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Design and Structural Analysis of a Passive Ankle-Foot Prosthesis with Manually Adjustable Stiffness and having Two Degrees of Freedom

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Abstract

The majority of commercial Below Knee Prosthetics are Passive Prosthetics as they are lightweight, affordable, durable and require less maintenance. Since the human ankle is a set of highly integrated joints, ankle design is the most crucial aspect of a Below Knee (transtibial) prosthesis design process. In the ankle, the talocrural joint (which allows dorsiflexion-plantarflexion) and the subtalar joint (which allows inversion-eversion) play critical roles. The stated two joints provide the amputee the essential two degrees of freedom (2 DOF). This research work focuses on developing and analysing Passive Ankle-Foot Prosthesis to attain 2 DOF such that it could mimic the behaviour of a natural lost limb. Further, this study presents the integration of manual ankle stiffness modulation into the design for dorsiflexion-plantarflexion which can be altered by the amputee to a preferred stiffness for various ambulation requirements. The design proposed in this study also assimilates the features of an ESR and a SACH foot to a significant level; moreover, a keel design with improved terrain adaptability is also suggested. A novel design of a passive ankle-foot, that comprises the above characteristics, along with the results of structural analysis, are presented in this study.

Keywords: Passive Foot Prosthesis, Ankle-Foot Prosthesis, Two Degrees of Freedom, Manually Adjustable Stiffness, ESR Foot, SACH Foot

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1. Introduction

Studies show that the number of amputees around the world are increasing at an exponential rate [1]. This is mainly due to injuries, accidents, diseases, congenital defects or diseases and war. Earlier, people with such problems used to wear metallic or wooden structures or simply the walking sticks which were not pleasant to the amputee and they also require extra effort [2], also, they would not resemble the normal leg either. Prosthesis helps amputees to return to a satisfying social and working life and improves aesthetics. A prosthetic leg, in particular, is an apparatus designed as a substitution of missing limb that helps the amputee to walk comfortably without having any distractions. In recent times, many advanced studies have been conducted and the prostheses have evolved significantly [3], however, there exists challenges in terms of convenience, affordability and comfort. Through design and analysis proposed in this research work, it is expected that such issues would be addressed up to a significant extent if the same concepts are applied in the manufacturing process of the prosthesis. The proposed design is thoroughly tested and analysed considering all those factors above.

The prosthesis of a leg, at the transtibial level (below the knee, between the ankle joint and the knee joint), normally consists of three main parts *viz.* Ankle-Foot, Pylon and Socket [4]. Amputations at this level represent over 50% of the amputee population [5]. There are several variations in the prosthetic leg or the foot. All those variations can be broadly categorised into three types [6]: (a) Conventional or Passive Foot: it does not have active movement and provide basic functionality, (b) Powered or Active Foot: it provides external power through motors and consequently it has the ability to act, and (c) Bionic Foot: in this type of foot, sensors are used that detect signals from user's muscles and behaves almost like a natural foot. Further, Conventional or Passive prosthesis can be categorised as Solid Ankle Cushion Heel (SACH) Prosthesis and Energy Store and Return (ESR) Prosthesis [6]. Although, there are possibilities of several research areas in different parts of the foot prosthesis, this research work focuses on the study of the design and structural analysis of ankle-foot only.

Current Passive Prosthetic foot designs consist of either one degree of freedom [7] or with adjustable ankle stiffness [8], but not both. Some designs even lack both features and focus only on optimizing the weight using 3D printed foot and topology optimization technique for some rigid kinds of prostheses [9] as the weight of the prosthetic directly affects the mobility of the amputees as well as the cost. To optimize the weight, this research work has adapted the similar topology optimization method and some specific materials for components have been suggested to achieve the same. In some designs, plantarflexion-dorsiflexion, **Fig. 1**, is available even in passive prosthetic feet but they are based on only one degree of freedom (1 DOF) [10], i.e. inversion-eversion is not available, **Fig. 1**. This creates discomfort while walking through difficult or uneven terrains with one degree of freedom. Therefore, in the design presented in this research work, an additional second degree of freedom for inversion-eversion is proposed so that walking experience and stability of the amputee, through difficult terrain conditions, could be improved. Moreover, in most of the passive foot designs, the stiffness for dorsiflexion and plantarflexion are either fixed or not considered at all [10, 11]. It is proven that the required amount of stiffness varies from one amputee to another [12]. To rectify these drawbacks, researchers invented the adjustable ankle stiffness design for passive foot prosthesis [8]. Though Active Prosthetic leg designs with two degrees of freedom and adjustable stiffness are available [14, 15], they are very costly and hence are not affordable by most of the amputees specially in developing world; moreover, their handling and maintenance is also very critical. Here, in the design presented in this study, the passive ankle-foot can attain 2 DOF for better terrain adaptability and amputee's comfort.

