Ankle joint rotator prototype designed for creating different angles of rotation at the ankle joint in performing various daily activities

T P Li and M S H Bhuian*

School of Mechanical Engineering, Engineering Campus, University of Science Malaysia, 14300 Nibong Tebal, Pulau Pinang, Malaysia.

Email: sayem@usm.my; sayem_um@yahoo.com

Abstract. The prosthetic ankle joint in lower limb prosthesis replaces the missing ankle of the amputee. The prosthesis users want the prosthesis to enable them creating the desired angle of rotation at the ankle joint like that of a healthy biological ankle. The ankle joint prostheses currently available in the market are unable to produce sagittal plane rotations for squatting and kneeling postures. Absence of a proper ankle joint rotator and lack of their universal adaptability have limited the utility and the performance of the prosthetic ankle joint. An ankle joint rotator capable of enabling its users to squat and kneel with ease has been designed. A model of the knee joint rotator has been developed, and simulation has been carried to out to verify the functionality of the design before fabrication. The new ankle joint rotator was found capable of withstanding an external force of 3000N with a minimum safety factor of 5.18. The newly developed ankle joint rotator is able to facilitate the squatting and kneeling postures safely by enabling the prosthetic ankle joint to rotate in different angles.

1. Introduction

The prevalence of limb loss and amputation due to congenital effect, war effect, accident, natural disaster and so on has been increasing steadily around the world. Amputation or limb defect causes difficulties to the subjects in performing different daily activities. It creates the need of getting help from different assistive devices depending on the nature of the disability. The amputees have been aided by walking stick/cane, walking frame, crutch, wheelchair, motor wheelchair, stroller, motor stroller, and more recently prosthesis is being used to rehabilitate them [1, 2]. A prosthetic limb or joint is a kind of prosthesis that replaces a missing limb and joint respectively. In recent years, the design of the prosthesis has been significantly improved by incorporating some extra features as well as introducing new controlling methods. In advanced and more improved designs of prosthetic limb and joint, more control is given to the users by employing different control system, muscle of carbon fiber, mechanical linkages, motors, computer microprocessors, and innovative combinations of these technologies mentioned [3]. The essential factors like weight-force ratio, strength, durability, adaptability, wear-ability, degree of freedom, resistance to environment, functional capabilities, etc. are being addressed seriously to develop a more efficient prosthesis arrangement. The desired movement of prosthetic limb is obtained with the help of different types of joints, sensors, controllers and actuators. The prosthetic joints of the prosthesis assist users to produce necessary movement in the prosthesis to yield different posture required in performing different daily activities. From literature and market study,
it has been found that most of the ankle joint prosthesis can only rotate medially and laterally. Though numerous types of ankle joint prosthesis is available in the market, none of these are proving sagittal plane rotation flexibility to its users. This type of rotation flexibility is very much essential for producing, squatting and kneeling posture in performing different daily activities. In order to overcome the limitation of sagittal plane rotation, a universality adaptable ankle joint rotator that enabling squatting and kneeling movements for the lower-limb prosthesis user has to be developed.

2. Ankle joint prosthesis

Ankle joint plays an important role in the gait cycle during forward progression of the human body. It plays the most significant role in creating different body postures like squatting and kneeling. The foot and ankle act as a medium between the body and ground adjust themselves flexibly in order to achieve a harmonious coupling for successful movements [4, 5]. The ankle joint prosthesis is used to reproduce the same functions in the absence of the biological ankle. The main function of the ankle-foot design is to facilitate the terrain adaptability in maintaining natural gait patterns and stability for a person with single limb transtibial amputation [6]. Several factors like the functionality, ease of use, comfort, structural strength, mass, size, visual appearance, sound, passive support, energy, output power and torque delivery, lateral flexibility, shock tolerance, variability of use, durability, personalization, modularity and cost, etc. affect the design of the prosthetic devices [7, 8]. The stiffness is also considered as a variable in designing a functional prosthetic ankle joint [9]. The stability of prosthesis, necessary propulsion and body weight support in the gait cycle are influenced by the ground reaction force (GRF) [10]. The user needs have to be fulfilled, and the technical feasibility has to be achieved after taking all these factors into consideration. A prosthesis should be designed such a way that it is capable of mimicking the ankle movements during different activities [11]. A lower-limb prosthesis is usually equipped with a socket, a pylon, an SACH foot, and an ankle joint rotator. The foot and pylon are usually connected to the ankle joint rotator which merely permits the ankle joint to rotate in the sagittal plane. Therefore, it is indispensable to design such an ankle joint rotator that allows the prosthesis to rotate to some desired angle when bending is required during performing different daily activities.

