DESIGN AND ANALYSIS OF ANKLE FOOT ORTHOSIS FOR DISABLED CHILDREN

S. Mohamaddan[1], N.Z. Ishak[1], A.M. Aizuddin[1], S. Yamamoto[2], S.Z.M. Dawal[3], E.B. Safawi[4] and H. Khamis[1]

[1]Department of Mechanical and Manufacturing, Faculty of Engineering Universiti Malaysia Sarawak, 94300 Kota Samarahan, Sarawak, Malaysia.

[2]Department of Bioscience and Engineering, College of Systems Engineering and Science, Shibaura Institute of Technology, 3308570 Saitama City, Japan.

[3]Department of Mechanical Engineering, Faculty of Engineering, University of Malaya, 50603 Kuala Lumpur, Malaysia.

[4]Department of Surgery, Faculty of Medicine and Health Science, University Malaysia Sarawak, Kota Samarahan, Sarawak, Malaysia.

Corresponding Author's Email: [1]mshahrol@unimas.my

Article History: Received 16 August 2017; Revised 25 October 2017; Accepted 10 December 2017

ABSTRACT: Ankle Foot Orthosis (AFO) is a brace or device that is worn on the lower leg to support and correct the foot and ankle position. AFO is also used to correct the foot drop. In this paper, a new design of AFO is proposed and its analysis using AUTODESK Inventor will be discussed. The design concept was based on the short and long size of pneumatic artificial muscle (PAM). The PAM are custom made in the laboratory with the short and long size are 150mm and 250mm respectively. Single point statics analysis including reaction force and moment at selected points were conducted for both designs. Based on the von Mises stress, displacement, safety factor and PAM experiment result, the long size design is selected for this research. Fabrication and further testing needs to be conducted in order to evaluate the device.

KEYWORDS: *Ankle Foot Orthosis; Brace; Foot Drop; Design*

1.0 INTRODUCTION

The human foot plays an important role in human motions such as stable standing, walking, running, jumping and etc. According to [1], the complexity of the foot causes difficulty in understanding and analyzing the mechanism of motion especially by means of quantification. In general the human foot consists of three sections which are the forefoot, midfoot and hindfoot. The skeleton structures are build from phalanges, metatarsals, talus, calcaneus and other parts and are supported by muscles, ligaments and tendons. The biomechanics of each part plays an important role in building up the kinetic and balancing system.

Ankle Foot Orthosis (AFO) is a brace or device that is commonly used for the lower limb [2]. The device is used to correct the instabilities of the lower limb and the ankle angle (foot drop). By using AFO, the user may improve the walking pattern performance by proper control motion of the device. Also, using AFO will improve the foot mobility or can be used as rehabilitation devices to correct the motor patterns [3].

AFO can be categorised into three groups which are passive, semi-active and fully active [4-5]. Passive AFO is used to fix or articulate the foot joints. Semi-active AFO is used to modulate damping at the joints and fully active AFO is used to produce torque for propulsive assistance and motion control. AFO can be used to support the disabled children for example those with cerebral palsy (CP). CP is a group of disorders of impaired motor and sensory function. Due to the brain impairment at the early stage, CP children have non progressive disorder of movement and posture which leadsto low level of fitness, physical activity and trouble with communication [6].

Children with hemiplegia CP (half body paralyzed) have a tendency to walk with the toes where the affected foot strikes the ground first instead of the usual heel strike and sometimes will leads in trip and then fall [7-8]. This is due to the excessive plantarflexion and weak dorsiflexion during swing phase (in gait cycle) which also known as “foot drop”. Foot drop is a condition in which the foot is not effectively clear the ground due to weak or absent dorsiflexors [9], causing gait pattern steppage-type [10]. AFO can be used to avoid the foot drop from occuring by applying it to the children's leg or through rehabilitation by strengthening the related muscles. AFO uses different types of actuator to control the movement. Pneumatic artificial muscle (PAM) is one of the widely applied actuator. PAM is a type of actuator that has a linear contractile motion operated by air pressure which utilises a pneumatic bladder. The PAM works when it is pressurized where the PAM is inflated and shortens. When the gas is sucked out, the membrane will squeze. The core element is a flexible reinforced closed membrane which is attached to both ends.

