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Simulation of a Low Cost Powered Ankle-Foot Prosthesis during Stair Ascent and Descent Gaits

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Abstract: ***Human ankle is a synovial hinge joint where the tibia and fibula bones of leg meet the talus bone of the foot. The joint allows the dorsiflexion and plantar flexion movement of the foot during various stances of walking, running, climbing etc. Transtibial prosthesis helps to regain the function of lost foot. The advancement in transtibial prosthesis using myoelectric driven powered ankle foot prosthesis helped to achieve the most natural gaits in walking, climbing, and running etc. through nerve signals from the brain by nerve rewiring surgery which is very costly in INDIA. Most transtibial amputee cannot afford such advance technology in prosthesis to fulfill the loss caused, therefore, these amputee use conventional prosthetic leg that has no motion in ankle joints. In this paper, a design of an ankle foot device is presented to assist transtibial amputees during stair ascent and descent gaits. The device permits the dorsiflexion and plantarflexion movement of the prosthetic ankle during stair ambulation mimicking the gait pattern of normal human ankle. The dorsiflexion and plantarflexion movement is controlled by an actuator using PID. A 3D model, control scheme, and analysis of prosthetic device are presented in this paper. The objective of this paper is to present an easily affordable prosthetic device that is capable of assisting transtibial amputee during stair ambulation.***

Keywords: Powered ankle, PID controller, stair ambulation, FEM

1. Introduction

The loss of a limb is a major disability. The persons having lower limb amputation experience difficulties with mobility and balancing the body on one leg. A unilateral amputee tries to spend less weight and time on amputated leg as compared to sound leg. This results in higher metabolic cost of sound leg by higher energy consumption because of which amputee prefer walking at speed of 30-40% slower than normal able bodies [1], [2] and asymmetrical gait pattern is observed [3]-[5]. The body structure of the amputee is also changed. The knee flexion, hip extension, and ankle dorsiflexion movement of the unaffected leg is higher than the affected side.

The biomechanics of human ankle have shown that it provides net positive work during progression and varies impedance during moderate to fast walking speed [6], [7]-[10].Amputation has proven to have serious psychological, social and economic effect on the lives of human being. Amputation has effect on body image and well-being of the amputee [11]. Many amputees have problem to work after lower limb amputation and may have to change their work as well [12]. For transtibial amputee, comfort, required physical functions, and economic are the primary questions that have to be answered [13]. Ankle-foot prosthesis serves the basic requirement to fulfill the body structure of the amputee but fails to provide the functions of human ankle.

Fixed ankle foot prosthesis (Jaipur foot prosthesis) for transtibial amputees cannot provide natural gait of stair ambulation and causes the utilization of more energy during stair ascent and descent gaits [14]. Using myoelectric driven stair ascent descent powered ankle-foot prosthesis for transtibial amputees in INDIA is way more expensive for the middle class amputees. Advancement is being made in this field to develop low cost powered ankle-foot prosthesis for stair ascent and descent gait. Effort to build such a device that provides natural gait during stair ascent and decent are put forth by the researchers and many among them have achieved the objective of the device but still other parameters such as low cost and light weight powered ankle-foot prosthesis are still the major issues in this field. In this paper, the objective is to develop low cost transtibial prosthesis with angular movement in ankle joint like dorsiflexion and plantar flexion to assist stair ascent and descent gaits without using myoelectric signals from residual limb muscles, mimicking the biomechanical behavior of human stair ascent and descent gaits. The device consists of a PID interfaced with an electric motor. The PID uses signals from sensors as input and transmits the required angular movement through motor to the ankle joint.

2. Design and Materials

The biomechanics of human ankle during stair ascent descent gaits showed that the human ankle acts like a passive device (spring and damper). The prosthetic design could be modeled using spring and dampening in the foot. Therefore, the criteria set for designing the prosthetic foot is: a) storing and releasing energy like a spring, and b) absorbing shock due to vertical load during stair descent gait. In addition to these criteria, the passive prosthetic device requires addition push-off vertical force to lift the weight of the amputee during stair ascent gaits. The additional push-off force is provided by the active high torque actuator. The prosthetic foot can be designed with complete passive devices [17]. Biomechanical analysis during stair ascent and descent gait reveals that the center of mass of a healthy subject undergoes cyclic vertical translation. Convergence and divergence between center of mass and center of pressure of the human body activity represents stability and instability respectively [18], [19]. The magnitude of divergence between center of mass and center of pressure of the human body is greater during stair descent than stair ascent. This shows that stair descent gait is more of a dynamic process resulting in greater instability [20].