3. Design of ankle joint rotator

The ankle joint rotator has been designed in such a way that it allows rotation in the sagittal plane (plantar- and dorsiflexion) rather than focusing on rotators in the lateral and medial planes like that of existing ankle joint rotator. The ankle joint rotator design has been performed considering two angles of rotation for the squatting and kneeling postures respectively. The design and simulation of the ankle joint rotator has been carried out using the SolidWorks 2019 software. The modelling and simulation have been run on the ankle joint rotator design to determine the maximum stress that can be withstood and the displacement that would occur in the components.

The main design parameters of the ankle joint rotator were rotation angle, weight and size. Two angles of rotations of 60° and 45° were chosen, lowest minimum weight and smallest in height to make sure fitting it within the space available between the shank, and foot were opted for the design. The designed ankle joint rotator was comprised of a female component, a male component, a rotator pin, and a spring where the first three components were designed and fabricated, and the spring was procured from the market.

The female component was designed to act as a connector to the lower end of the pylon and also to assist in angle adjustment. The inverted pyramid on the top section of the female component is to be connected to the pylon with screw from four sides of the pylon lower end. The size of the inverted pyramid was designed to be universally adaptable. The internal hemispheric shape provided room for rotational to the male component. The three holes of 6.00mm diameter on the lateral side of the female component represents three respective angles for standing (0°), squatting (60°) and kneeling (45°). The 10.20mm diameter hole of the female component has to be mounted on the male component with a M10 nut-bolt in the rotator assemble.
The male component was designed to be fitted with the female component. The cylindrical shape of the male component helped the rotator to create rotation when to adjust the angle of the ankle at different position. The 6.00mm hole on the lateral side of the male component has to be aligned with any of the three holes in the female component for angle adjustment. The 10.20mm hole at the center of the male component has to be aligned with the same diameter hole of the female component to assemble it with a M10 nut-bolt arrangement. The cross-body extension of the cylindrical section of the male component acted as a connecter to the prosthetic foot. The four 7.00mm holes around the periphery of the extension were to connect the male component with the foot using screw. The holes are slightly slanted at 10° to provide a stronger grip to the foot.

The rotator pin acted as a common locking means for the male and female components during adjustment of angle of rotation. After assembling and aligning the male and female components at the upright position (0°), the rotator pin attached with a spring connected to the base of the hole at 0° of the male component. The spring is positioned in the spring housing of the male component market with a box in the design. Both parts will be locked in the position by the rotator pin. When rotation is required, the rotator pin has to be pushed into the hole of the female component to allow the male component to rotate. After the holes of the male and female parts are aligned at a desired angle, the rotator pin has to be released to lock both the male and female components again. Figure 1 shows the different components and the assembly of the ankle joint rotator design.
4. Modeling and Simulation results
The modeling and simulation of the ankle joint rotator design was carried out using SolidWorks 2019 software. The static model was developed for finite-element analysis of the ankle joint rotator assembly. Titanium alloy Ti-6Al-4V was selected as the material of the different components of the ankle joint rotator.

For the static studies, Fixed Geometry was selected as fixtures for the ankle joint rotator. Fixed Geometry was applied to those eight surfaces which would be connected to the pylon and foot with screws. The boundary condition setup and mesh creation are shown in Figure 2.

