Design of Passive Energy Storage and Return Ankle Foot Prosthesis for Transtibial Amputees

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Abstract

Lack of sturdy and cost-effective ankle-foot prosthesis for amputees is a deterrent to their quality of lives. This research was aimed at designing a passive ankle foot prosthesis which is robust and cost effective, catering to the needs of amputees who are active and traverse on different terrains (activity levels K3 to K4). Through surveys and gait analysis, anthropometric data was derived and a generalised graph which best represents the torque-angle curve of healthy Human's ankle. An articulative ankle-foot prosthesis with a defined ankle joint was found to provide best traction and balance at sole. The use of unidirectional compression springs for dorsi-flexion and plantar-flexion satisfy kinematic requirements. The simplified design has features of less induced stress and low overall weight. The design mimics ankle movement, provides adequate comfort and conforms to the basic requirements of an ankle-foot prosthesis in Indian context.

Keywords: *Prosthetic ankle, Transtibial amputation, Plantar-flexion, Dorsi-flexion, Passive prosthesis*

1.0 Introduction

The motion of human ankle during walking gait is a repetitive process with a cycle of alternating plantar-flexion and dorsi-flexion. The ankle exhibits properties of a torsional spring which has a proportionally varying stiffness. It also varies with different phases of gait in a cycle and anthropometrics of the person. Ankle-foot prosthesis is used for aiding locomotion after transtibial or transfemoral amputation [1]. To replicate the characteristics of the ankle under all gait conditions, an active ankle-foot prosthesis powering its motion is required. The prosthetics use motors driven by a power source and controlled through ECU. They are relatively expensive and unaffordable [2-3]. Commercially designed prosthetic ankles are passive and non-articulated causing feet and tibia to rotate about a locus of centre of rotation, which negatively impacts gait of amputee [4-6]. These designs follow the principle of energy storage

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and return (ESR), which cannot follow the moment angle curve for the range at which the human ankle acts but can be manufactured at affordable rates. The materials for the design are selected to keep the net weight of the ankle less than 1000 gram. The proposed prosthetic design is made articulated and the mechanism is mounted on a support structure called the keel. The keel is a structural member. It has to bear all the vertical loads with durability. Carbon fibre is a widely accepted choice for the keel because of high strength to weight ratio [7]. In commercial designs, energy is stored in the keel during dorsiflexion, due to bending, to provide moment during push off. These keel designs are non-articulated. Use of springs can ensure the same feature of ESR while installing an articulated joint to it. This paper presents a methodology for designing a passive ankle-foot prosthesis using articulated joint, ESR using springs, and mechanism mounted on carbon fibre keel.

2.0 Design of ankle foot prosthetic

2.1 Conceptual design

Using Gait Analysis and Anthropometric data of patients, relevant data and boundary conditions were derived. A generalized torque-angle curve as well as dorsiflexion and plantar flexion angle limits were obtained. Using Catia V5 and Solidworks, modelling of parts and assembly were developed. Hypermesh 13.0 was used for discretisation static analysis performed using ANSYS 19.0.

Concept design was performed considering an articulated and passive prosthesis. Keel design as the foundation of the model replaces foot base. The design provides housing to other parts and bears the maximum load without failure. Restricting movement along the sagittal plane, the ankle joints were replaced with bearings, which is ideal for carrying moments and motion similar to the joints. Two springs mimicking functions of muscles and tendons individually dedicated for dorsiflexion and plantar flexion are used. The bearing housing and springs are mounted on the extended flange of keel. Frame as vertical member idealises shin and its properties to bear vertical loads. Universal pyramid adapter is mounted on frame along with springs. The conceptual model and foot movements are shown in Fig. 1(a) and Fig. 1(b) respectively.

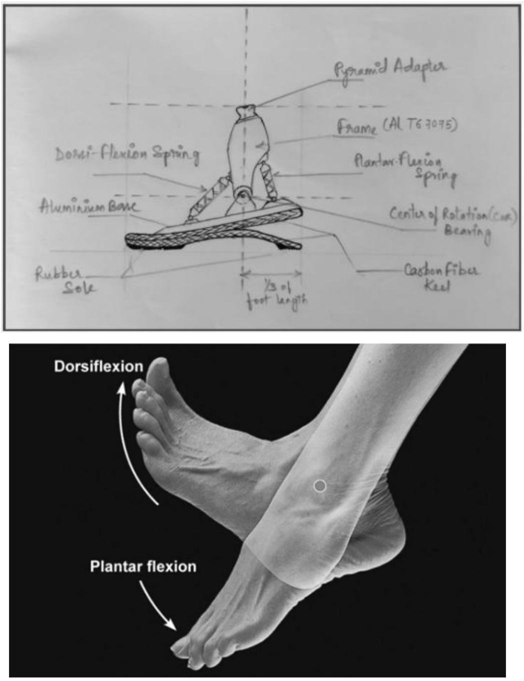


Fig. 1. a) Conceptual design of Ankle foot prosthetic and b) Dorsiflexion and plantar flexion movements of foot

Final design of the prototype was arrived iteratively considering cost, reliability, weight reduction, stability and aesthetics (Fig. 2 and Table 1).

