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Design of Passive Anthropomorphic Ankle Prosthesis using Epicyclic gear train and its Testing

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Keywords – Prosthetic ankle, Passive Ankle joint, epi cyclic gear train, Ankle torque characteristics

Abstract

Ankle prosthesis provide functional performance for amputees. Conventional prosthesis like SACH foot are popular in low income countries. Other prosthesis like Flex-foot capable of storing energy during stance and assisting forward propulsion in dorsiflexion have single flexible carbon fiber shank instead of an ankle joint. Both SACH and flex foot provide limited range of motion up to 14 degree. We have developed a prosthetic ankle joint design which has range of motion, torque characteristics and ankle stiffness similar to that of natural ankle. Incorporating motion analysis, mechanical testing and computer analysis of ankle model, a passive energy returning ankle joint was validated experimentally using mechanical testing which showed 11.02% and 5.49% error in theoretical torque and average ankle stiffness values respectively with total range of motion of 20 ^{o} in dorsiflexion.

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1. Introduction

Amputation affects both physical and mental well being of the patient. It is associated with a decrease in quality of life of the amputees [1]. In India around 5.5 million people suffer from disability in movement [2].Lower limb amputation constitute major part of disabled population [3]. Foot prosthesis help such patients regain partial mobility. During locomotion the ankle-foot joint plays and important role in the support of body weight and control of walking kinetics. [4-5]. A gait cycle is defined as heel strike to the next heel strike on the same foot. In the final phase of gait cycle the ankle joint pushes off the floor propelling the body forward into the subsequent swing phase thus the ankle-foot joint provides necessary kinetics to the prosthesis to drastically reduce the effort required for locomotion [6]. There are many energy storage and release (ESAR) feet in the market. The model under consideration has aepicyclic gear train based ankle joint system which returns energy during later phase of dorsiflexion [7]. Natural ankle torque characteristics is replicated by a spring loaded lever made integral with the sun gear of epicyclic gear train [9]

The objective of this study is to achieve kinematic performance of ankle prosthesis similar to that of an able bodied gait at slower speeds. This includes achieving non-linear torsional stiffness of ankle, validation of theoretical average joint stiffness and range of motion of 20^0 in dorsiflexion. Mathematical model of ankle joint with epicyclic gear train was used to find ankle torque characteristics. Experimental verification of ankle torque was carried out by measurement of force required to flex the ankle with incremental change in dorsiflexion [11]

2. Research Method

The product of the force applied to a joint and the perpendicular distance between the line of the force and the joint centre of rotation can be defined as ankle torque. Natural ankle angle-moment data allows the torque to be calculated.The relationship between passive ankle dorsiflexion angle varied with the torque applied was found by Babbage et al (1987) and Chesworth and Vandervoort (1988). The relatonship between torque and passive ankle dorsiflexion displacement was found to be non-linear with increasing slope along the range of motion.