Based on the above criteria, a monolithic prosthetic foot is designed in accordance with the functions of spring and dampening for storing and releasing energy and preventing shock from vertical loads. The design has greater gripping capability with the surface to prevent instability. The ankle part of the foot acts like a damper to prevent jerks. The middle region of the foot, under loading stretches outwards producing frictional force for better gripping with the surface and toe region of the foot acts like cantilever spring. The monolithic foot is composed of carbon fiber composite. Carbon fiber composite foot is a light weight and extremely strong foot capable of withstanding weight more than average weight of human being. Carbon fiber composite is commonly used where high strength to weight ratio is required. The design is capable of absorbing shock and storing energy and releasing it when required.

The foot is attached with high density polyethylene (HDPE) chassis for holding the electronic arrangement for the device. HDPE is used for designing chassis to support electric motor, electronic circuit, and battery. HDPE has excellent corrosion resistant property with climatic changes, high strength, and widely available.

The chassis is covered with stump made of High density polyethylene (HDPE). HDPE material is used for making stump. Jaipur foot organization, for past few years, is using the same material for making stump [14]. HDPE is light weight and high impact resistant thermoplastic capable of withstanding climatic changes. The stump has a socket attachment for fitting the residual limb of the amputee which is presently being used by most of the people in India. The complete mechanical design of the prosthetic device is shown in figure 1.

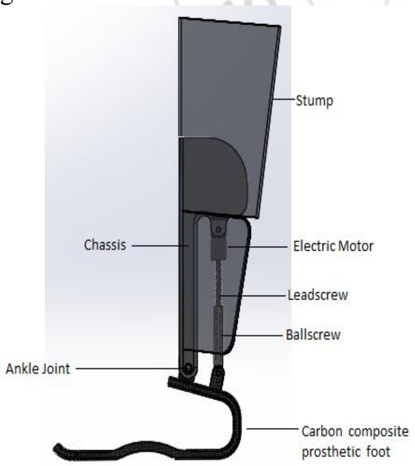


Figure 1: 3D Model of the prosthesis

3. Control Scheme

Human gait cycle is divided into stance phase and swing phase. The stance phase of walking on level surface starts at striking of the heel on the surface and ends at lifting toe from the surface. The swing phase start at toe off from the surface till the heel strikes back on the surface of the same foot [7].

The definition of stance and swing phase for stair ascent gait is similar to that of level surface walking but the definition of the stance and swing phase of gait cycle during stair descent gait is different. In stair descent gait cycle the stance phase starts at toe striking on the surface of one foot and ends at striking the toe of same foot again [15], [16].

The stance phase of stair ascent is divided into four sub-phases: two dorsiflexion phases for storing energy and two plantarflexion phases for releasing the stored energy. During the swing phase of stair ascent gait the foot changes its position preparing for striking the foot on the surface as shown in figure 2. The stance phase of stair descent gait is divided into three sub-phases: two controlled dorsiflexion for power absorption and one plantarflexion for power generation. The swing phase re-positions the foot for next toe strike on the surface as shown in figure 2 [8].

The stair ascent gait starts with first dorsiflexion phase in which the ankle acts like a passive device linear spring for storing energy, and balances the body as shown in figure 2 (a). The energy is then released by the foot during plantarflexion phase and helps in lifting the body up, figure 2 (b). Third phase i.e. dorsiflexion phase initiates the body for forward progression by storing energy in the foot as shown in figure 2 (c).

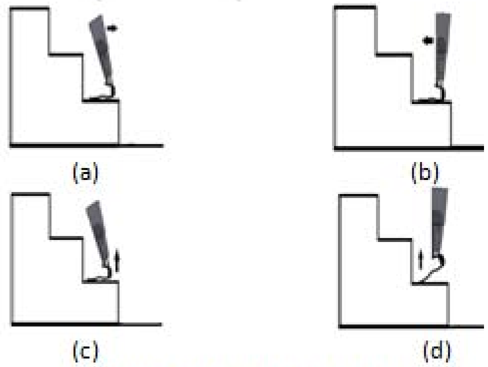


Figure 2: Phases of Stair ascent.