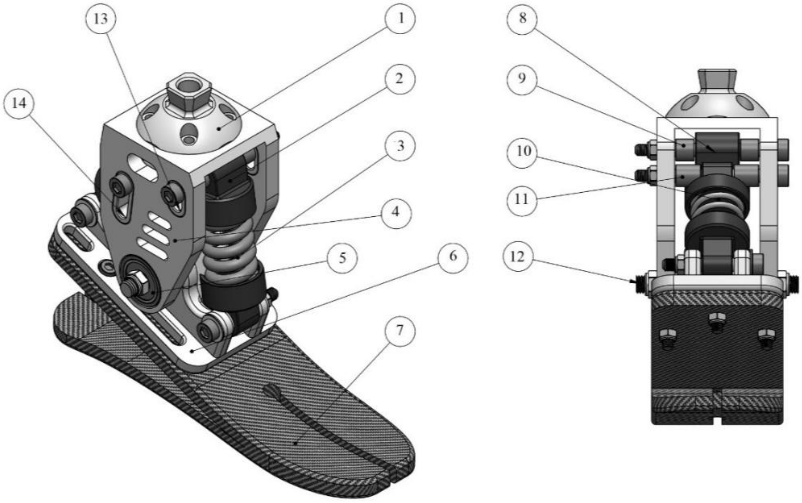


Fig. 2. Assembly of ankle-foot prosthetic

Table 1. Specifications of ankle-foot prosthetic assembly

Part No	Description	Material	Weight (g)
1	Pyramid Adapter	Stainless Steel	100
2	Dorsi Cap	Delrin 2700	20.26
3	Dorsi Spring	Oil Tempered Chrome Silicon	72.06
4	Frame	Al7075 T6	160.92
5	Piso Bearing	Proprietary	64
6	Ankle Base	Al7075 T6	181.74
7	CF Keel	3K 2X2 Twill 240 gsm Carbon Fibre	200
8	Plantar Cap	Delrin 2700	16.4
9	Dorsi Spacer	Nylon 101	1.38
10	Plantar Spring	Stainless Steel	12.52
11	Plantar Spacer	Nylon 101	1.38
12	Axle	Stainless Steel	28.09
13	Dorsi Bushing	Nylon 101	3.08
14	Plantar Bushing	Nylon 101	4.3
		Total Weight (g)	866.13

Fig. 3. Position of spring a) Dorsiflexion (toes closer to the shin) and b) Plantarflexion (toes away from shin)

3.0 FEA Results

Loading of Axle – Bearings which are press fitted into the frame housing are mounted at the ends of the axle. The loading is similar to 4 - point bending except that the two middle bearings offer uniformly distributed load. Maximum spring force of 2650 N (dorsi spring) acts at angle 10º with respect to horizontal. Maximum vertical load of 960N (jumping condition). Worst case scenario is considered with an effective load of 2600N at the bearings (Fig.4).

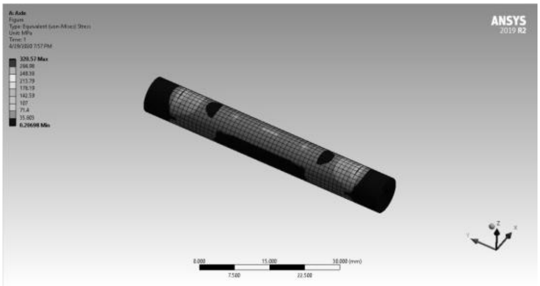


Fig. 4. von-Mises stresses in the axle (320.57 MPa)

Ankle Base: von-Mises stresses 5.15 MPa during jumping, 37.46 MPa during dorsi-flexion (Fig. 5b) and 3.31MPa during plantar-flexion (Fig. 5) indicate that ankle base is safe (yield stress of Al 7075 T6 (372 MPa).

