have been solved. The final engineering drawing will be produce and is known as as-built drawing. All the details regarding fabrication of DAFO are stated inside this drawing.

3. Results

3.1 Assembly

Figure 1: The prototype of the DAFO that is assembled by using all the parts.

3.2 Orthographic view of DAFO Assembly

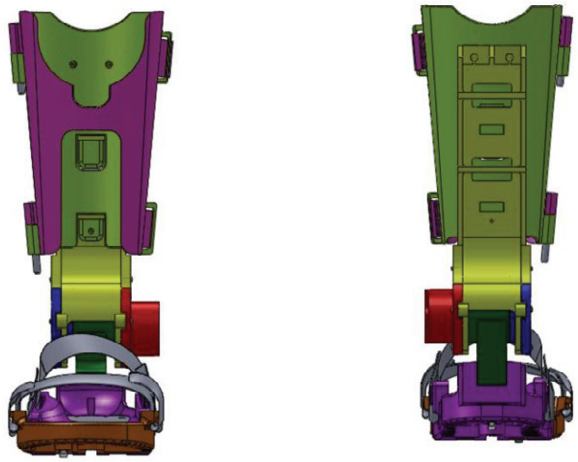

Figure 2A&B: Front View (left) and Rear View (right).

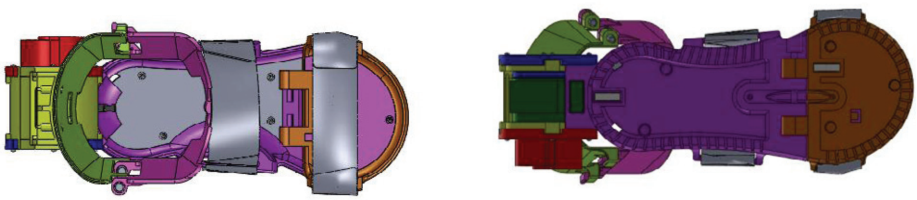

Figure 2C & D: Top View (left) and Bottom View (right).

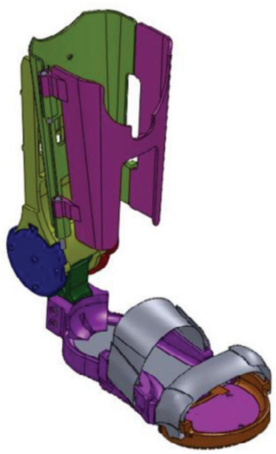

Figure 2E: Isometric View.

3.3 Functional Test

The functional test was conducted in the lab and based on human testify. The performance was good even though the prototype using rapid prototype materials. The controller board also functions as it programmed. The DC motor was performed a job based on signal provide by two (2) limit switch at the bottom part of lower foot. The gait cycle was shown on Figure 3 and its description represented in Table 1.