In addition, the desired features of both an ESR and a SACH foot are also embedded in the design put forth in this research work. Studies have been conducted to compare the characteristics of these types of feet with their advantages and disadvantages [16]. It is shown that an ESR foot provides better gait during heel-off [17] whereas a SACH foot provides improved stability during heel-strike [18], **Fig. 2**. To obtain the cushioning effect like the same obtained in previous study [18], the design of the keel profile has been optimised and the material has been selected accordingly. In the study, a specific blade profile has been selected to incorporate the properties of an ESR foot which also serves as the keel [19]. However, rather than using the same blade for both the keel and for the ESR purpose, a separate blade has been proposed in the design in this paper which is basically an inclined plank as depicted in **Fig. 5** and is fixed to the keel using screws. Hence, this research work presents a passive foot design which not only comprises features such as 2 DOF and a manually adjustable ankle stiffness in one novel design but also the same design provides the amputee an affordable and comfortable passive ankle-foot which is thoroughly tested and analysed for the safety and ergonomics as well.

2. Materials and Methods

The proposed prosthesis comprises two degrees of freedom (2 DOF) and a manual adjustment mechanism that regulates the ankle stiffness. The aim is to design, develop and analyse a simpler yet functional passive-ankle-foot-prosthesis that replicates the lost limb's functionality. The objectives of the design are the following:

- Resemble the proportions and structure of a natural ankle-foot.
- Provide a completely mechanical adjustment system to adjust the stiffness manually.
- Incorporate a 2 DOF i.e., plantarflexion-dorsiflexion and inversion-eversion motions, **Fig. 1**.
- Implement the features of both a SACH and an ESR foot.
- Develop an affordable, durable, safe, lightweight and ergonomically suitable ankle-foot prosthesis.

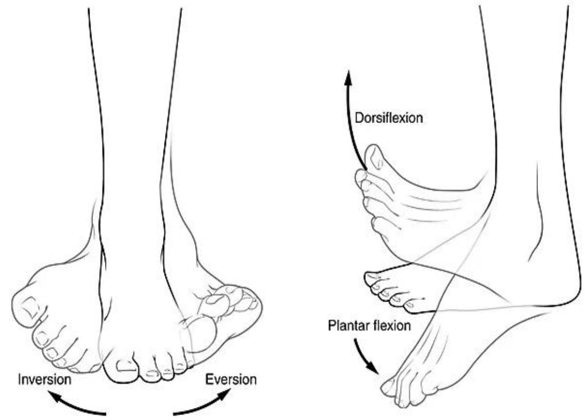

Fig. 1. Foot Motions [13]

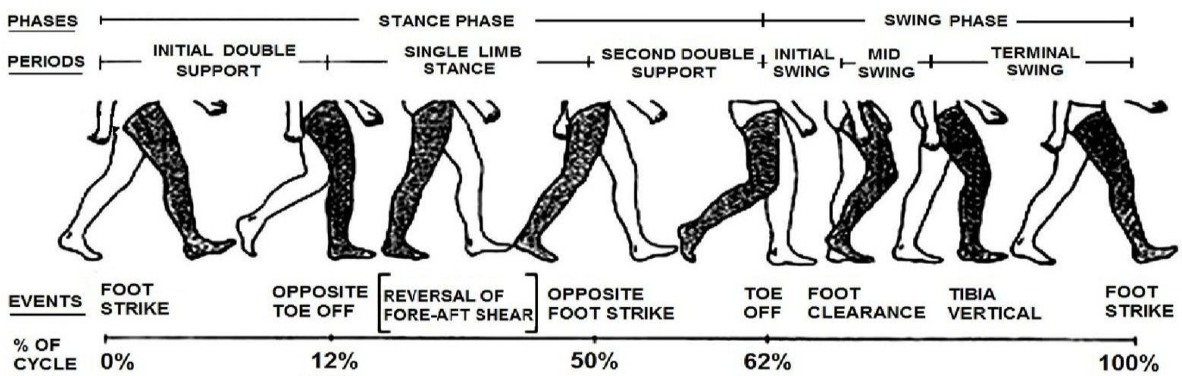

Fig. 2. Human Gait during Normal Walking [15]

In order to discuss the methodology in detail, this section has been divided into three sub-sections. The first and second portions address the architecture and development of the adjustment mechanism and 2 DOF mechanism respectively, while the third part presents the entire prosthesis design and structure. All the designs are created using Autodesk Fusion 360 whereas the structural analysis is performed on ANSYS.

