Design and Development of an Assistive Ankle Joint for a Portable Orthotic Device

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Abstract: **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. Patients having ankle joint disability often suffers from foot drop. This work presents an active ankle-foot orthosis (AAFO) that was designed to allow two degree-of-freedom motion while serving to maintain proper foot position for patients with lower limb disorder. . In this study, an active ankle-foot orthosis (AAFO) is developed which can control the dorsi/ plantarflexion of the ankle joint to prevent foot drop and toe drag during walking. To prevent slapping foot after heel strike, ankle joint has to be controlled actively to minimize forefoot collision with the ground. In the late stance, ankle joint also has to be controlled to provide the toe clearance and help the push-off. The goal of the present work is to design an exoskeleton structure using the available human modelling data.. The trajectory of the ankle joint is planned using two via points. The foot sole will be provided with a flexible layer at the bottom to help reduce the torque requirements of the actuator, since it is observed that foot returns some of the energy given to it by the actuator itself.**

Keywords: **Assistive devices, AAFO, Ankle joint assistance, Deformable sole, Orthotic devices**

I. INTRODUCTION

Orthotic devices are intended to support the ankle, correct deformities, and prevent further occurrences[1]. A key goal of orthotic treatment is to assist the patient in achieving a measure of normal function. Ferris et. al. [15] 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.[16] developed a dorsiflexion assist, controlled by a spring. Dorsiflexion correction is achieved via the compression force of a spring within the assist device. Blaya 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 orthoses manufactured. All these orthoses are single axis or are elastically deformable. The limitation in normal inversion-eversion adds to the discomfort and does not provide a natural motion to the ankle [17].

In this paper, an ankle-foot orthosis with two degrees-of freedom is proposed. The two motions incorporated are dorsiflexion-plantarflexion and inversion-eversion motion. Both the motions are actively controlled by two dc stepper motors. It can be an integral part of another rehabilitation device. So, if the position of the leg in the gait cycle is available at all times, then the motion of the ankle can be controlled more accurately.

II. DESIGN OF THE ORTHOSIS

The design of an orthotic device or any biomedical device has to be done keeping in mind the ergonomics of the application. The ergonomic design of an orthotic device involves optimising the dimensions to suit the human's foot and lower limb. The device designed should be able to imitate the joint characteristics of ankle joint by having the same size as of a human foot. The human modelling data will be available for the foot. Using those proportionate dimensions, the device is modelled in some modelling software like solid works. The modelled device is then optimised for the loads acting on the device for a failure free operation.

The design should satisfy the following biomechanics during a normal walking step. The stance phase of walking can be divided into three sub-phases:

1. *Powered Plantar Flexion*

It is the first stage in the cycle. Begins after the foot is flat and ends at the instant of toe-off.

2. *Controlled Dorsiflexion*

Begins at toe-off and ends at heel-strike. During SP (Swing Phase), the ankle can be modelled as a position source to reset the foot to a desired equilibrium position before the next heel strike

3. *Controlled Plantar Flexion.*

Begins at heel-strike and ends at foot-flat.

Using the above biomechanical descriptions, the design goals for the prosthesis are summarized as follows:

1. The prosthesis should be at a weight and height similar to the intact limb

2. The system must deliver a large instantaneous output power and torque during push-off.
3. The system must be capable of controlling joint position during the swing phase

The human modelling data is available for a human of height H and having a bodyweight W. The approximate model for the ankle and foot is presented in the fig 2.1 given below.

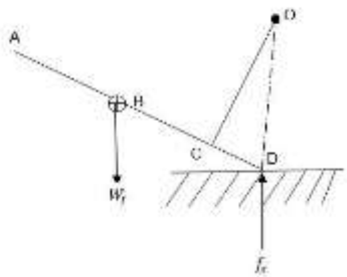

Fig 2.1: Figure showing the foot link lengths for a human of height H.

