Development of an Ankle Foot Orthosis for Hemiplegic Children

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***Abstract*—Hemiplegia is a half body paralysis which causes disability in mobility function. Hemiplegia is normally discovered since early birth and is not curable. Treatment such as physical therapy can be carried out for the hemiplegic patient to prevent muscle contraction, especially at the early age. In this research, a tool for the physical therapy and gait assistance known as ankle foot orthosis (AFO) was developed for the hemiplegic children. The AFO was based on the active concept that mobilised the ankle by preventing excessive plantarflexion and allowed dorsiflexion. A linear type DC (direct current) motor was used as the actuator. The maximum range of motion (ROM) was +20° for the dorsiflexion and -20° for plantarflexion movement. The prototype was fabricated using 3D printing. Simple control for the device was developed using Arduino kits. The development of a new AFO is hoped to support the rehabilitation of the hemiplegic children.**

***Index Terms*—Ankle Foot Orthosis; Dorsiflexion; Gait Assistance; Hemiplegic**

I. INTRODUCTION

Hemiplegia causes impairments on one side of arm and leg. Hemiplegic children are facing a problem with the affected leg and interrupted by the shortening of muscles [1]. As a result, abnormal gait patterns would occur among the hemiplegic patients. Rehabilitation is conducted to support hemiplegic patients by means of both physically and psychologically. One of the basic management is to keep the hemiplegic children to stay active for preventing muscles contraction.

Ankle foot orthosis (AFO) is used as a tool for the physical therapy. The key usage of AFO is to restrict, control and assist the range of ankle’s motion at the desired angle during gait phases. Most of the orthosis devices were concentrating on the restriction and control function on dorsi-plantarflexion. The design of orthosis was based on imitating the normal human gait [2]. Thus, the normal gait pattern was investigated and recorded especially at the ankle’s angle. Dorsi-plantarflexion is one of the most crucial motions that involved in walking.

AFO can be divided into static and dynamic types. Solid ankle foot orthosis (SAFO) is the example of static types of AFO. SAFO is the simplest type of orthosis device. The device consists of single rigid bracing that moulded to suit the heel by using straps. The rigidity of the device allowed restriction for both dorsiflexion and plantarflexion. According to [3], the SAFO is more suitable for patients with higher level of impairment due to the high restriction function and stability.

Hinged ankle foot orthosis (HAFO) and active ankle foot orthosis (AAFO) are examples of dynamic types of AFO. HAFO was designed by implementing hinges on the ankle that allowed freedom of dorsiflexion and plantarflexion motion. The design of flexible ankle joints encountered the weakness of SAFO by preventing plantarflexion and allowed more dorsiflexion. It was concluded by [4] that HAFO helps enhanced the gait pattern in the way of stride length, walking with higher velocity, preventing plantarflexion, improving hip flexion and knee kinematics.

Active ankle foot orthosis (AAFO) is an innovating hinged AFO that applied with the powered actuator, control or sensors. The AAFO would help significantly in therapy management with providing assistive power at the affected ankle [5]. The design of AAFO was aimed to improve gait and assist in therapy by having more control on the ankle movement such as stiffness, authorises the control on plantarflexion angle, receives and gives feedback according to the data detected by sensors. In this paper, the design, fabrication and control of a new AFO based on the active concept are discussed.

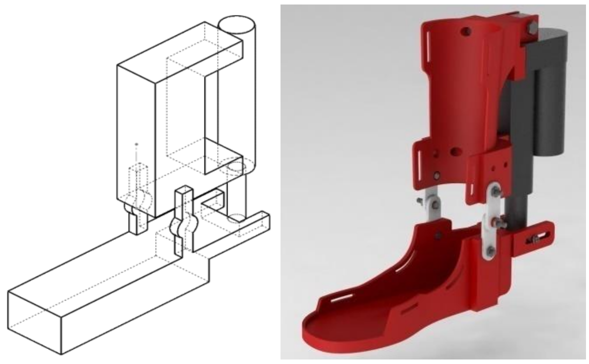
II. MATERIALS AND METHOD

A. *Design Process*

The design process is referred to the different phases involved to develop the ankle foot orthosis (AFO). It includes conceptual, embodiment and detailed design as proposed by [6]. The conceptual design refers to the drafting process that aimed to visualise the initial ideas generated for the new product. Pugh concept selection, a decision analytic tool using score rating was used to narrow down multiple design concepts, from types of AFO to material selection to generate the best design.