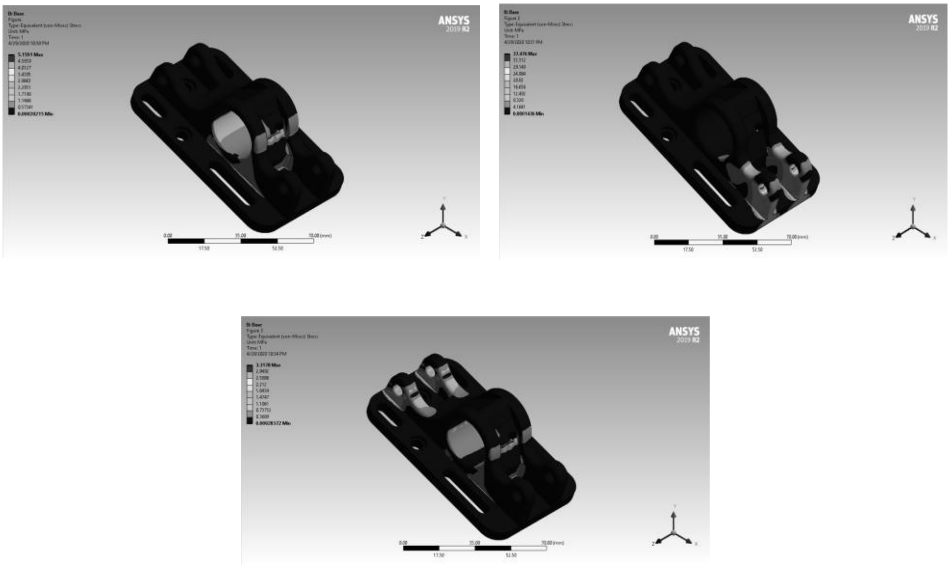
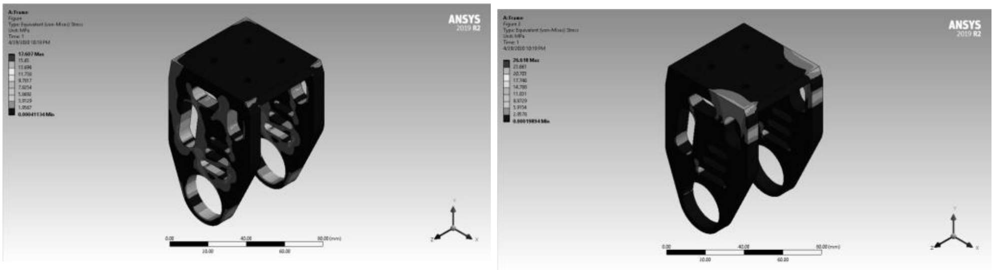


Fig. 5. Stresses in ankle base during a) Jumping, b) Dorsi-flexion and c) Plantar-flexion

Ankle Frame: Stresses during jumping (17.6 MPa), dorsi-flexon (26.61MPa) and plantar-flexion **(**8.16MPa) are shown in Fig. 6 indicating that the ankle frame is safe.



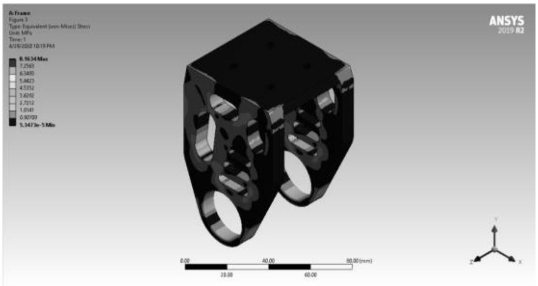


Fig. 6. Von-Mises stresses in ankle frame during a) Jumping, b) Dorsi-flexion and c) Plantar-flexion

Spring cap: Dorsi spring cap takes more load than that of the plantar spring cap. Fig.7 shows maximum stress of 47.27 MPa which is well below UTS of Delrin (62.05MPa). Hence the spring cap is safe.

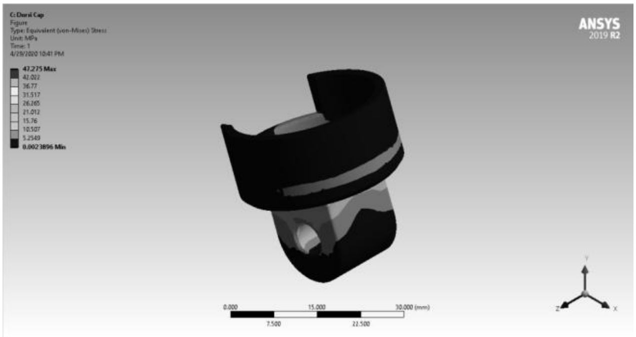


Fig. 7. von-Mises stresses in dorsi spring cap

4.0 Conclusions

A robust and cost effective passive ankle foot prosthesis catering to the needs of amputees was designed and analysed. The components were tested for three cases i.e. dorsiflexion, plantarflexion and vertical jumping. Finite Element Analysis indicated that the stresses induced in ankle, ankle base, ankle frame and spring cap were found be within safe limits with high factor of safety. The prototype was tested for jumping, K3 and K4 activity level users and was found satisfactory.

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