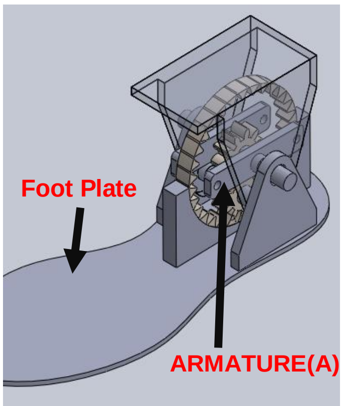


Figure 1a. Location of armature

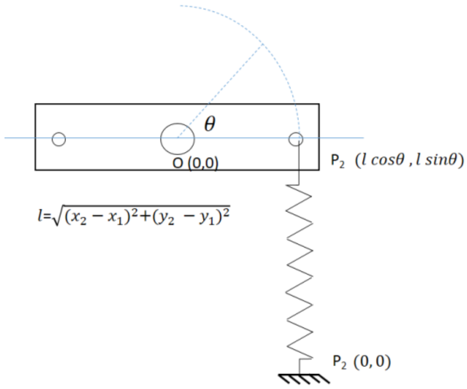


Figure 1b. Deflection of spring attached to the armature

The required spring stiffness for testing the prototype was determined by performing linear regression of theorotical torque (Ta). An epicyclic gear train was coupled with the armature as shown in figure 1a to amplify the torque (Ta) generated by spring-armature. For analytical calculation of torque the foot plate of the ankle was assumed fixed.In Figure 1b The spring is assumed to be installed with negligible pretention. Deflection of spring with change in armature(A) angleθ was calculated using distance formula Equation 1. Component of the Force(F) normal to the armature (A) generated due to deflection of spring was used to calculate Torque (T) which was furthur amplified by epicyclic gear train to give Ankle Torque (Ta). In Equation 1 parameter theta θ is the angular displacement of armature attached to the spring. K is the spring stiffness and l is the armature length.

$$F = k * l * \left(\sqrt{3 + 2(sin\theta - cos\theta)} - 1\right) \qquad (1)$$

Force generated by the spring was resolved to in the direction normal to the armature to calculate torque as shown in Figure 2. In natural ankle joint as the toe goes up with amplitude ΔY causing dorsiflexion θ_d then due to inherent properties of ankle muscles, ankle torque is increased. Centre of pressure of foot shifts forward and bio mechanical consequence of this shift is increase in torque from the foot which has to be balanced by the ankle [11]. Hence theorotical torque generated by ankle was found out by the equation 2

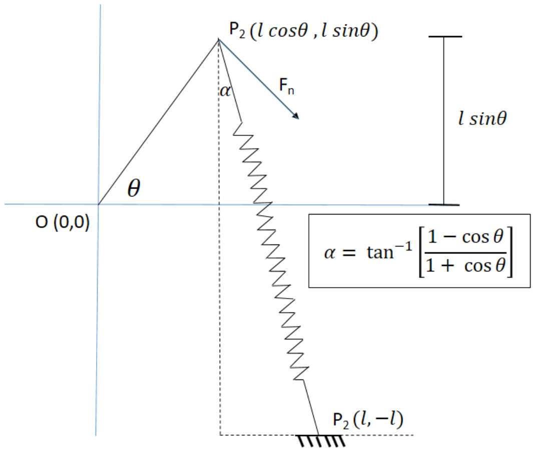


Figure 2. Geometry of Force Analysis

$$T_{ankle} = l * F_n * K_g \qquad (2)$$

Where Fn is the normal component of Force F generated by the spring , l is the length of Armature and Kg is the Amplification factor due to epicyclic gear train. Neglecting viscous and inertial components for slow incremental change in angle of dorsiflexion, average ankle stiffness could be found out be linear regression of torque vs angle data obtained from multiple values of armature angle θ.

3. Results and Analysis

After considering range of motion of able bodied ankle in dorsiflexion, epicyclic gear train was designed and kinematic analysis of ankle model was carried out using Simulink. As shown in Figure 4(a) and 4(b) Sun gear and ring gear were made integral with the armature and the bottom bracket respectively. Planet gear was connected to the upper bracket via revolute joint. During dorsiflexion, the gear train was equivalent to an epicyclic gear train with ring gear fixed and angular deflection given to the planet-sun arm. This resulted in amplification of torque on the foot-plate constraining the dorsiflexion angle to required value.

For kinematic analysis, angular displacement relative to upper bracket was given the foot plate with magnitude corresponding to the peak torque in dorsiflexion of natural ankle. Deflection of the spring provided reaction moment at sun gear through armature.This moment is further amplified by the epicyclic gear train connected to give required ankle torque for push off which also constrained the range of motion of the joint. The epicyclic gear train was designed in such a way that 27 degree angular deflection of ankle resulted to 81 degree deflection of armature.