2.1 Adjustable Stiffness Mechanism

In previous studies, it is proven that it is crucial to match a patient with the right stiffness for their general mobility and perhaps their long-term health [12]. But there are limited prostheses available whose stiffness could be varied, specifically, for plantarflexion-dorsiflexion. To address this issue, a study proposed an ankle-foot whose stiffness could be adjusted by varying the support of the spring along the longitudinal axis of the leaf spring using a DC motor [20]. Another research in the same field suggested a semi-active foot with flexible keel whose fulcrum could be changed using a DC motor to achieve the desired stiffness [21]. In a design, adjustable leaf springs are used which are placed vertically and the fulcrum location is regulated by servomotor [14]. Another study suggested a variable toe-joint to resolve the above-mentioned issue [22]. In a paper, the authors proposed the concept of a stiffness adjustable powered ankle-foot prosthesis by combining a typical SEA actuator and a length adjustable lever arm [23]. All these prostheses are either active or semi-active. The similar design as [20] with slight modification has been put forth in which the motion is achieved completely manually [8]. This research work has adapted the design proposed by the latter with a change that the slider moves on an inclined plane rather than on the horizontal plane. This inclined plane, with the aid of the same leaf spring, helps in to provide the features of an ESR foot [24].

The stiffness adjusting process is shown schematically in **Fig. 3.** The lead screw (not shown in the figure) is constrained at both ends in such a way that when rotated, the link (called slider) connected to it moves translationally which basically works on the principle of nut and bolt mechanism. The leaf spring, which is fixed at one end and free on another, is deflected by the force '**P**' generated by the cam transmission as shown in the figure. The stiffness of the spring changes when the support slider moves. This change in spring stiffness would cause a comparable change in ankle stiffness. The amount of deflection of the leaf spring depends upon the location of the support slider which is set by the amputees as per the requirement using the lead screw knob. Energy stored in the leaf spring in the form of strain energy, is given by the relation, $\boldsymbol{U = F^2l^3/6EI}$. Where, *'F'* is the reaction force at the terminal stance, '*l*' is the length of the spring, '*E*' is the modulus of elasticity of the material and '*I*' is the moment of inertia. The distance '*x*' moved by the slider support when the screw is rotated through an angle 'θ' is given by the relation $\boldsymbol{x = l\theta/2\Pi}$, where '*l*' is the lead. The mechanism is intended to have a maximum travel distance of 110 mm for the support slider. The number of screw rotations for this travel was arbitrarily set as 55, and so the screw lead was found to be 2 mm. As a result, during a complete screw turn, the slider travels 2 mm, as specified by the relation above. Moreover, in the design proposed, the components of forces play vital role because the force received at the free end of the leaf spring is not normal unlike what was proposed in [20] and [8] and unlike to what is shown in the figure alongside.

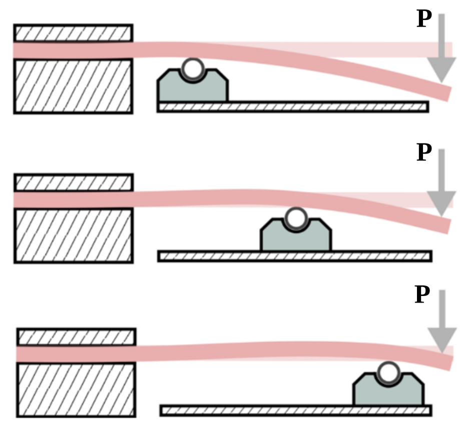

Fig. 3. Stiffness Mechanism [22]

2.2 Two Degrees of Freedom (2 DOF) Mechanism

To mimic the natural human gait cycle, the ankle-foot prosthesis must possess at least two degrees of freedom [28, 32]. Most of the current Passive Prosthetic foot designs consist of only one degree of freedom [7, 10]. However, in a study, two degrees of freedom mechanism has been discussed but the entire ankle-foot architecture is not proposed [29]. In another research work, researchers have developed two degrees of freedom in passive ankle foot prosthesis using cable and pulley mechanism [30]. Although two degrees of freedom is rare in passive ankle foot prosthesis, it is profoundly implemented in most of the active foot prostheses [26, 27, 31, 33]. As one of the major objectives of the research presented in this study is to develop a passive foot with 2 DOF, the design proposed in the previous researches has been adopted [10, 27] and modified to meet the other objectives as explained in the beginning of **Section 2**.