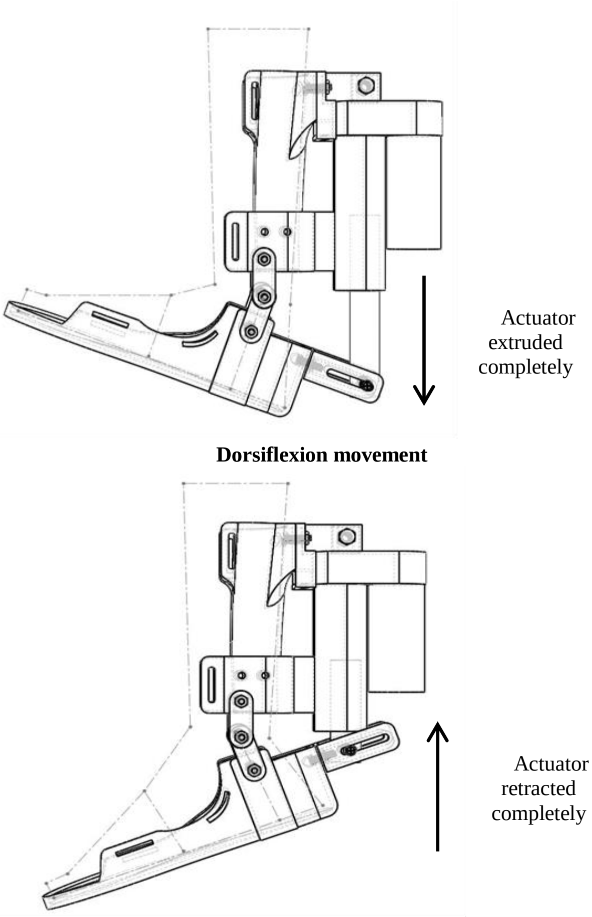
The embodiment refers to the configurations of the selected design concept. The arrangement of parts such as a hinge, foot braces and motor were decided in this phase. Product architecture helps visualised the possible parts and elements needed in the design. Besides, analysis of related factors such as the ground floor reaction and range of motion were carried out during embodiment design phase. The analysis was conducted to identify the specification of the actuator to be used. The constructed product architecture for this research is shown in Figure 1(a).

The new AFO was based on the active concept. The AFO was designed with one degree of freedom that allowed movement of dorsiflexion and plantarflexion as shown in Figure 2. Since the mechanism was developed to restrict uncontrolled plantarflexion and support the movement of dorsiflexion, the dorsiflexion angle was designed at the maximum range. At the same time, the minimum angle was designed for the plantarflexion movement by considering human biomechanics limit and walking ankle as a reference. Lastly, in detailed design, the selected concept was specified and drawn using computer-aided design (CAD) software. Figure 1(b) shows the three dimensional (3D) design of the new AFO.



(a) (b)

Figure 1: The (a) constructed product architecture and (b) 3D design of a new AFO



Plantarflexion movement

Figure 2: The design concept

B. *Electrical and Electronics Components*

A DC (direct current) motor was used as the actuator for the new AFO. The linear type actuator allowed one linear direction of extension and contraction movement that controlled the dorsiflexion and plantarflexion mechanism. The linear actuator was selected because of the large torque, accurate stroke length and sustainable for long-term use. The selected linear actuator enables 51mm stroke length and loads rated within 900N. CT-UNO Arduino board was used as a microcontroller for the AFO. It was used together with Cytron 10A motor driver shield (Shield-MD-10 R2) to control the direction and speed of the actuator.

III. RESULTS AND DISCUSSION

A. *The Prototype*

The prototype of the ankle foot orthosis (AFO) is shown in Figure 3. An actuator is connected at the backside of the foot brace, and the transferred kinetic energy enables the mobility function. As the affected foot is attached to the AFO, the dorsiflexion and plantarflexion are performed during the mobility function. The allowed angle of plantarflexion and dorsiflexion are based on the biomechanics of human foot ankle as well as the ankle angle during walking.

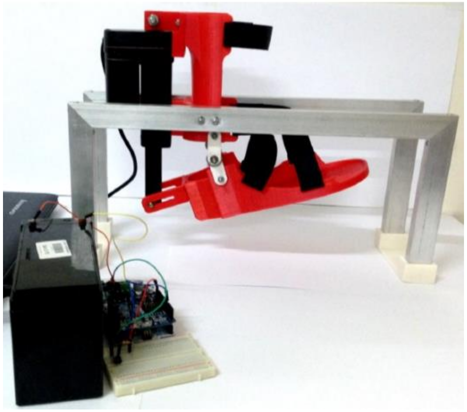


Figure 3: The AFO prototype

Table 1 shows the maximum range of motion (ROM) for the ankle. It includes the biological ROM, biological ROM during walking and ROM for the designed AFO. According to [2], the maximum biological ROM is +20° for dorsiflexion and -50° for plantarflexion. The maximum biological ROM during walking is +10º for dorsiflexion and -20º for plantarflexion. The ROM for designed AFO was set to be +20º for dorsiflexion and -20º for the plantarflexion.