Where W_f is the weight of the foot. Point B is the point at which the weight of the foot acts (i.e., the centre of mass). Point D denotes the point at which the foot sole would be connected to the limb. f_x is the ground reaction force acting on the foot sole, which is assumed to be vertical .H is the total body height.

Table 2.1: Proportionate Foot Link Lengths

Link	Length
AB	.06 H
CD	.03H
AC	.12H

Weight of the foot, W_f =0.15 W (Body Weight)

Analysis of the model

The device was modelled with the set of dimensions given in table 2.1 for human heighted 170 cm and of weight 50 kg. The modelled part was analysed using the analysis software Solid Works Cosmos. The analysis conducted was a static one. Rather than doing a dynamic analysis the model was designed by conducting a static analysis taking the maximum load that will act on the part during dynamic conditions.

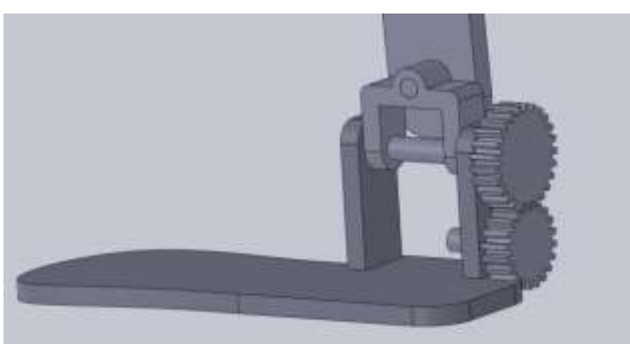

Fig 2.2: Modelled ankle foot orthotic device

The load acting on the foot sole changes during the different phases of walking. When the foot sole touches the ground, the load acting on the foot sole will be the ground reaction set up by the bodyweight of the human[2]. When the foot sole is in swing motion the load acting on the foot sole will be the weight of the foot sole plus the weight of the foot itself. Hence the foot sole is designed taking the load acting to be the bodyweight (when one of the feet is in swing motion and the other foot is in touch with the ground). The material used for the analysis was Al 1100 H16. The results of the analysis are displayed below. The images are plotted using a magnification factor of 60.