The fourth phase is again a plantarflexion phase in which the body moves forward by releasing the stored energy and with an assistance of actuator as shown in figure 2 (d). The second dorsiflexion phase stores energy acting like a passive spring device as shown in figure 2 (c). The final phase of stair ascent is powered plantarflexion, figure 2 (d), in which the stored energy of the previous phase combined with actuator torque is utilized to lift the amputee from the surface [2].

The stair descent gait strikes toe first on the surface of stair as shown in figure 3 (a). Before this swing phase comes in action during which the device re-position itself for striking heel first on the surface by the help of an actuator. The first phase of stair descent gait is dorsiflexion in which the device makes foot flat contact with the surface as shown by down arrow in figure 3 (b). This phase acts like a damper for preventing shock due to vertical load on the foot [21]. This phase is followed by second dorsiflexion angular movement for storing energy, acting like a spring figure 3 (c). The final phase of the stair descent gait is plantarflexion phase in which the stored energy is released as shown in figure 3 (d) and swing phase comes into play [2].

Controlling the angular movement of ankle during stair ascent and descent gait is a crucial system for powered ankle foot prosthesis at low cost. For controlling the gait cycle of stair ambulation, PID, input sensors, and high torque Stepper motor is used. Two switches are placed under the foot; one under the toe and other under the heel. These two switches acts as sensors for sensing the surface contact and the signal is fed to the PID. The PID on receiving the signals actuates the motor through motor driver after amplifying the power required by the motor to provide high torque. An infrared sensor is used for detecting the stairs. It acts as input sensor to the device. The complete electronic arrangement is attached externally to the device.

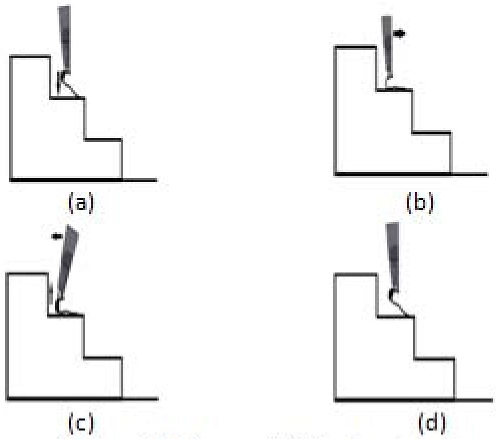


Figure 3: Phases of Stair decent.

During stair ascent swing phase the stairs are in front of the amputee and infrared sensor senses the obstruction and sends signal to the PID which in return sends the signal to the motor driver for positioning the ankle joint in dorsiflexion position to strike foot on the stair surface. Similarly during stair descent swing phase the absence of obstruction in front of infrared sensor sends signal to PID for controlling the ankle position to plantarflexion for striking toe first on stair surface. The maximum angle during dorsiflexion and plantarflexion movement is not to exceed the data shown in table 1. The angular motion is controlled through stepper motor.

Table 1: The angular motion measured in degrees during stair ascent descent gaits.

Phase	Human ankle range	Prosthetic device range
Dorsiflexion	10^{o} - 30^{o}	20^{o}
Plantarflexion	20^{o} - 50^{o}	40^{o}

The stance phase of stair ascent and descent gait is controlled through switches. The input signal from one switch rotates the motor in clockwise/counter clockwise through signal from PID till the foot-flat position of the ankle is attained. During stance phase the angular position of dorsiflexion tends to remain as stated in table 1 and remaining angular position is utilized in storing energy that can be utilized in powered plantarflexion. The overall control scheme is shown in figure 4.