In this proposed design, the 2 DOF mechanism is obtained mechanically. There are mainly two motions that occur at the ankle joint, i.e., Dorsiflexion-Plantarflexion and Inversion-Eversion. Dorsiflexion occurs during heel strike to heel-off and Plantar flexion occurs during toe-off to pre-swing, **Fig. 2**. While walking, at heel strike, the ankle plantarflexes and the distance between the tibial component and the toes increases. As the user progresses to the stance phase, the ankle flexes. During dorsiflexion, the body's center of mass is directly above the foot's center of pressure and the foot is compressed [25]. In the design, **Fig. 4(c)**, the plantarflexion-dorsiflexion movement is aided by a cam which is fixed on a shaft whose axis is called Sagittal Axis. The cam is followed by a cylindrical follower which further transfers the motion to the leaf spring through the roller bracket. The leaf spring bends when it receives the force from the cam as depicted in **Fig. 3** The ankle, in the design proposed in this research work, rotates between 15° and 25° during dorsiflexion and plantarflexion respectively. Prosthetic foot which rotates between 15 degrees and 25 degrees during dorsiflexion and plantarflexion allows easier walking [26].

The Coronal Axis, which is perpendicular and intersecting to the Sagittal Axis, is the axis about which inversion-eversion movement is achieved. Due to the person's self-weight, the foot tends to tilt inward or outward (eversion-inversion) during the stance phase when it lands on rocky terrain. The frontal plane twisting action of the prosthetic ankle supports a more natural stride as well as rough terrain walking for amputees. **Fig. 4(b)** represents the eversion-inversion movement of the ankle foot with the help of a couple of piston-cylinder dampers on the left and right side of the ankle. The dampers are supported by the Upper Ankle Block and Connecting Link of the ankle-foot. A couple of connecting rods are used to connect the ankle to the dampers for the above stated movement. During the stance phase of walking on an uneven surface, a portion of the ground reaction force owing to body weight is held in helical springs inside the cylinder and released during the swing phase for foot neutralization. The ankle rotates up to 20° in either direction for the comfort of the amputee as well as for the safety of the components during eversion-inversion. A stopper, **Fig. 4(b)**, is adopted in the front of the shaft at Coronal Axis to restrict the motion to above mentioned angle as suggested in the previous research [27].