PAM has many advantages such as flexibility and elasticity which is similar to skeletal muscle behaviour. Besides, PAM is a light weight and quiet system which is suitable for medical application and rehabilitation. PAM is also suitable for under water application [11]. However, there are also several disadvantages in using PAM. PAM is a non-linear system where due to the elasticity and small vibration, the precision of the device or robot decreases. The speed of PAM system is also considered low. Therefore, PAM is most suitable in applications where high elasticity and low precision can be accepted [11]. There are several types of PAM such as pleated PAM, braided, embedded and netted muscles.

In this paper, the braided muscle or also known as McKibben muscles is used. The McKibben artificial can imitate almost the human muslces otther than other types [5]. Thus, PAM are desirable for AFO application because they are inherently compliant, light weight and capable of high forces [12-14]. The objective of this paper is to discuss the design and analysis of two different AFO for disabled children. The design was based on pneumatic artificial muscle (PAM) and the analysis was conducted using the design software, AUTODESK Inventor. The next section will discuss the methodology, results and discussion from this research.

2.0 METHODOLOGY

2.1 Anthropometric Measurement of the Foot

The first step of this study was to conduct the anthropometric measurements of the foot. The measurements were conducted in order to have sample measurements of the children foot. Five children aged 12 years old were selected as the sample. There were in total 18 areas of the lower limb that were selected as shown in Table 1.

Table 1: Anthropometric measurement area

No	Dimension	No	Dimension
1.	Tibia length	10.	Heel breadth
2.	Calf girth	11.	Ball girth
3.	Knee girth	12.	Instep girth
4.	Ankle girth	13.	Short heel girth
5.	Foot length	14.	Sphyrion height
6.	Ball of foot length	15.	Sphyrion fibular height
7.	Outside ball of foot length	16.	Navicular height
8.	Foot breath diagonal	17.	Toe height
9.	Foot breath horizontal	18.	Instep height

Figure 1 shows an example of anthropometric measurements at the calf girth and navicular height area. Standard professional anthropometer tools (Rosscraft) were used during the process. The measurements were conducted in order to have a reference size (mean size) of the children foot.

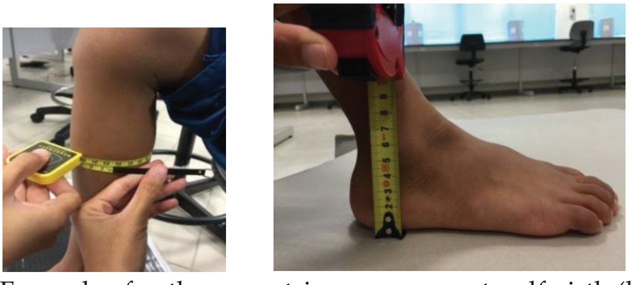


Figure 1: Example of anthropometric measurement; calf girth (left) and navicular height (right)

2.2 Design Concept and Analysis

The design concept of the AFO was based on the pneumatic artificial muscle (PAM) system. The design should be compact and able to avoid the foot drop from occurred. The design was based on the active AFO concept where it will be applied for the rehabilitation purposes.

Two sizes of PAM which is 150mm (short) and 250mm (long) were tested in the design. The different size configurations will be referred to as short and long respectively.

2.3 Design, Fabrication and Experiment of Air Muscle Actuator

In house design and fabrication of the pneumatic artificial muscle (PAM) was conducted for this research. Firstly, the FLEXO PET or mesh stripe with 25mm diameter was selected as the cover. The length of the cover will be 40mm longer than the desired length. For example, 290mm will be used for the 250mm length PAM (long size PAM).

Secondly, the rubber tube with 25mm diameter was used for the air movement. The rubber tube was cut 30mm longer than the desired length. For the long size PAM (250mm), 280mm will be provided. After that, the rubber tube was connected to the custom made shaft at both ends as shown in Figure 2 (left). Then, the mesh strip was pulled on to cover the rubber tube and a ring was put at both ends of mesh stripe as shown in Figure 2 (right). The three jaw chuck was used to tighten the ring. Lastly, the ring was covered using adhesive tape in order to prevent air leak.