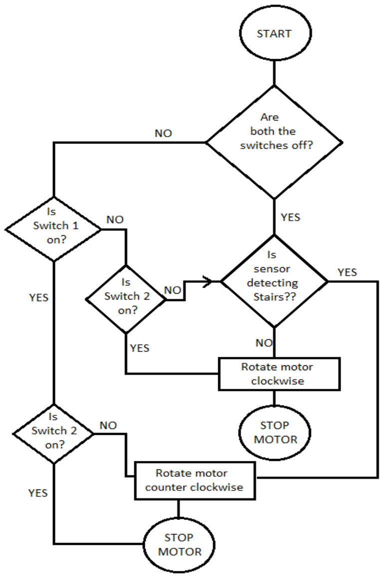


Figure 4: Flowchart Control scheme

The exoskeleton model with PID controller is shown in figure 5

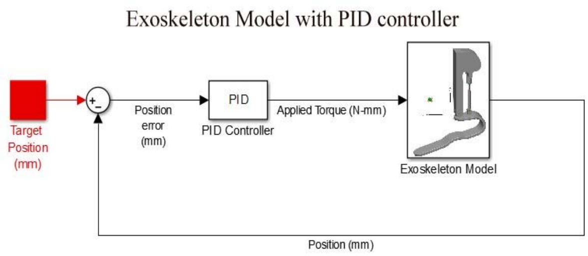


Figure 5 : PID control scheme

4. Analysis

During stance phase of stair ascent descent gait cycle, the ankle acts as a kinematic link joined at ankle. The ankle angle can be determined and represented as shown in figure 6. The positive value of angle represents ankle dorsiflexion and negative value represents ankle plantarflexion.

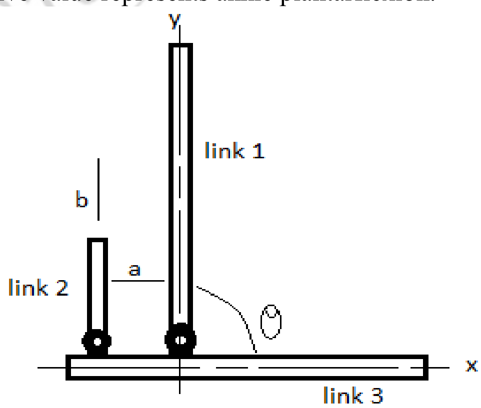


Figure 6: Kinematic links of ankle joint.

The Achilles tendon of the foot plays a major role in adjusting the ankle angle during walking, running, and climbing etc. The rupture of Achilles tendon hinders the movement of the ankle. The tibia and fibula bones of leg join the foot at talus. Considering foot, tibia, and Achilles tendon as kinematic link connected as hinge joint as shown in figure 6. The ankle angle and angular velocity can be determined by controlling the vertical displacement ‗b‘ of link 2. The distance ‗a‘ between link 1 and link 2 also contributes in calculating the angular velocity of the ankle. Keeping in view that the distance ‗a‘ of natural human ankle never changes, therefore, it is kept constant. The magnitude of displacement ‗b‘ below x-axis is considered negative that results in positive value of ‗θ‘ i.e. dorsiflexion movement of the ankle. The displacement ‗b‘ above x-axis is considered positive resulting in negative value of ‗θ‘ i.e. plantarflexion movement of the ankle.

The link 2 is attached with motor of the design presented in this paper. The link 2 undergoes vertical displacement when motor attached to it rotates in clockwise/counter clockwise direction. The motor shaft is leadscrew with pitch ‗p‘ and link 2 is a ballscrew with same pitch, therefore, rotation of motor shaft i.e. leadscrew will cause vertical displacement ‗b‘ in ballscrew. This vertical displacement ‗b‘ of ballscrew will cause angular displacement of the ankle in terms of ‗θ‘.

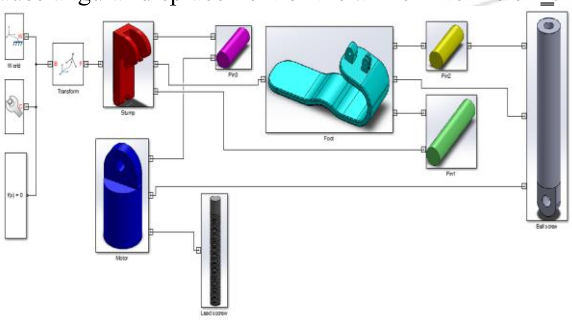
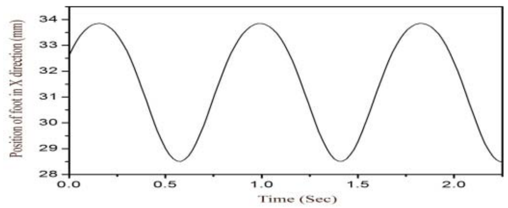
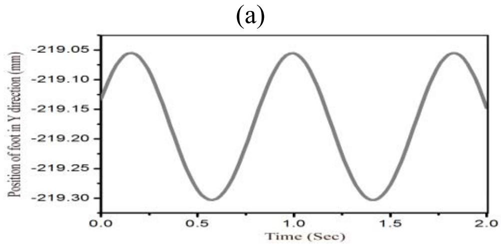