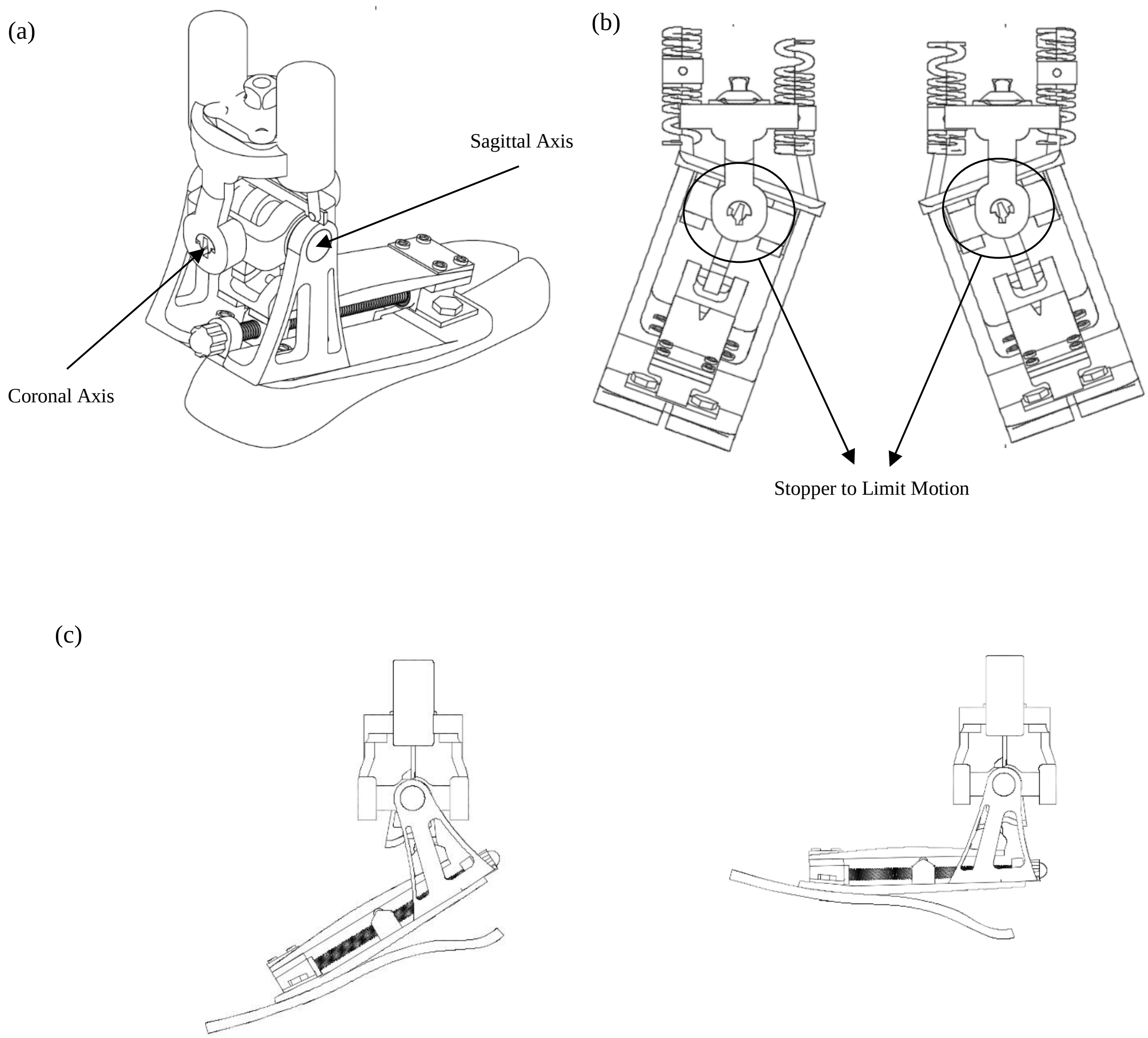

Fig. 4. Ankle Foot: (a) Axes; (b) Inversion-Eversion Motion with Stopper to Limit the Motion; (c) Dorsiflexion-Plantarflexion Motion

2.3 Overall Design and Specifications

Mainly, the design consists of the following components: (a) Keel, (b) Slider Support, (c) Housings, (d) Leaf Spring, (e) Slider (f) Cam and Follower (g) Adapter (h) Upper Ankle Block (i) Connecting Link (j) Lead Screw and (k) Dampers. The detailed views and nomenclature of the design are illustrated in **Fig. 5**.

The arches, in the Keel design, is created to maintain the body balance. It gives a cushioning effect to the amputee like a SACH foot to prevent the amputee from the unnecessary jerks during heel-strike and works as an elastic component that can store and release energy like an ESR foot; thereby, reducing the metabolic cost of strolling. These features are vital for the amputee in term of comfortability. The Housing is one of the main components of the design which bears most of the weight of the amputee. Further, Cam, Springs-Dampers and Adapter are supported on it. As the Housing is directly fixed to the slider support, it transfers the forces to the latter. The housing design has been optimized for weight reduction up to 22.3% (from 140.4g to 109.1g) using Topology Optimization method without compromising the safety. Similarly, Upper Ankle Block weight was reduced to 30.5% (from 411.3g to 285.5g) using the same method. The Connecting Link connects Upper Ankle Block and the Dampers. Next important component in the design is the inclined Slider Support which not only aids in to achieve the features of an ESR foot but also prevents any mechanical damage to the components of the prosthetic foot. Cam profile has been adopted from the previous research for the required angle of deflection in the leaf spring during dorsiflexion-plantarflexion [8], however, its weight has been optimized to 19.09% (from 31.25g to 25.3g). Piston-Cylinder Dampers with Helical Springs are used to assist in inversion-eversion. The slider consists of a roller on which the leaf spring is supported. The roller rolls in contact with the leaf spring and the slider is moved by rotating the Lead Screw using the Knob provided at extreme right as shown in **Fig. 5**. The lead screw is a standard acme-threaded screw with the required lead as discussed in sub-heading **2.1**.

The parameters, based on which the design is created, are given in **Table 1.** The parameters of the prosthesis are set and maintained in such a way that it matches with the characteristics of a missing biological foot.