Figure 2: The custom made shaft component (left) and ring cover to prevent air leak (right)

The fabricated PAM is shown in Figure 3. The PAM was experimented using laboratory setup in order to understand the air flow in the rubber tube and the characteristics of the short and long size. In other words, the experiment was conducted in order to evaluate the inflation and contraction behavior of the PAM.

Figure 3: The fabricated pneumatic artificial muscle

3.0 RESULTS AND DISCUSSION

3.1 Anthropometric Data

Based on the measurements, the anthropometric result is shown in Table 2. The result was based on the dimensions of 12-year-old children. The measurement results involved the mean, standard deviation (SD) and coefficient of variation (CV) of the foot. Five children were used as the subjects. The measurement is considered as a basis for the children's foot size. The measurement was used to design the AFO.

Table 2: Anthropometric measurement results [15]

Dimension	n = 5		
	Mean	SD	CV (%)
1. Tibia length	32.59	3.60	4.38
2. Calf girth	30.20	5.09	4.13
3. Knee girth	31.26	3.98	2.87
4. Ankle girth	18.82	2.08	4.65
5. Foot length	21.20	1.58	1.91
6. Ball of foot length	15.63	1.49	5.08
7. Outside ball of foot length	13.74	1.12	6.74
8. Foot breath diagonal	8.74	0.82	3.17
9. Foot breath horizontal	8.70	0.86	2.71
10. Heel breadth	5.41	0.78	7.02
11. Ball girth	20.69	1.52	1.93
12. Instep girth	20.30	1.91	3.73
13. Short heel girth	24.66	9.98	3.65
14. Sphyrion height	8.43	0.39	4.42
15. Sphyrion fibular height	7.40	0.72	10.81
16. Navicular height	5.61	0.43	6.86
17. Toe height	1.52	0.10	5.34
18. Instep height	4.63	0.49	11.03

3.2 Analysis of Designs 1 and 2

The final design of the AFO is shown in Figure 4. The short and long size of the PAM is shown in Figure 4 (left) and 4 (right) respectively. In a general mechanism, a sensor will be placed at the heel and toe area. As the toe touches off the ground, the sensor at toe area will activate and the PAM will start to actuate.

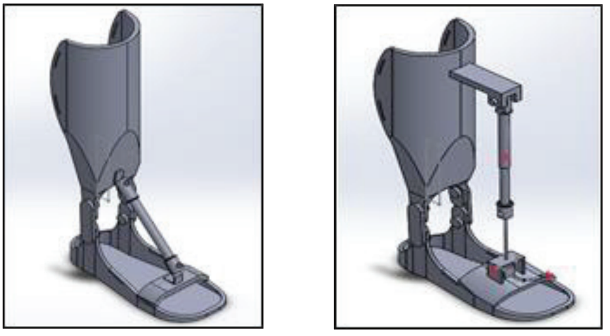


Figure 4: The design concept of the AFO: short (left) and long (right) system

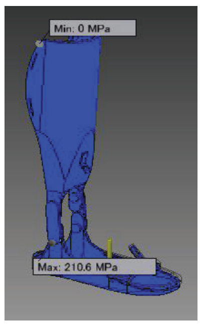
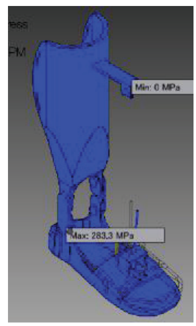
At this phase, air pressure is applied to the PAM and the high pressure gas will expand and the actuator will shorten and inflate generated the contraction force. This phase can resist plantarflexion to occur during swing. During heel strike, the PAM will be contracted and go back to its normal state as the sensor is placed at the heel area.

The simulation result using AUTODESK Inventor is shown in Table 3. Three analyses were conducted for both designs. The analysis includes von Mises stress, displacement and safety factor of the device. The von Mises stress analysis was conducted in order to understand whether the designed material will yield when subjected to a complex loading condition. The safety factor analysis was conducted in order to understand the capacity of the system beyond the expected loads or actual loads.

In both analysis, the load is assumed to be 35kg similar to the weight of the children. Design 1 has minimum of 0MPa and maximum of 210.6MPa von Mises stress. The displacement is between 0mm (minimum) to 7.8mm (maximum). Lastly, the safety factor of Design 1 is between 3.1 (minimum) to 15 (maximum).