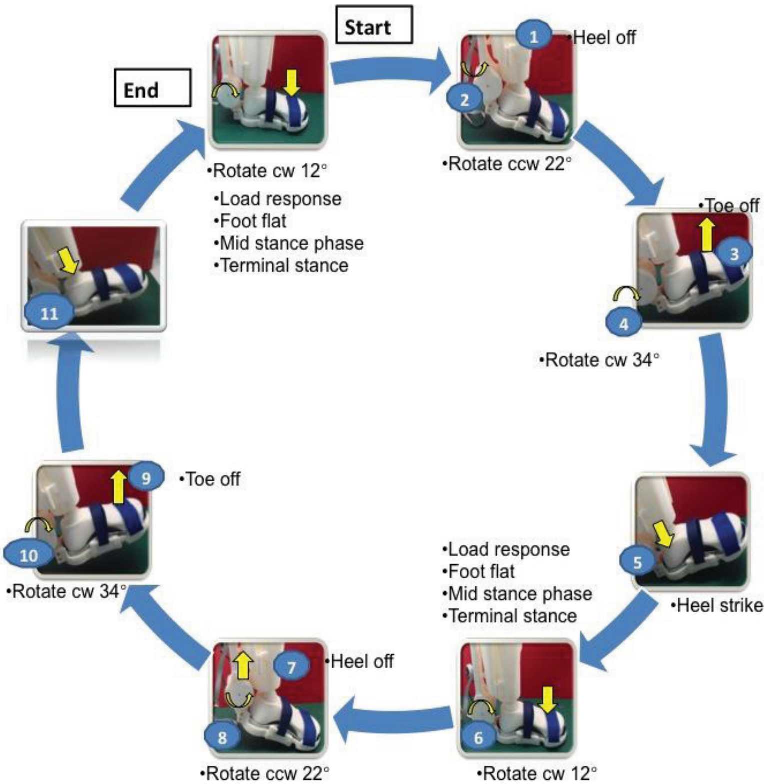

Figure 3 : The new DAFO walking gait sequences

Table 1 : The Description for DAFO Walking Gait Sequences

# Sequences	Descriptions
1,2	The cycle started from normal standing. In this condition, both limit switches has been pressed. The motor stop, no reaction or movement. When the leg was pulled upward, the motor rotated counter clock wise 22° to the maximum angle of plantarflexion. The heel off the position was started to perform.
3,4	The ankle-foot now perform toe off. The ankle foot start to move toward, both of the switches (front and rear) already released. The motor performs dorsiflexion by rotating clockwise 34° to the maximum dorsiflexion angle.
5,6	The ankle-foot now performed heel strike. The rear limit switch touches the ground and pressed. Except the front limit switch still in released condition. Since the rear limit switch is pressed and front limit switch is released, the motor now rotates clockwise 12° to perform foot flat. A load response from right foot to problem foot (left). In flat condition, the normal right ankle foot will swing toward for further movement. No reaction at all since both of switches was pressed.
7,8	The right ankle-foot will stay the position while the left ankle foot will start to swing and perform heel off. The front limit switch is pressed and rear limit switch released and motor is rotate counter clock wise 22° back to perform plantarflexion.
9,10	The toe off was performed again. The motor rotated 34° in counter clock wise to perform dorsiflexion at maximum angle.
11	Heel strike was performed. The motor rotate clockwise 12° when front limit switch is released and rear limit switch is pressed. Foot flat is performed, load response from right foot to problem foot (left). The normal right ankle-foot will swing forward. Mid-stance phase was performed again. The walking cycle completed.

3.4 Fabrication Costs Estimation

Table 2 represented the overall costs estimation with total time needed to build the prototype. To calculate the prototype cost, the total times of FDM machine needed to complete the fabrication.

Table 2: The Costing Table for DAFO's Plastic Components.

Components	Build Hours	Materials	Quantities
Foot Base	15.53	ABS	1
Foot toe	7.20	ABS	1
Calf Support P2	14.03	ABS	1
Arm Link	8.40	ABS	1
Shin Support	14.45	ABS	1
Plug Cover Right Metal	1.57	ABS	1
Plug Cover Left	3.55	ABS	1
Toe Cap	0.59	ABS	1
Base Cap	1.22	ABS	1
Calf Support Front P2	13.47	ABS	1
Controller Casing	13.09	ABS	1
Controller Casing Cover	1.45	ABS	1
Belt Lock	1.47	ABS	1
Switch Lock	0.44	ABS	1
Switch	0.8	ABS	1
Lock Pin	0.48	ABS	2
TOTAL HOURS	97.74		

We found out that the time needed of FDM machine to fabricate is 97.74 hours. We estimated the cost based on RM 150/hours. Therefore, in the present study, the total cost to build the mechanical part 97.74 hours more or less costs approximately RM14, 461.

Table 3: The Metal Cost Estimation for DAFO's Metal Component.

No	Part Name	Build Hours	Material	Quantity
1	Metal Block	2	Aluminium	1

The metal block is cost at RM300. The metal block is fabricated using EDM method. In addition, the controller board and its accessories including the 9V battery and motor are cost at RM800. Therefore, the total cost for the whole assemblies of newly designed-DAFO is the summation of RM14, 461, RM300 and RM800. Our present calculation estimated that the total cost to produce alpha prototype is RM15, 561.

3.5 Costing Effective

The cut-off price in developing alpha DAFO prototype is much higher than estimation cost produce in this present study. The market cost of developing alpha prototype up to RM200, 000.

4. Discussion

This newly design DAFO with ideal cost is presented in this study. The price reduction in producing a one degree of freedom DAFO is reduce into 100 fold compared to the products existed in the market. One of the advantages of the present design is the incorporation of orthosis using only one motor component which to help the patients move their ankle and leg accordingly. The electro-mechanical device in the present study however, to be considered new in Malaysia market. The only available products in local market are from the static version of DAFO. On the other side (comfortless aspect), the smoothness of walking movement can be adjustable. The correct gait pattern can be achieved by adjusting the speed rotation in the motor. The patient can easily modify the rotational of motor speed by changing the suitable values in the controller assemble. The speed modification can be controlled manually using portable computers, program or teleconference with the doctor or specialist live from hospital. The controller is powered by lithium polymer battery with capacity of 11.1V, 2200mAh. The present device equipped with rechargeable type of battery and secured by the stabilizer built-in circuit. The battery charging process as simple as plug and play which is the connection of the charging connector to the controller without bring out the battery from casing. The end users do not need to worry with the over power turning produced by the motor. The Poka yoke method is already applied in the design of shin support [6]. The ribs embedded on the shin support react as a stopper when the motor rotates the arm to respective angle.

5. Conclusions

The development of new mechanism of dynamic ankle-foot orthosis was successfully fabricated in this current study. The main material that have been using in this study is polypropylene that reduce the cost of development and yet effective. Further evaluation need to be tested accordingly prior to use as important device in rehabilitation therapy.

Conflict of interest statement

The author(s) declare that they have no competing interests

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