Abstract -- In this paper a new prosthetic foot is presented to solve the problem of limited ankle range of motion, while still maintaining natural gait patterns and stability. The design consists of separate physiological ankle ranges of motion for kneeling and walking that were implemented through the use of a modified ball and socket joint. The foot rotates around the ball in the anterior/posterior direction during gait and translates into the second groove when plantar flexion rotation exceeds 40°, in order to be able to rotate further in kneeling. Additionally, viscoelastic rubber ligaments and skin materials provide essential compliance and resistance to the foot. A 3D prototype was created for this design which successfully demonstrated the full ankle range of motion during kneeling and during gait, with controlled transition between each motion.

Index Terms -- ankle, prosthetic foot, plantar flexion, range of motion, transtibial amputee

I. INTRODUCTION

TRANSTIBIAL amputees have a variety of prosthetic foot options which attempt to restore their natural gait patterns and ankle range of motion. Such foot options are chosen based on their daily activities, occupational demands and personal parameters such as age and weight [1]. Popular prosthetic feet on the market include dynamic response feet, such as Flex Foot®, which currently allow for the most natural gait and multi-axis feet which have six degrees of rotation at the ankle joint [1]. However, such prosthetic foot designs lack the flexibility necessary for amputees to perform activities such as kneeling and putting on shoes, which imparts limitations on the user. This problem is the basis for the development of a more functional prosthetic foot. The proposed design must have increased flexibility to facilitate kneeling, while maintaining or enhancing the normal gait patterns that are created by current, top of the line prosthetics. The foot must also provide stability and balance to the amputee. Calculations and dimensions for this design are based on an average North American male with a transtibial amputation who has a foot size of 8. The prosthetic foot design is also directed towards low levels of activity. The main concept behind the design included replicating physiological ranges of motion for kneeling and gait from values found in research papers. A 3D prototype was created that successfully showcased the range of motion and function of the prosthetic ankle joint. The final design is a novel solution to the problem in that complete physiological ankle range of motion and natural gait patterns are no longer mutually exclusive.

II. DESIGN OVERVIEW

This design recreates the physiological aspects of the human foot that allows for the execution of kneeling and natural gait motions. The range of motion (ROM) that an ankle experiences during normal gait includes maximum average angles of 31° plantar flexion and 14° dorsiflexion [2]. In kneeling there is a plantar flexion ROM of 57° ± 19° [3]. In order to ensure a sufficient ROM for kneeling, while preventing excess ankle motion during gait, separate grooves in which the ankle joint rotates were created (Figure 1). Once rotation in the anterior/posterior plane exceeds 40°, the ball and shaft is able to translate into the secondary groove which provides an increase in the plantar flexion angle. To allow this movement, a modified ball and socket joint is implemented such that medial-lateral movement of the foot prosthetic is minimal, but the full range of flexor motion required in gait and in kneeling is not compromised. This design is purely mechanical in nature, and it relies on the properties and orientation of the different component materials to attain the desired plantar and dorsiflexion angles. Rubber ligaments and skin are also included in the design to provide compliance and aesthetic appeal.

III. DETAILED DESIGN

A. Ball and Socket Joint

The ball and shaft component of the joint are made from titanium to ensure that they are strong enough to withstand the loads applied during gait. The socket is designed using a shaped polyethylene base that includes the two grooves for maximum plantar flexion in gait and kneeling respectively. The amputee can activate the kneeling component of the ankle joint by depressing the foot in the plantar flexion direction. This movement forces the ball into the second groove that
allows the user additional plantar flexion movement for kneeling. Once the pressure is removed, the viscoelasticity of the ligaments is such that the ankle returns to a neutral position.

B. Anterior/Posterior and Side Ligaments

The ball and socket joint mimics the anatomical structure of the ankle by including roughly cylindrical silicone rubber ligaments anterior and posterior to the joint. These viscoelastic ligaments provide stability to the amputee and ensure that when the foot is in a neutral position, no plantar or dorsiflexion occurs. The side ligaments prevent medial-lateral translation of the ball and socket joint. Additionally, since the side ligaments taper in the anterior and posterior directions they do not inhibit the flexion of the foot (Figure 2).

![Figure 2: 3D view of the prosthetic foot](image)

C. Internal Keel and External Cosmesis

The base of the foot is composed of a carbon fiber keel around which the external rubber cosmesis is formed in the shape of a foot. Both the keel and the rubber foot store energy during stance that is returned to the amputee during the toe-off stage of the gait cycle. The external cosmesis makes the foot more aesthetically pleasing.

D. Manufacturing

Manufacturing the prosthetic foot requires precise milling with a tolerance of 0.1 mm for the ball and socket joint to ensure a smooth transition between the two grooves.

IV. DISCUSSION

The proposed design presents a more functional prosthetic foot than those which are currently available. The increased degree of flexion allotted in the ankle joint of this model allows for greater usability when dressing or kneeling as well as moderate flexion for a more natural gait cycle. However, this increased flexion does not compromise the safety or stability of the user. This design has been developed to withstand the expected loads from the amputee with adequate factors of safety. As well, materials have been selected that are able to resist the environmental conditions to which the prosthetic may be subjected. The materials used are commonly employed in the prosthetics industry and as such, are not believed to cause any adverse environmental effects. In addition, only common manufacturing processes are required which make use of energy efficient machinery.

The design process proved to be quite iterative. Much was learned throughout the development of the device that had to be corrected or further evaluated. For example, it was determined that increased stability in the medial-lateral axis was needed. This was corrected by modifying the ball of the joint to have flat sides to minimize unwanted motion in this plane. Rubber ligaments were also added on the sides to further restrict movement. It was also discovered that a common prosthetic covering would not be suitable for this design due to the increased demands for flexibility. Therefore, a more elastic cosmesis has been proposed. As well, many different materials were evaluated before the most suitable was selected for each component.

Some limitations that are present in this design include a possible high frequency of maintenance for this design. This is mainly due to loss of material compliance and resistance over time from the viscoelastic ligaments and ligament rupture.

Many recommendations can be made for future development of this design. Mainly, it would be beneficial to build and test a prototype of this design. The prototype testing would assess the full usability of the design. Human subject testing would provide valuable feedback as to whether this design is in fact an improvement from current prosthetic designs. This could include such subjective parameters as the comfort level, stability, ease of use and user preference. User preference relates to whether the user believes that the prosthetic foot allows for a more natural gait cycle and whether it allows the amputee to kneel or dress more efficiently. In addition, the subjects could make further proposals for possible improvements or additions which they would like to see added to the prosthetic.

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REFERENCES