The Design 2 shows that the von Mises stress is between 0MPa (minimum) to 283.3MPa (maximum). At the same time, Design 2 have between 0mm (minimum) to 8mm (maximum) displacement and the safety factor is between 1.14 (minimum) to 15 (maximum). Design 2 experience higher stresses compared to Design 1. Therefore, it has a lower minimum safety factor. This indicates that in Design 2, there is a probability of failure compared to Design 1. However, Design 2 is still considered acceptable since the safety factor value is more than 1 (lower than 1 can be considered as weak design).

Table 3: Simulation results for Designs 1 and 2

	Design 1		Design 2	
Dimension				
	Max	Min	Max	Min
Von Mises stress (MPa)	210.6	0	283.3	0
Displacement (mm)	7.8	0	8.0	0
Safety factor	15	3.1	15	1.4

3.3 The Air Muscle Actuator Experiment

The experiment result is shown in Figures 5 and 6. Figure 5 shows that the short size PAM (150mm) inflated at 0 second. At the same time, the PAM started to contract at 0.15mm displacements. The contraction continued until approximately 0.7 second before the actuator failed.

At the same time, the long size PAM (250mm) managed to perform inflation and contraction until 20 second (experiment stop) as shown in Figure 6. The experiment shows that 250mm PAM has the inflation and contraction behavior that is needed to operate the AFO mechanism. However, the 150mm PAM is considered not appropriate as the actuator since it was blown up at 0.7 second after the air and load was supplied to the PAM.

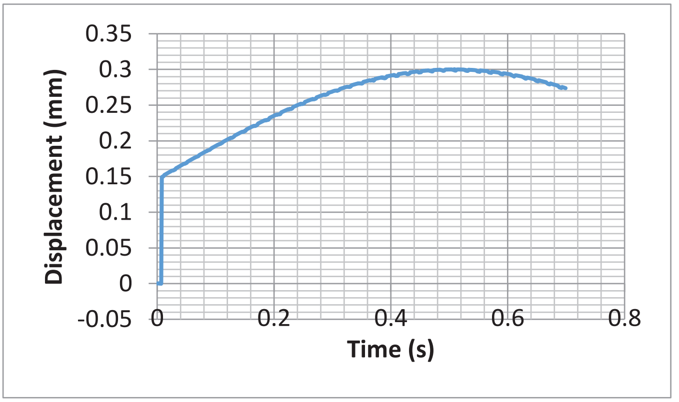


Figure 5: The fabricated pneumatic artificial muscle (short)

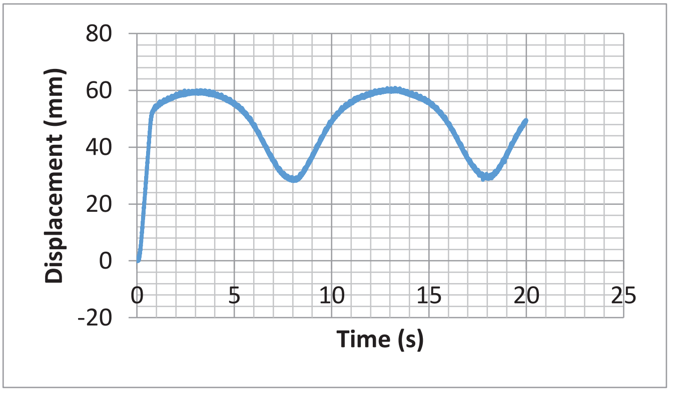


Figure 6: The fabricated pneumatic artificial muscle (long)

4.0 CONCLUSION

This research discussed the design and analysis of the ankle foot orthosis (AFO) using the pneumatic artificial muscle (PAM). The design was based on the anthropometric measurement data conducted with five children (all 12 years old). Two designs were proposed using short and long PAM. The design analysis using AUTODESK Inventor shows that Design 2 with long PAM (250mm) has higher von Mises stress value and lower minimum safety factor compared to Design 1 with short PAM (150mm). However, due to the ability of 250mm PAM to perform inflation and contraction behavior that is needed for the AFO mechanism, Design 2 was selected for this research. As a future work, the fabrication, control and testing of the device is need to be conducted in order to evaluate the system.