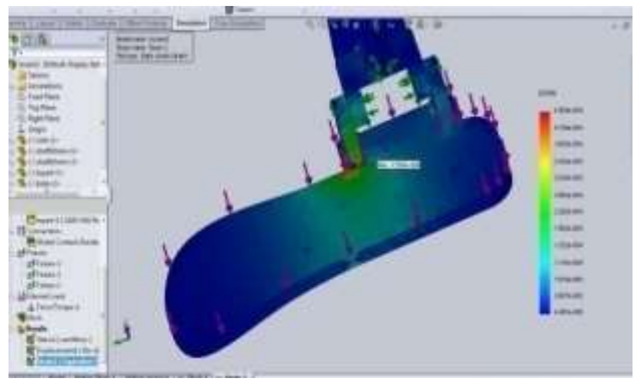

Fig 2.2: Strain distribution in the device

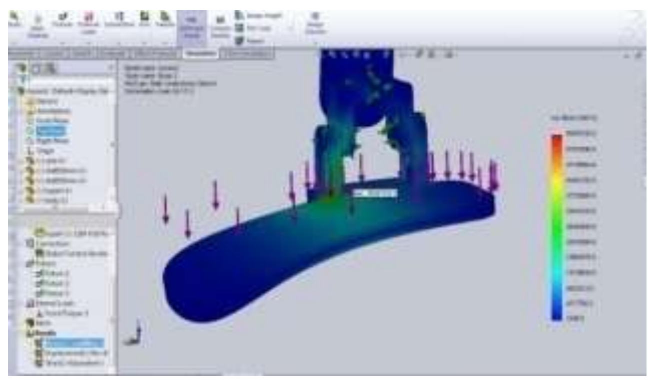

Fig2.3: Stress distribution in the device

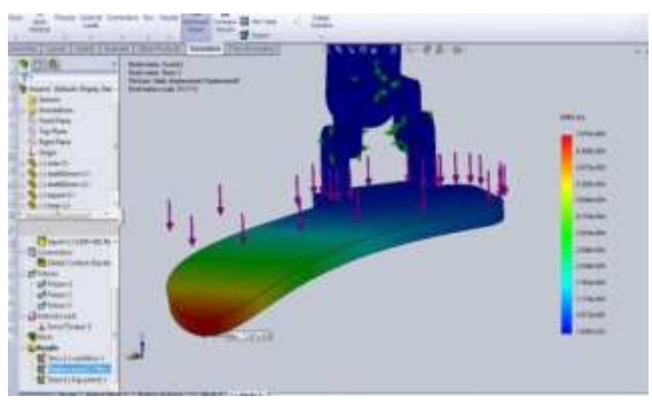

Fig 2.4: Displacement due to the load in the device

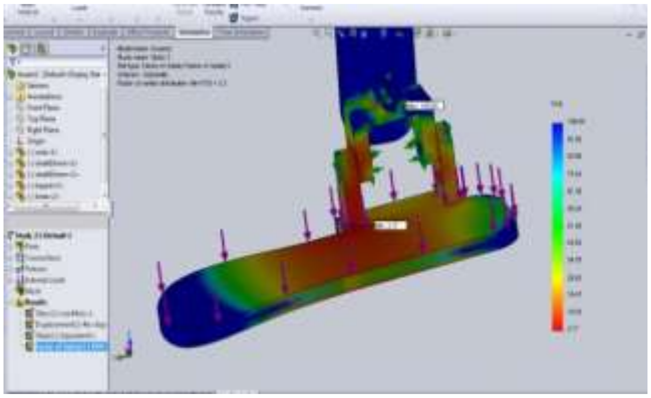

Fig 2.5: Factor of safety distribution in the device

Once the static analysis is over, it can be seen that the dimensions that have been used are either too large or small for the device. So those dimensions are optimized for a better factor of safety distribution (min FOS=2.2) and the final dimensions are obtained. Among the gears in mesh, one acts as a planet gear which rotates over the other larger gear. The gears were designed for bending strength using the Lewis equation. Also the number of teeth was determined to avoid the interference. The dimensions of the gears are given in the table below.

Table 2.2 Gear dimensions.

Gear 1	P.D	40
	O.D	44
	THICKNESS	15
	MODULE	2
Gear 2	P.D	50
	O.D	54
	THICKNESS	15
	MODULE	2

There are two parts in the model. One sole and one part used to connect the sole with the lower limb (top part). Due to the peculiar shape of the part, the parts were casted using sand casting method. Contraction allowances and machining allowances were given. The parts were then assembled using the gear 1 and gear 2 as shown in the fig 2.2. This will later be connected to the lower limb exoskeleton.

Fig 2.7: Fabricated ankle foot orthotic device.

III. MODELLING OF THE ANKLE FOOT ORTHOSIS

In this section the kinematic modelling, static modelling, and the dynamic modelling of the ankle foot orthosis has been described. The kinematic modelling is done to determine the position of the end point in the foot sole w.r.t the ankle joint so that the device can be manually controlled. In kinematic modelling, using transformation matrices the position and orientation of the axes can be specified. If the transformation matrix of the end point w.r.t the ankle joint is given, the position and the orientation of the end point can be found out for different values of rotation. The transformation matrix obtained for the ankle joint device designed is given below

$$ {}^{0}T_2 = \begin{bmatrix} C_1C_2 & -C_1S_2 & S_1 & 70C_1C_2 + 34C_1 \\ S_1C_2 & -S_1S_2 & -C_1 & 70S_1C_2 + 34S_1 \\ S_2 & C_2 & 0 & 70S_2 \\ 0 & 0 & 0 & 1 \end{bmatrix} $$

The static modelling is done to determine the torques and the forces acting on the joint when the ankle foot orthosis is in static condition. In static modelling the device is considered to be locked so that the load acting on the foot sole is assumed to be transferring through the links like in a structure. The load acting on the foot sole is considered to be vertical neglecting the other components.