A force of 3000N equivalent the user of weight 100kg was applied on the external curved surface of female component of the ankle joint rotator as the External Loads. The external curved surface of the female component was divided into two parts to enable force to be applied on the entire curved surface. Two different cases of no rotation (standing upright) and ankle rotating (squatting and kneeling) were considered for setting up the boundary condition and running the simulation. Then mesh has been created before running the simulation. Four Points Jacobian solid mesh, with total nodes of 15280, total element of 8944 with size of 4.42311 mm, and a maximum aspect ratio of 7.0568 were chosen for creating the mesh.

The simulation results for stress, strain, displacement analysis, and factor of safety were generated for evaluation of the ankle joint rotator design.
At the first place, without any rotation at the ankle joint rotator case has been chosen to simulate the standing posture of the prosthesis. Then, with rotation case has been selected to simulate the squatting and keeling conditions. The stress, strain, displacement, and factor of safety analyses have been carried out to see the stress distribution, strain development, displacement occurred and safety of the design respectively.

From the Figure 3, the maximum equivalent stress developed for standing posture is $8.575 \times 10^{4} N/m^2$, which is considerably low comparing to the tensile strength of the titanium alloy Ti-6Al-4V material of $8.273 \times 10^{4} N/m^2$. The maximum equivalent strain developed in the ankle joint rotator is $6.627 \times 10^{-4}$, which is trivial to make any significant distortion or any quantifiable change in the shape of the components. This indicates that the material used for the ankle joint rotator elements can withstand the load applied by the prosthesis user while standing. The highest displacement occurred in the structural member under load is $5.089 \times 10^{-2} mm$, which is insignificant and negligible for the ankle joint rotator assembly. The least displacement value indicates that the elements of the ankle joint rotator do not dislocate unnecessarily when in use. If the displacement value was high, it could have caused instability.
in the prosthesis arrangement. The minimal factor of safety has obtained for the ankle joint rotator component is 9.649 for the standing position. This indicates that the design is capable of withstanding the weight of the user while standing.

For squatting and keeling postures, the maximum equivalent stress development found to be 1.452x10^6 N/m², which is few times less than the tensile strength of the titanium alloy Ti-6Al-4V material of 8.27371x10^6 N/m². The maximum equivalent strain developed in the ankle joint rotator is 1.101x10^-3 which is considerably low to make any significant change to the shape of the ankle joint rotator components. Therefore, the material used for the ankle joint rotator elements can sustain the load applied by the user while producing rotation at the ankle joint. The biggest displacement occurred in the components of the rotator under load is 1.198x10^-4 mm, which is too small to affect the rotator assembly. The small displacement value directs to the stability of the rotator assembly and the prosthesis arrangement also. For rotation at the ankle joint, the lowest factor of safety of the rotator components has been found to be 5.698. Although the stress during rotation is greater than that at the standing position, the safety factor is still good enough to serve the purpose.

Comparing to the minimum acceptable safety factor of 1.2, the design is proven to be capable of withstanding an external force up to 3000N without any occurrence of failure.

4.1. Ankle joint rotator prototype fabrication

After finalizing the design, a prototype has been fabricated using an Alpha T2liFB 3-axes CNC high speed milling machine. Aluminium Grade 6061 material has been used to fabricate the components of the ankle joint rotator. The different components of the ankle joint rotator and their assembly are shown in Figure 4.

![Ankle joint rotator prototype and its components.](image)