ACKNOWLEDGMENTS

This research is funded by the Ministry of Higher Education Malaysia (MOHE) under the Research Acculturation Collaboration Effort [RACE/c(4)/1333/2016(6)]. The authors would like to thank Universiti Malaysia Sarawak (UNIMAS), University Malaya (UM) and Shibaura Institute of Technology, Japan for providing the facilities for this research.

REFERENCES

[1] A. Bahler, "The Biomechanics of the Foot", *Clinical Prosthetics and Orthotics*, vol. 10, no. 1, pp. 8-14, 1986.

[2] M. Wingstrand, G. Hagglund and E. Rodby-Bousquet, "Ankle-foot orthoses in children with cerebral palsy: a cross sectional population based Study of 2200 Children", *BMC Musculoskeletal Disorders*, vol. 15, no.1, pp. 1-7, 2014.

[3] P.C. Kao and D.P. Ferris, "Motor adaptation during dorsiflexion-assisted walking with a powered orthosis", *Gait & Posture*, vol. 29, no. 2, pp. 230-236, 2009.

[4] K.A. Shorter, J. Xia, E.T. Hsiao-Wecksler, W.K. Durfee and G.F. Kogler, "Technologies for powered ankle-foot orthotic systems: possibilities and challenges", *IEEE/ASME Transactions on Mechatronics*, vol. 18, no. 1, pp. 337-347, 2013.

[5] K.A. Shorter, "The Design and Control of Active Ankle Foot Orthoses", Ph.D. dissertation, University of Illinois, Urbana-Champaign, 2011.

[6] P. Rosenbaum, N. Paneth, A. Leviton, M. Goldstein, M. Bax, D. Damiano and B. Jacobsson, "A report: the definition and classification of cerebral palsy", *Development Children & Child Neurology*, vol. 49, no. s109, pp. 8-14, 2007.

[7] Y.I. Park, B. Chen, D. Young, L. Stirling, R.J. Wood, E. Goldfiled and R. Nagpal, "Bio-inspired active soft orthotic device for ankle foot pathologies", in IEEE/RSJ International Conference on Intelligent Robots and Systems, San Francisco, USA, 2011.

[8] J. Romkes, A.K. Hell and R. Brunner, "Changes in muscle activity in children with hemiplegic cerebral palsy while walking with and without ankle-foot orthoses," *Gait & Posture*, vol. 24, no. 4, pp. 467-474, 2006.

[9] A. Smalley *"AFOs for foot drop" Development Children & Child Neurology*, vol. 54, no. s113, pp. 29-33, 2014.

[10] R. Chin, E.T. Hsiao-Wecksler, E. Loth, G. Kogler, S.D. Manwaring, S.N. Tyson and J.N. Gilmer, "A pneumatic power harvesting ankle-foot orthosis to prevent foot-drop", *Journal of Neuro Engineering and Rehabilitation*, vol. 6, no. 1, pp. 1-11, 2009.

[11] T.Y. Choi, S. Jin and J.J. Lee, "Implementation of a robot actuated by artificial pneumatic muscles", in SICE-ICASE International Joint Conference, Busan, South Korea, 2006, pp. 4733-4737.

[12] G.K. Klute, J.M. Czerniecki and B. Hannaford, "McKibben artificial muscles: pneumatic actuators with biomechanical intelligence", in IEEE/ASME International Conference on Advanced Intelligent Mechatronics, Atlanta, USA, 1999, pp. 221-226.

[13] D.B. Reynolds, D.W. Repperger, C.A. Phillips and G. Bandry, "Modeling the dynamic characteristics of pneumatic muscle", *Annals of Biomedical Engineering*, vol. 31, no. 3, pp. 310-317, 2003.

[14] B. Tondu and P. Lopez, "Modeling and control of mckibben artificial muscle robot actuators", *IEEE Control Systems*, vol. 20, no. 2, pp. 15-38, 2000.

[15] N.Z. Ishak, S. Mohamaddan, A.M.N.A. Kamaruddin, H. Khamis, S. Yamamoto and S.Z.M. Dawal, "Development of Ankle Foot Orthosis (AFO) using pneumatic artificial muscle for disable children", *MATEC Web of Conferences*, vol. 87, pp. 1-6, 2017.