$$ f_x = 500\ N $$

$$ {}^{i}fi = {}_{i+1}^{\ \ i}R\ {}^{i+1}f_{i+1} $$

$$ {}^{i}\eta i = {}_{i+1}^{\ \ i}R\ {}^{i+1}\eta_{i+1} + {}^{i}P_{i+1} \times {}^{i}f_i $$

Finally the joint torque required will be found out by taking the dot product of the joint axis vector with the moment vector.

$$ \tau i = {}^{i}\eta_i^T\ {}^{i}Z_i $$

Hence the force and the torque acting on the joint axis when the device is performing the flexion motion is found out as,

$$ {}^{0}f_0 = \begin{bmatrix} 500C_1 \\ 500S_1 \\ 0 \end{bmatrix} = \begin{bmatrix} 171 \\ 469.8 \\ 0 \end{bmatrix} $$

$$ {}^{0}\eta_0 = \begin{bmatrix} 0 \\ 0 \\ 17S_1 \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ 5.813 \end{bmatrix} $$

Hence the torque acting at the joints will be 5.813 N.

Dynamic modelling is to be done to determine the dynamic torque requirements of the device. But for that, the prerequisite will be a trajectory planning. Trajectory planning determines the angles given at the respective joints in a time dependent manner. The path traversed by the foot sole is divided into three stages and for each of the three stages, an equation for angle traversed is found out. In the first stage the rotation will be clockwise from zero to 20° and in the second stage the angular rotation will be in the counter clockwise direction from -20 to 30°. in the last and the final stage the rotation will be from 30 to zero ° in the clockwise direction

The foot sole is provided with a rubber sole at the bottom. It is been found out that in biped humanoid robots using a deformable sole will reduce the torque requirements of the device. A deformable sole will deform when a torque is applied on it and the link will be given an additional inclination. The additional inclination depends on the material property of the sole.

$$\theta = \tan^{-1}\left(\frac{3h\tau}{2l^3AE}\right)$$

The deformable sole used in the present work is rubber .Considering the material properties of the rubber and taking the length as 250 mm, h as 10 mm, maximum torque acting on the sole as 17 Nm ,the inclination angle is obtained as 2.5°

Hence angular rotation needed to give an inclination to the link becomes reduced. The torque requirement of the device depends on the angular rotation .Hence the torque will be saved. Considering the above correction the angular rotation in the first and the last stage will be updated and the equation for the angular rotation is obtained as

$$\theta_1(t) = -.91629\, t^2 + 0.61086\, t^3$$

$$\theta_2(t) = -.3490 + 2.6175\, t^2 - 1.745\, t^3$$

$$\theta_3(t) = .5235 - 1.4398 t^2 + .9599\, t^3$$

Taking the time derivatives of the above equation w.r.t time, the angular velocity and angular acceleration can be found out.

For dynamic analysis, Lagrangian Euler method is used in this work. It is an energy based method .In this method it defines a quantity L called Lagrangian which is given by

$$\mathcal{L} = K - P\ ,$$

Where K and P are respectively the kinetic and potential energy of the respective links. Torque can be obtained from Lagrangian using the equation,

$$\frac{d}{dt}\left(\frac{\partial L}{\partial \dot{q}_i}\right) - \frac{\partial L}{\partial q_i} = \tau_i \text{ , for } i = 1,2 \ldots .n$$

The ankle joint designed is having two degree of freedom. To formulate the dynamic modelling equations the centre of mass of each links has to be found out. The links are assumed to be linear links having mass at their centre of mass. The line diagram is shown below.