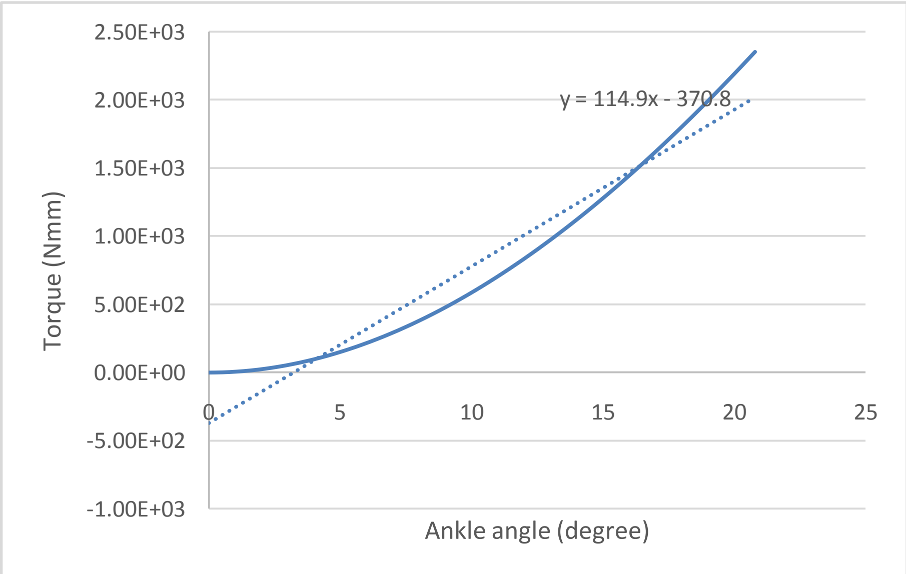
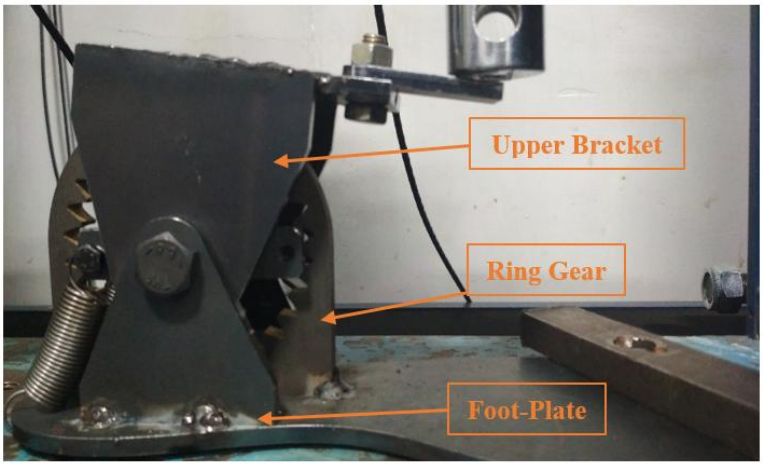


Figure 3. Ankle Torque in dorsiflexion plot obtained from simulink model

3.1. Experimental Setup

Prototype of the joint was made using laser cut sheet metal further welded to make brackets and other components of the assembly. The footplate was braced and locked to the platform to provide horizontal datum as shown in Figure 4a. The upper bracket was made parallel to the footplate with the help of gauges. Spring was installed between the armature and the footplate with negligible pretention. Ankle Force relative to the footplate was registered by the 1 ton load cell of UTM. Speed of head was set to 3mm/min constant in nature to minimize viscous and inertial component in the torque response. Force values from the test load cell were then used to calculate the equivalent torque response in dorsiflexion .Vertical input displacement of the probe was fixed at a value corresponding to 27 degree in foot dorsiflexion.