Figure 7: Simulink model of the prosthetic device

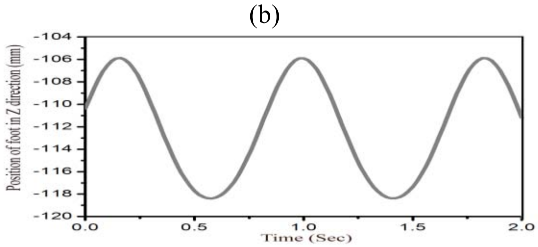
Controlling the motor through PID by programming using the logic shown in figure 4 and using matlab model, shown in figure 7, the simulation is carried out under no load conditions. The graphs obtained between angular displacement and gait cycle during stair ascent and descent and corresponding angular velocity are shown in figure 8.



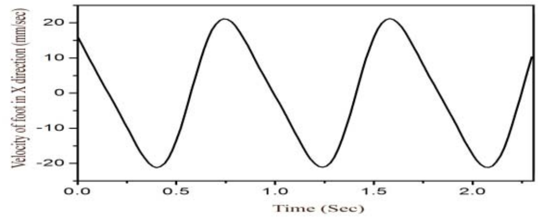
(a)



(b)



(c)



(d)

Figure 8: Graphs of displacement and velocity (d) of the prosthetic device along x(a), y(b), and z (c)direction.

The result of finite element analysis of stump of the prosthetic device as shown in figure 9 under loading of average human weight is shown in table 2.

Table 2: Data from Finite Element Analysis of stump.

	Minimum		Maximum	
	Value	Time (s)	Value	Time (s)
Stress: von Mises (Pa)	137	0	2.75E+05	0
Stress: Shear (Pa)	72.2	0	1.41E+05	0
Stress: Principal (Pa)	-2.76E+05	0	2.52E+05	0
Strain: von Mises (mm/mm)	5.90E-10	0	1.18E-06	0
Strain: Shear (mm/mm)	9.31E-10	0	1.82E-06	0
Strain: Principal (mm/mm)	-1.38E-06	0	1.09E-06	0
Displacement: Magnitude (mm)	9.62E-13	0	0.000845	0

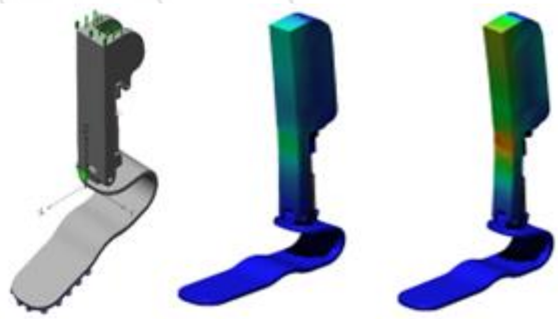


Figure 9: Finite element analysis of stump.

5. Results

A 3D design, control scheme, and light weight material of a prosthetic ankle device are presented and the attachment technique of the device with the residual limb is same as already being used like Jaipur foot i.e. sockets attachment. The design can store energy in dorsiflexion phase and release it during plantarflexion phase. Under average loading of person, the device is capable of withstand dynamic loading as the stress and strain induced on the device is very less.

The control system is simple and affordable and the results from motion analysis of the design have shown that the device is capable of providing similar gaits as of the natural human ankle behavior during stair ambulation. The weight of the prosthetic device calculated from parts volume and material density was less than 2.5kg. The complete weight of the device including the electronics for control system is expected not to increase 3kg.

6. Future Scope

In future work we plan to build a prototype and analyze its biomechanics for stair ambulation. The calculation of the weight and simulation of the actual prototype is to be studied.

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