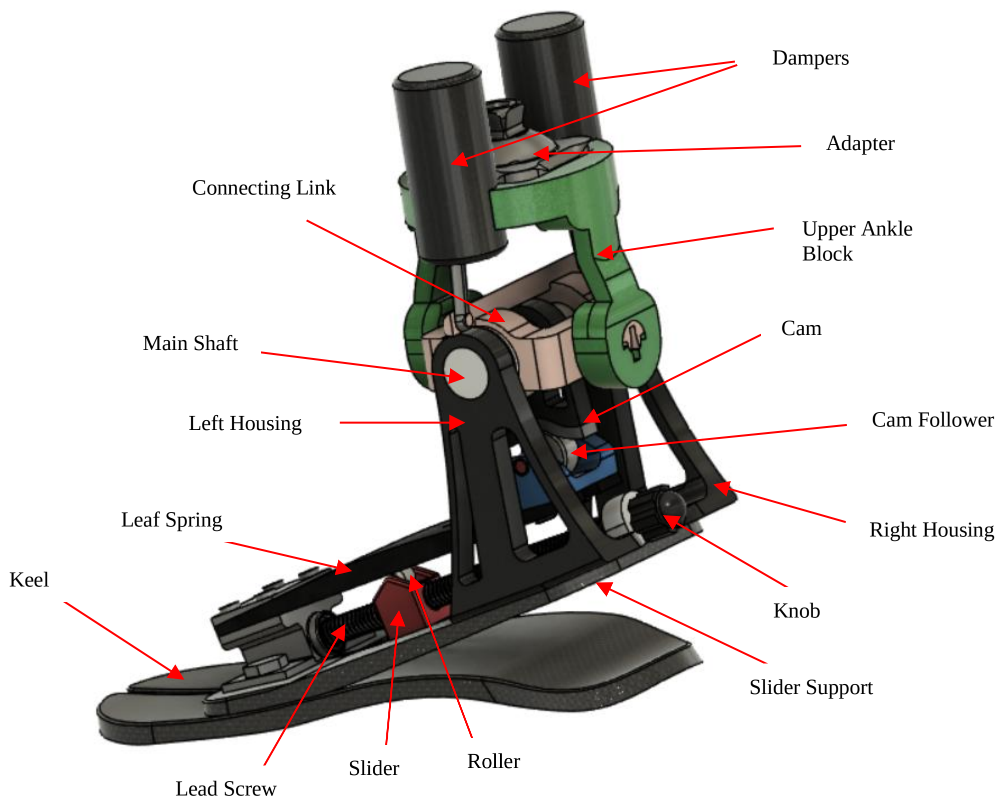

Fig. 5. Parts of the Prosthetic Ankle Foot

The material selection of different parts of prosthetic foot is very important as the foot must withstand the amputee's weight and torque, at the same time, it should not make the prosthetic foot heavier, moreover; the components should not fail during application. Selection of suitable materials for the components plays a significant role in this stage. The materials are assigned to the components very cautiously taking into considerations all those factors. Types of the materials used for components in the design of the ankle foot prosthesis are presented in **Table 2.** Similarly, the Mechanical properties of selected materials are listed in **Table 3**.

Table 1. Design Parameters/Specification

Description	Values	
	Avg. Human Foot [34]	Prosthesis
Length of prosthetic foot (mm)	260	250
Width of prosthetic foot (mm)	94	90
Toe length (mm)	50	59.4
Height of the Foot up to ankle joint (mm)	70	80
Weight of the ankle foot (kg)	2	2.0083
Max. allowable Dorsiflexion (degrees)	20	15
Max. allowable Plantarflexion (degrees)	40	25
Max. Eversion angle (degrees)	20	20
Max. Inversion angle (degrees)	30	20
Max. travel distance of support slider (mm)	-	110
Factor of Safety (Overall)	-	7

Table 2. List of Materials used for Fundamental Components

Component	Material
Helical Springs	Stainless steel, 302, annealed
Connecting Rods (Damper)	Aluminium alloy, wrought, 7075, T6
Slider	Aluminium alloy, wrought, 7075, T6
Cam Follower	Low alloy steel, 4130, annealed
Slider Support	Composite, Carbon fibre reinforced carbon matrix
Lead Screw	Structure Steel
Keel	Composite, Carbon fibre reinforced carbon matrix
Leaf Spring	Composite, PA12/glass fibre, woven fabric, biaxial
Slider Roller	Low alloy steel, 4130, annealed
Cam Profile	Carbon steel, 1060, annealed
Main Shaft	Aluminium alloy, wrought, 7075, T6
Housing	Aluminium alloy, wrought, 7075, T6
Connecting Link (Sagittal Axis)	Aluminium alloy, wrought, 7075, T6
Upper Ankle Block (Coronal Axis)	Aluminium alloy, wrought, 7075, T6
Damper Cylinder	Aluminium alloy, wrought, 7075, T6
Pyramid Adapter	Aluminium alloy, wrought, 7075, T6
Piston (Damper)	Aluminium alloy, wrought, 7075, T6