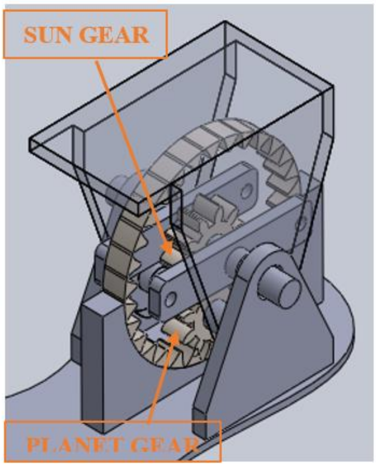


Figure 4(a) Test Setup for Torque measurement on Dorsiflexion   Figure 4(b) assembly of Ankle model

3.2. Test Results

Range of Motion test was performed first, measuring the angle before and after the full deflection of ankle spring which represented toe off during a step. Measurement revealed that the upper bracket pickup point for the UTM had to be lowered by 20 mm in order to get 12 degree dorsiflexion of ankle. This point also corresponds to the value of angular deflection when maximum torque occurs during toe off. Linear regression of torque data found by analytical model and experimental results in the second half of the stance phase as shown in Figure 3 and Figure 4b respectively. Average joint stiffness was found by calculating the slope of linear regression. Variation of both analytical and experimental ankle torque with ankle angle exhibited non-linear nature with increase in slope over the range of motion

Table 1. Peak torque values from multibody simulation and experiment

	Torque(Nmm)	Average Joint Stiffness(Nmm/Degree)	Range of Motion
Simulation	**2240**	**114.9**	**20**
Experimental	**1993**	**108.92**	**19.7**
Percent Error	**11.02 %**	**5.49 %**	**1.5%**

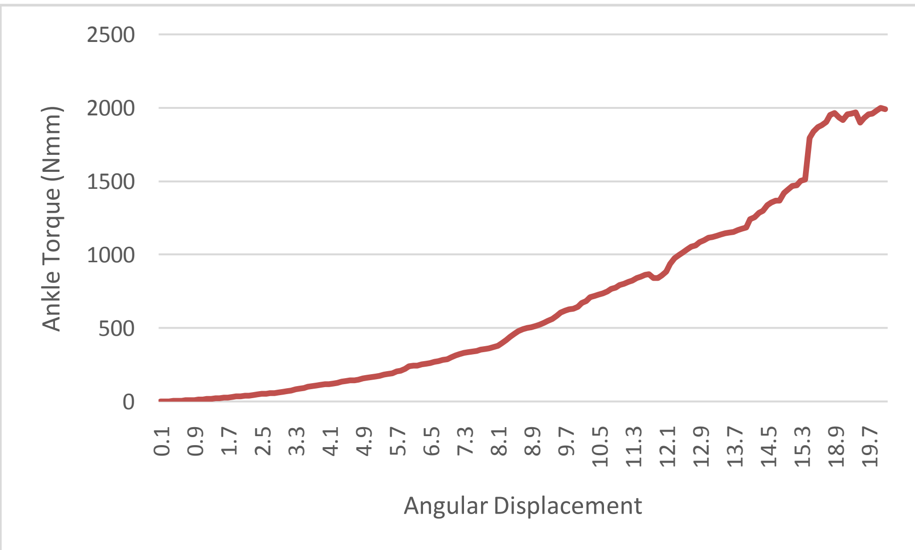


Figure 4(b) Experimental Torque response with exponential nature

4. Conclusion (10pt)

The results indicate that range of motion of up to 19.7^0 in dorsiflexion could be achieved with the prototype. Plot of ankle torque in dorsiflexion with ankle angle exhibits non-linear characteristics with increasing slope over the range of motion. Peak torque value from analytical solution shows agreement with the test results with error of 11.05 percent. Average Torsional Stiffness of ankle was obtained from linear regression of data. The reported error is minimal in case of torsional stiffness of ankle. Testing validated the capacity of the system to absorb energy during rollover and release the stored energy with sufficient torque during push off. Hence the mechanical behavior of the system is verified and torque equations can be used to design prosthetic ankle joint specific to amputee's weight, height and activity requirements. Implementation of this joint in prototype proves suitability of epicyclic gear train for prosthetic ankle joint in order to regulate ankle torque during push off

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