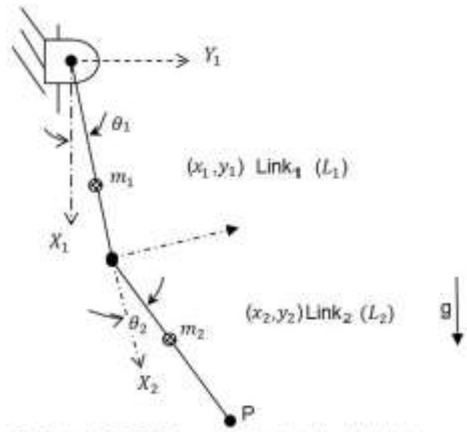

Fig 3.1: A 2 DOF planar articulated ankle joint

The Lagrangian for the two link manipulator is obtained as follows

$$\mathcal{L}=\frac{1}{2}\left(\frac{1}{3}m_1+m_2\right)L_1{}^2\dot{\theta}_1{}^2+\frac{1}{6}m_2L_2{}^2\left(\dot{\theta}_1{}^2+\dot{\theta}_2{}^2+2\dot{\theta}_1\dot{\theta}_2\right)$$
$$+\frac{1}{2}m_2L_1L_2C_2\left(\dot{\theta}_1{}^2+\dot{\theta}_1\dot{\theta}_2\right)-\left[\frac{1}{2}m_1(L_1-L_1\cos\theta_1\right)+$$
$$m_2[(L_1+L_2)-L_1\cos\theta_1-L_2\cos(\theta_1+\theta_2)]]g$$

In the present work since only a normal straight line walking is considered, torque required at the joint 1 is considered. Now to find the torque required at the joint 1, the Lagrangian will be substituted in the equation .The torque required in the joint 1 will be obtained as,

$$\tau_1=\left[\left(\frac{1}{3}m_1+m_2\right)L_1{}^2+\frac{1}{3}m_2L_2{}^2+m_2L_1L_2C_2\right]\ddot{\theta}_1+$$
$$\left[m_2\left(\frac{1}{3}L_2{}^2+\frac{1}{2}L_1L_2C_2\right)\right]\ddot{\theta}_2-m_2L_1L_2\sin\theta_2\dot{\theta}_1\dot{\theta}_2-$$
$$\frac{1}{2}m_2L_1L_2\sin\theta_2\dot{\theta}_2{}^2+\frac{1}{2}m_1L_1\sin\theta_1+m_2(L_1\sin\theta_1+L_2\sin(\theta_1+\theta_2))$$

Substituting for the above terms torque is obtained as $\tau_1 = 45$ mNm .it is been noted that when there is no sole deformation, the torque is obtained as *55* mNm.hence using a deformable sole with the foot orthotic device helps to reduce the torque requirements.

IV. RESULTS AND DISCUSSIONS

The device was modelled and analysed in the solid works. The dimensions modified to get a minimum FOS of 2.2. After the analysis the stress, strain and displacement distribution was verified .Their maximum values falls within the allowable range

	Von Misess stress	strain	displacement
Max value	5.658e7	4.564e-004	7.047e-004

The weight of the device comes to be 1.7kg.The commercially available assistive devices like the HAL weigh about 15 kg in the lower limb part. By using a proper polymer of light weight and good strength the weight can still be reduced .

In the present work, only a normal straight line motion is considered, as the device considered is for rehabilitation. But in the case of biped robots, walking on sloped surfaces, conditions of running has been extensively studied. If these can be applied to an assistive device for human, it will enhance the capabilities of the exoskeleton system

REFERENCES

[1] Abhilash S S, Manu V Thottackkad, "Trajectory Planning of a One Degree of Freedom Assistive Robotic Knee", International Journal of Latest Technology in Engineering, Management & Applied Science (IJLTEMAS) Volume VI, Issue I, January 2017

[2] Abhilash S S, N Ramachandran, K S Sivanandan, "Design and Development of an Assistive Robotic Knee for a Portable Active Orthotic Device", International Conference on Advanced Computing and Communication. AJCE Kottayam, May 2010

[3] Sungjae Hwang, Jungyoon Kim, Jinbock Y, Kisik Tae, Kihong Ryu, Youngho Kim, "Development of an Active Ankle Foot Orthosis for the Prevention of Foot Drop and Toe Drag ", International Conference On *Biomedical And Pharmaceutical Engineering 2006 (ICBPE 2006)*

[4] Samuel K. Au, Jeff Weber, and Hugh Herr, "Biomechanical Design of a Powered Ankle-Foot Prosthesis ", Proceedings of the 2007 IEEE 10th International Conference on Rehabilitation Robotics, June 12-15, Noordwijk, The Netherlands.