Table 1
The Range of Motion (ROM)

Movement	Human Maximum Biological ROM	Human Maximum Biological during Walking	Designed AFO's ROM
Dorsiflexion	+ 20°	+ 10°	+ 20°
Plantarflexion	- 50°	- 20°	- 20°

To obtain the desired ROM of AFO, the position of the actuator which acts as the artificial muscle of lower limb was set, and the required stroke length was calculated with the aids of free body diagram as shown in Figure 4. The actuator was positioned with horizontal distance at the end of the actuator to the hinge pivot as 70mm. The required stroke length for the natural position (0°) was calculated with simple trigonometric as shown in Equation (1).

$$\tan(20) = x/70 \quad (1)$$

Based on the calculation, the required stroke length for the AFO was set to be approximately 25mm (x = 25.48mm). Thus, the foot brace would perform plantarflexion with -20° when the actuator is in fully stroked length of 50mm, remain in natural position (0°) when actuator extracts to approximately 25mm and dorsiflexion with +20° when the actuator is fully retracted.

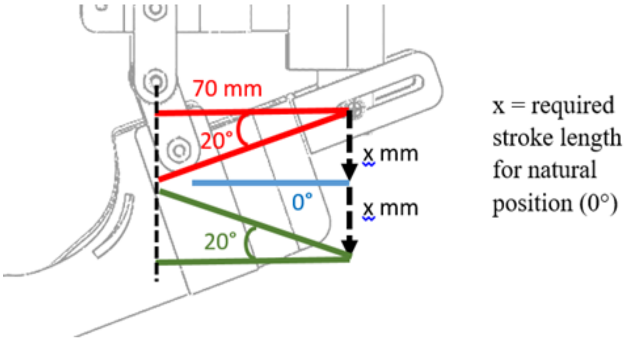


Figure 4: Free body diagram to calculate required stroke length

Besides the stroke length, the moment of the hinge and required forces were calculated to ensure the force exerted by the actuator is adequate for supporting the ground reaction force. Due to the limitation of data collection, body weight and foot segment weight were assumed with accordance of data from others studies.

As recorded by [7], the weight of 11 years old male children is estimated in the range of 29kg to 62kg with a median value of 34.28kg. As for foot segment weight, it was taken from anthropometric data which are approximately 1.431% to 1.765% of body weight [8]. Figure 5 shows the free body diagram of the designed mechanism and adequate forces applied were proven through the calculations.

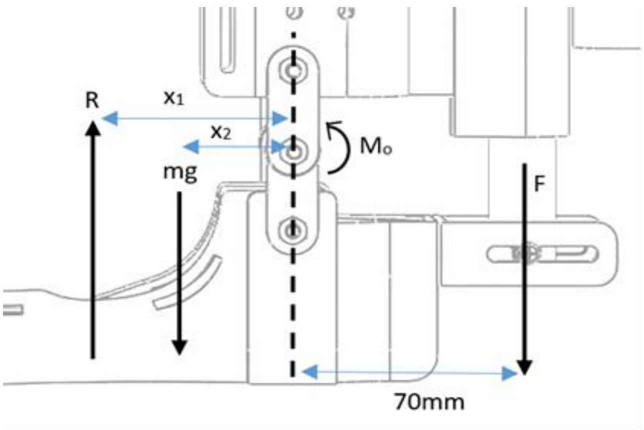


Figure 5: Free body diagram

where: F = Required force
R = Ground reaction force by body mass
m = Foot mass
g = Gravitational force
x = Estimated distance
M_o= Moment of force

The distance x_1 and x_2 are estimated to be 50mm and 20mm respectively while the total body weight of the 11 years old subject is estimated to be 50kg with 0.75kg (1.5% of body weight) of foot weight. The analysis of the required force is calculated using Equation (2) and (3). Thus, the required force by the actuator should be more than 348.30N.

$$+M_o = mg(x_2) - R(x_1) \quad (2)$$

$$+M_o = -F(0.07) \quad (3)$$

The final prototype was fabricated using a 3D printer. The lower limb and foot braces were designed to fit accurately to patient's leg. The edges of braces were filleted to prevent any sharp edges. Custom design and fitting the affected limb would improve the user's experience and comfortability. In general, contoured foot beds (divided into the horizontal and vertical curve) would bring comfortability to the foot as well as helping in weight distribution. The arch shape of designed foot brace is highlighted in Figure 6.