3. Results and Discussion

3.1 Structural Analysis of Critical Components

Table 3. Material Properties

Material	Density (g/cc)	Young's modulus (GPa)	Poisson's ratio	Bulk Modulus (GPa)	Shear Modulus (GPa)	Tensile Yield Strength (MPa)	Ultimate Tensile Strength (MPa)
Aluminium alloy, wrought, 7075, T6 (at 22.2℃)	2.81	71.7	0.33	71.68	26.9	436.2	538
Composite, Carbon fibre reinforced carbon matrix	1.55	183	0.3198	87.745	15	666.7	503.4 @ 23℃
Composite, PA12/glass fibre, woven fabric, biaxial	1.7	76	0.1049	82.426	38	440.1	379.5 @ 23℃
Structural Steel	7.75	200	0.3	160	79	340	360
Stainless steel, 302, annealed	7.86	193	0.28	142	77	275	585
Low alloy steel, 4130, annealed	7.85	200	0.27	140	80	435	560
Carbon steel, 1060, annealed	7.85	190	0.29	140	80	485	620

3.2 Leaf Spring Deflection Analysis

The relation between the stiffness and the slider position was analysed using MATLAB. The slider position was started at 50 mm from fixed end with gradually shifting the slider till 150 mm towards free end, **Fig. 13(b)**. The relation $\boldsymbol{F = kx}$ was used for the calculation where 'F' is the force received at the free end of the spring, 'k' is the stiffness of the spring and 'x' is the amount of deflection. The amount of deflection at the intervals used in this study was taken from the structural analysis of the leaf spring. The result obtained is plotted in the graph as shown in **Fig.**

13(a).

3.3 Properties of the Prosthesis

(a) (b)

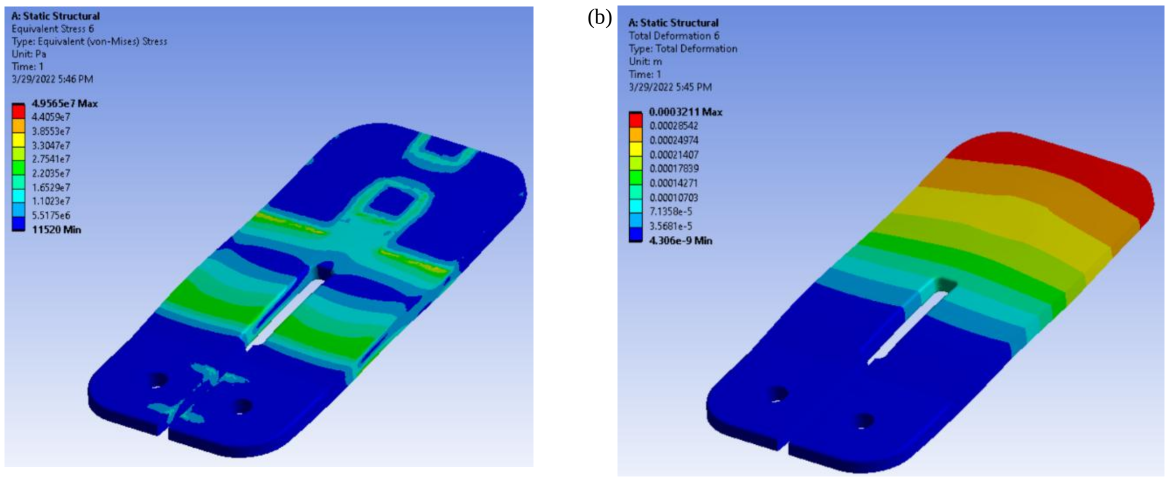

Fig. 11. Connecting Link: (a) Stress Distribution (b) Deformation

(a) (b)