Due to the limitations of the CNC machine, the four holes on the cross body extension of the cylindrical male component was machined linearly instead of at an angle of 10° inclination. The rotator pin was fabricated using the lathe machine to a diameter of 5.8mm. The inverted pyramid part of the female component was prepared using the Precision Wire-Cut EDM machine with a dimension of 15mm x 15mm x 10mm. The male and female components were assembled using a M10 x 60mm screw. The
Aluminium 6061 made ankle joint rotator prototype has been installed at the ankle joint of the transtibial lower limb prosthesis. The preliminary investigation has shown that the ankle joint rotator was capable of producing a relative rotational movement between the male and female components to adjust the angle of ankle rotation and lock it at two desired angles of 60° and 45°. It has been seen that the locking mechanism was performing well to lock and unlock the male and female components in place when necessary. However, there were still certain drawbacks in the design. Due to inadequate dimensional data availability, the joint interfacing were not perfectly matched. There was some gap observed between the external curved face of the female component and the curved surface of the pylon end, which caused some disparity in fitting the ankle joint rotator to the pylon of the lower-limb prosthesis. Similar discrepancy has been found at the connection interface between the cylindrical cross-body extension of male component and the prosthetic foot adapter. The minor interface matching disparity between components can be overcome by modifying the interfacing surface of the components based on the precise dimensional data to fit the curved surfaces on both pylon and prosthetic foot adapter. Figure 5 shows the ankle joint rotator prototype installed in a transtibial lower limb prosthesis.

The performance of the ankle joint rotator installed in a lower-limb prosthesis is yet to be tested. The stability index, fall risk index, gait cycle analysis, and user feedback collections are in the process. The performance of the ankle joint rotator can be stated after obtaining and proper analysis of all these tests results data.

5. Conclusions
The ankle joint rotator designed for providing two angles of rotation for squatting and kneeling postures was successfully developed. The rotator mechanism was seen to be functional; despite some difficulties, the design was found adaptable to the lower-limb prosthesis available in the market. The simulation results have approved the feasibility of the design; the stress, strain and displacement, and factor of safety analysis results confirmed the safety of the ankle joint rotator design. The minimum safety factor of the ankle joint rotator components during standing and rotating was 9.649 and 5.698 respectively, which are considerably higher than the minimum factor of safety requirement. Though, performance...
test is yet to be done, the simulation results and preliminary investigation endorse the safety and usability of the ankle joint rotator design.

6. References

[1] Gao K, Chen S, Wang L, Zhang W, Kang Y, Dong Q, Zhou H and Li L 2010 Anterior cruciate ligament reconstruction with LARS artificial ligament: a multicenter study with 3- to 5-year follow-up. *Arthroscopy* 26(4) p 515-523.

[2] Al Shuaili N, Aslani N, Duff L and McGarry A 2019 Transtibial Prosthetic Socket Design and Suspension Mechanism: A Literature Review. *J. Prosthet. Orthot* 31(4) p 224-245.

[3] Hsu R W, Sim F H and Chao E Y 1999 Reoperation results after segmental prosthetic replacement of bone and joint for limb salvage. *J. Arthroplast* 14(5) p 519-526.

[4] Rodgers M M 1988 Dynamic Biomechanics of the Normal Foot and Ankle During Walking and Running. *Phys. Ther* 68(12) p 1822-1830.

[5] Bogey R A, Gitter A J and Barnes L A 2010 Determination of ankle muscle power in normal gait using an EMG-to-force processing approach. *J. Electromyogr. Kinesiol* 20(1) p 46-54.

[6] Masum H, Bhaumik S and Ray R 2014 Conceptual Design of a Powered Ankle-foot Prosthesis for Walking with Inversion and Eversion. *Procedia. Technol* 14 p 228-235.

[7] Au S K, Weber J and Herr H 2007 Biomechanical Design of a Powered Ankle-Foot Prosthesis. in 2007 IEEE 10th International Conference on Rehabilitation Robotics.

[8] Popovic M 2013 Biomechanics and Robotics.

[9] Argunusah Bayram H and Bayram M B 2018 Dynamic Functional Stiffness Index of the Ankle Joint During Daily Living. *J. Foot. Ankle. Surg* 57(4) p 668-674.

[10] Perry J and Schoneberger B 1992 Gait Analysis: Normal and Pathological Function. SLACK.

[11] Major M J, Twiste M, Kenney L P and Howard D 2014 The effects of prosthetic ankle stiffness on ankle and knee kinematics, prosthetic limb loading, and net metabolic cost of trans-tibial amputee gait. *Clin. Biomech* 29(1) p. 98-104.

Acknowledgments

The authors would like to thank the School of Mechanical Engineering, University of Science Malaysia for providing the facilities to carry out this work.