[5] Gregory S. Sawicki and Daniel P. Ferris, "Mechanics and energetics of level walking with powered ankle exoskeletons", The Journal of Experimental Biology 211, 1402-1413

[6] Hiroaki Hirai, Ryuta Ozawa, Satoru Goto, Hiroki Fujigaya, Shodo Yamasaki, Yasuhiko Hatanaka and Sadao Kawamura, "Development of an ankle-foot orthosis with a pneumatic passive element ",IEEE International Symposium on Robot and Human Interactive Communication (RO-MAN06), Hatfield, UK, September 6-8, 2006.

[7] Abhishek Agrawal, Sai K. Banala, Sunil K. Agrawal, " Design of a Two Degree-of-freedom Ankle-Foot Orthosis for Robotic Rehabilitation ",Proceedings of the 2005 IEEE 9th International Conference on Rehabilitation Robotics June 28 - July 1, 2005, Chicago, IL, USA.

[8] Maitray Shrivastava & Ashish Dutta & Anupam Saxena," Trajectory Generation Using GA for an 8 DOF Biped Robot with Deformation at the Sole of the Foot", Journal of intelligent robot systems 2007.

[9] Liquan Wang, Zhiwei Yu, and Hengnan Li, "Study on Optimal Design for Two DOF Parallel Ankle Joint Mechanism of a Biped Robot", Proceedings of 2008 IEEE International Conference on Mechatronics and Automation.

[10] Hideaki Minakata and Susumu Tadakuma, "A Study of Energy-Saving Shoes for Robot considering 3D Motion" , IEEE AMC'06-Istanbul, Turkey

[11] Qiang HUANG, Shuuji KAJITA, Noriho KOYACHI, Kenji KANEKO, Kazuhito YOKOI, Hirohiko ARAI, Kiyoshi KOMORIYA, and Kazuo TANE," A High Stability, Smooth Walking Pattern for a Biped. Robot", Proceedings of the 1999 IEEE International Conference on Robotics & Automation Detroit, Michigan May 1999.

[12] Conor James Walsh, Daniel Paluska, Kenneth Pasch, William Grand, Andrew Valiente, Hugh Herr, "Development of a lightweight, under actuated exoskeleton for load-carrying augmentation", Proceedings of the 2006 IEEE International Conference on Robotics and Automation Orlando, Florida - May 2006.US Patent 6443993, Sept. 3, 2002.

[13] D. H. Gates, "Characterizing ankle function during stair ascent, descent, and level walking for ankle prosthesis and orthosis design," Master's thesis, Boston University, 2004.

[14] Hasegawa, Y., Arakawa, T., Fukuda, "Trajectory Generation for biped locomotion robot", Mechatronics 10, 67-89(2000).

[15] D. P. Ferris, J. M. Czerniecki, and B. Hannaford, "An ankle foot orthosis (AFO) powered by artificial muscles", *In Proc. 25th Annu. Meeting American Society of Biomechanics*, San Diego, CA, 1999.

[16] S. Yamamoto, M. Ebina, S. Kubo, T. Hayashi, Y. Akita, and Y. Hayakawa, "Development of an Ankle-Foot Orthosis with Dorsiflexion Assist, Part 2: Structure and Evaluation",*Journal of Prosthetics and Orthotics*, Vol 11, Num 2, p 24, 1999.

[17] J. A. Blaya and H. Herr, "Adaptive Control of a Variable-Impedance "Ankle-Foot Orthosis to Assist Drop-Foot Gait", *IEEE Tran. on Neural Systems and Rehab. Engg*, Vol. 12, No. 1, March 2004.