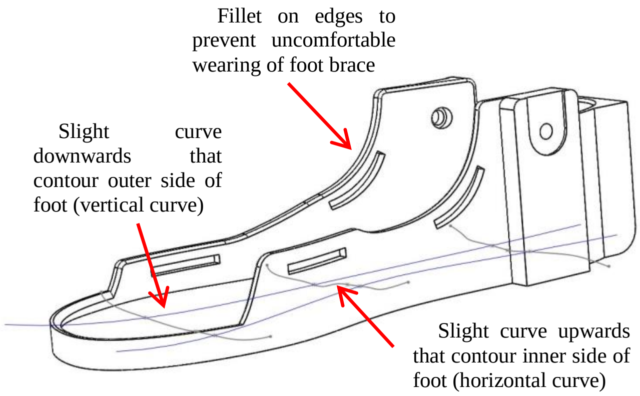


Figure 6: The design of foot bed

Also, the adhesive strap was designed with one-sided fold instead of the two-sided fold (that requiring two hands) to encounter the possibility of patient's right arm is affected to hemiplegia. By fixing the end of adhesive strap at left side, a user with right-sided hemiplegic would require less effort to pull the strap from right to left. Besides, another design concept is design for disassembling. The concept is to enable the user to disassemble each component or parts of the ankle foot orthosis (AFO) easily.

The main intention of the concept used in the AFO is to reduce the cost of repair by replacing parts instead of changing the whole AFO. Changes in the body such as the growth of height are common for children. Design for disassembling enable the user to change the unfit braces to newly custom-made braces without changing other parts such as hinges.

Design for disassembling also enable customisation on the appearance of AFO. Children can choose the colour combinations or any designed style of each part of AFO with their interest. The idea might improve self-confidently and lessen tediousness to use the AFO which eventually improve the frequency of the training activities.

Another concern to apply in the design concept is the use of mainly recyclable material which is polylactic acid (PLA) and acrylonitrile butadiene styrene (ABS). Design of disassembling brings convenient in recycling the product by lessening the works of separating the parts. The total weight of the AFO prototype without electrical components is around 1.18kg, and the total cost is about RM421.69 (about USD100).

B. *Software Programming*

The flowchart of the actuator (DC motor) control is shown in Figure 7. In general, the programming start with the system read the motor direction, speed and push button variables in the program. When the switch button is pushed for the first time, the motor started to extrude slowly from the natural position (ROM = 0°) until the maximum height to perform a dorsiflexion movement. After the movement reached the maximum height, the motor started to retract to perform a plantarflexion movement.

An overview of the movement can be seen previously in Figure 2. The movement (dorsiflexion and plantarflexion) is performed continuously (looping) until the switch button is pushed for the second time. During that time (button is pushed for the second time) the motor stops the on-going movement (the looping) and make a new movement to the natural position (ROM = 0°).

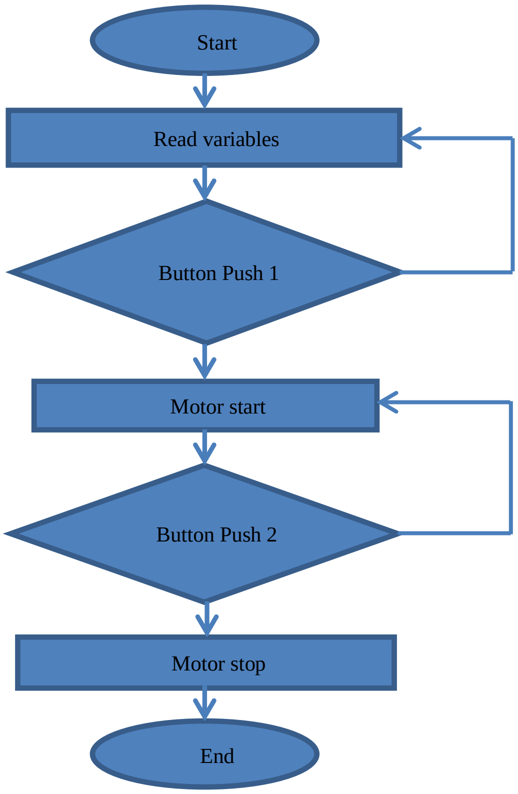


Figure 7: The flowchart of the control system

IV. CONCLUSION

The paper discussed the development of ankle foot orthosis (AFO) for hemiplegic children. The active concept AFO was designed and fabricated using 3D printing. The range of motion (ROM) was set up to be +20º for dorsiflexion and +20º for plantarflexion movement. The AFO only focused on the static rehabilitation where the patients need to wear the device while in the sitting position. Human testing needs to be conducted to evaluate the performance of the AFO.

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