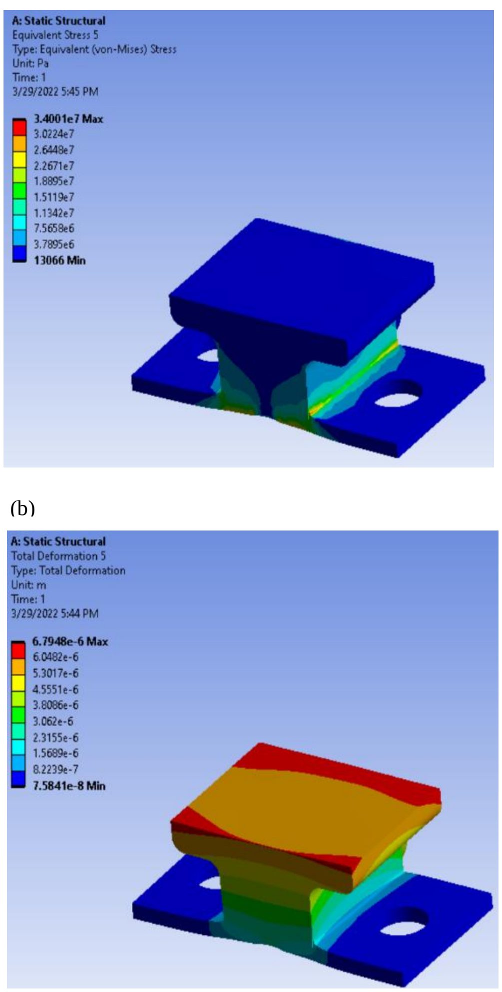

Fig. 12. Leaf Spring Support: (a) Stress Distribution (top) (b) Deformation (bottom)

(a) (b)

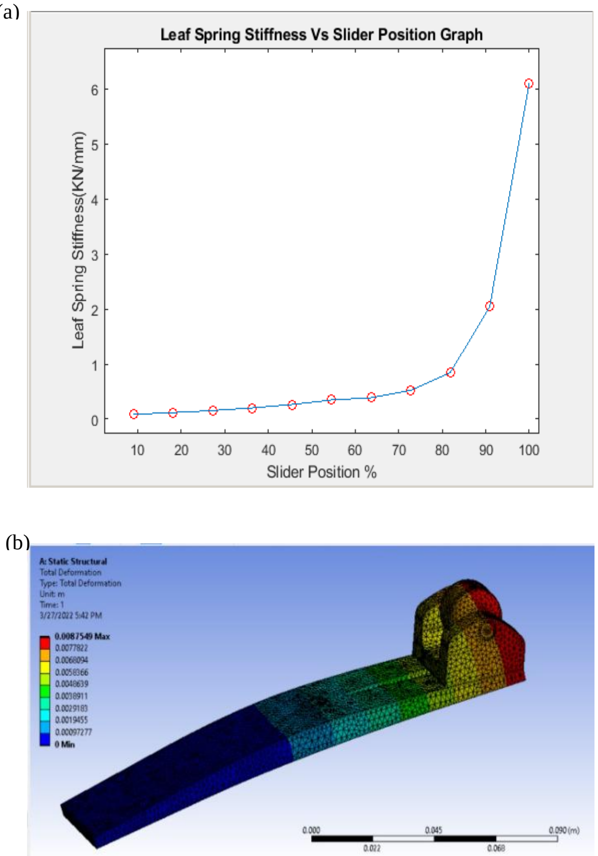

Fig. 13. (a) Stiffness vs Slider Position Graph (top) (b) Leaf Spring Under Deformation Analysis (bottom)

The dimensions of the developed prosthesis closely approximate those of the native ankle-foot as shown in **Table 1**. This is desired since the prosthetic would be a replica of the lost limb. The weight of the prosthesis was another factor considered. With all necessary materials used in the 3D model, the obtained weight was found to be approximately 2 kg. The weight of the normal foot is assumed to be 2.5% of body weight [34], therefore using 80 kg as body weight, the similar weight of a complete ankle-foot complex would be around 2 kg. As a result, the prosthetic nearly resembles the weight of the native ankle. Adjustable stiffness and 2 DOF, for a passive ankle-foot, are two exclusive features of the design presented in this study.

4. Conclusion and Future Work

The design and structural analysis of a passive ankle foot prosthesis with adjustable stiffness and having 2 DOF is presented in this study. The prosthesis' intended characteristics closely mimic those of an entire human ankle-foot complex. The prosthesis has a leaf spring whose stiffness can be adjusted depending upon the usage for plantarflexion and dorsiflexion motion. An additional one degree of freedom in this passive prosthesis is suggested for inversion-eversion motion. Moreover, some features of an ESR and a SACH foot is also included in the design. Structural research of critical elements of the prosthesis for its integrity revealed that the design can resist the ground reaction forces that the prosthesis would be subjected to during application. Finally, the effect of position of the slider on the stiffness of the leaf spring is discussed. Although the prosthesis closely mimics the functionality of natural ankle-foot, further studies are required to optimize the design for various terrain conditions.

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