3D-Printable Toe-joint Design of Prosthetic Foot

Hui-Jin Um[1], Heon-Su Kim[1], Woolim Hong[2], Hak-Sung Kim[3,*], and Pilwon Hur[4,*]

Abstract— **The toe joint is one of the important design factors for prosthetic foot. The toe joint provides feeling of springiness in toe-off step and its stiffness affects the ankle kinematics in robotic prosthesis during gait cycle. Moreover, since human toe joints exhibit nonlinear toe torque-angle behavior, these nonlinear characteristics should be considered when the prosthetic foot is designed to mimic human gait behavior more naturally. To implement nonlinear toe joint behavior without additional mechanical components such as actuators, sensors and electronic circuits, the structural foot design should be considered. In this study, the auxetic structure with negative Poisson's ratio was applied to the toe joint design and bending space was considered for stable bending deformation of prosthetic foot. Finite element analysis was performed to analyze the designed toe joint behavior. The mechanical properties of onyx material which is a short carbon fiber reinforced nylon filament were applied in the FE simulation, considering 3D printing manufacturing. The torque-angle graph for toe joint from a result of FEA was compared with the human toe torque-angle behavior. Consequently, the nonlinear toe stiffness characteristics were implemented through a structured single-part prosthetic design.**

I. INTRODUCTION

The lower limb prostheses have been widely studied for patients with lower limb amputations such as diseases, car accidents and war [1]. An important point in the design of the prosthetic foot is that it behaves like a human without uncomfortable feelings to wearers, considering the relationship between gait biomechanics and mechanical properties such as angular stiffness and damping. For this, there have been many studies of prosthetic foot through experiments and simulations, and as a result various types of prosthetic foot have been developed [2], [3]. In the study of the prosthetic foot, the ankle joint behavior and control has been the most extensively studied. However, the toe joint has not been considered extensively even though it is one of the important factors in foot design. It is important to note that toe joint affects the ankle kinetics and provides the springiness feeling in toe-off step [4], [5]. Since the nonlinear toe stiffness characteristics are found in human gait behavior, the prosthetic foot design that considers these nonlinear properties should be conducted. However, implementing the toe joint may require additional actuators, and sensors resulting in a complicated control system for the implementation of nonlinear toe stiffness [4], [6], [7]. These additional motor or control system not only make the manufacturing and management of prosthetic foot much more difficult, but also cause weight increase [5]. Therefore, structural design of prosthetic foot should be considered in order to implement toe joint without additional motors or complex control system. The auxetic structure that has negative Poisson's ratio has superior mechanical properties such as high shear properties, energy absorption, and impact behavior [8], [9]. Therefore, in this study, the auxetic structure was applied to the toe part of the prosthetic foot to mimic the nonlinear human toe joint behavior. Moreover, throughout the human gait cycle, the toe joint, in general, deforms more than 20 degrees. Thus, the bending properties of the toe joint structure are very important to flex more than 20 degrees without any fracture [10]. So, the bending space as well as the auxetic structure was considered for stable deformation during the push off. The finite element analysis was performed using the designed prosthetic foot. There are many difficulties in using the conventional method when manufacturing the prosthetic foot after designing such a structure in the form of a lattice and a curve. However, with the recent development of 3D printing technology, it became possible to manufacture the complicated structure in single step and it is possible to manufacture the designed prosthetic foot as a single part [11]–[13]. Therefore, in this study, considering manufacturing with the 3D printing technology, the toe joint design was performed with a single part, and the analysis was conducted using the onyx filament properties.

[1]Hui-Jin Um and Heon-Su Kim are with the Mechanical Engineering Department, Hanyang University, Seoul, South Korea (e-mail: gog9057@hanyang.ac.kr, khsu0212@gmail.com).

[2]Woolim Hong is with the J. Mike Walker '66 Department of Mechanical Engineering, Texas A&M University, College Station, TX 77843, USA (e-mail: ulim8819@tamu.edu).

[3]Hak-Sung Kim is with the Hanyang University, Seoul, South Korea. He is also with Institute of Nano Science and Technology, Seoul, South Korea (*corresponding author, phone: +82-2-2220-2898; e-mail: kima@hanyang.ac.kr).

[4]Pilwon Hur is with the School of Mechanical Engineering, Gwangju Institute of Science and Technology, Gwangju 61005, South Korea. He is also affiliated with the J. Mike Walker '66 Department of Mechanical Engineering, Texas A&M University, College Station, TX 77843, USA (*corresponding author, phone: +82-62-715-2408, fax: +82-62-715-2384, e-mail: pilwonhur@gist.ac.kr, pilwonhur@tamu.edu).

II. TOE JOINT OF PROSTHETIC FOOT DESIGN

A. *Human toe-joint property*

The human toe joint behavior during the stance phase was exhibited in Figure 1. During the gait cycle, the slope of toe torque-angle curve changes, meaning that the toe joint has variable stiffness characteristics according to the gait motion [10]. Therefore, one of the critical factors in prosthetic foot design is the variable toe joint stiffness, which can provide a general feeling of springiness in toe-off step. In human toe torque-angle curve, after the maximum toe torque value, the toe stiffness tends to increase from ① to ②. When this toe joint stiffness increase behavior is implemented, the prosthetic foot provides a human-like gait behavior.

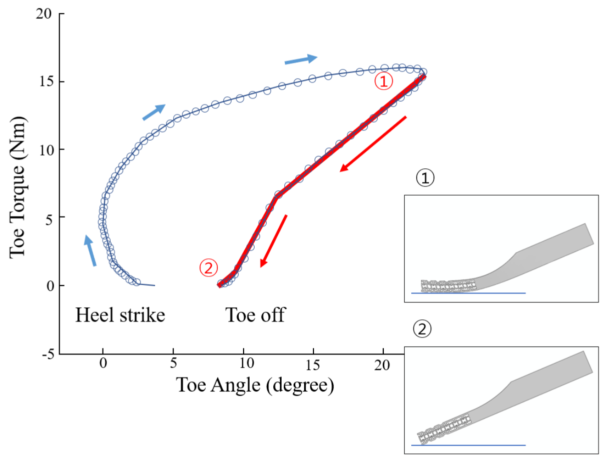

Fig. 1. The toe torque-angle graph of human which shows variable stiffness characteristics [10].

Therefore, in this study, toe part of the prosthetic foot design was conducted to describe the varying toe stiffness after maximum toe torque like human gait. Heel off and toe off terms are newly defined to deal with aforementioned gait cycle events. The heel-off (HO) step is defined as a state ① in Figure 1 when the toe joint showed maximum toe torque value. The toe-off (TO) step is defined as the state ② in Figure 1 at the end of the stance phase. Consequently, toe joint of prosthetic foot was designed considering nonlinear toe joint stiffness from HO to TO in the stance phase.

B. Prosthetic foot with variable stiffness

There are several studies that attempted to implement the toe stiffness of prosthetic foot. However, their designs were difficult to be manufactured due to complex structure [6], [14]. Also, the aforementioned designs usually require additional mechanical parts for the toe joint, such as motors and control systems. The additional parts not only increase the weight of the prosthetic foot, but also make it difficult to control the overall system. Therefore, we propose a 3D printable foot structure (i.e., re-entrant and honeycomb structure [15]) to mimic human foot characteristics without additional mechanical part.

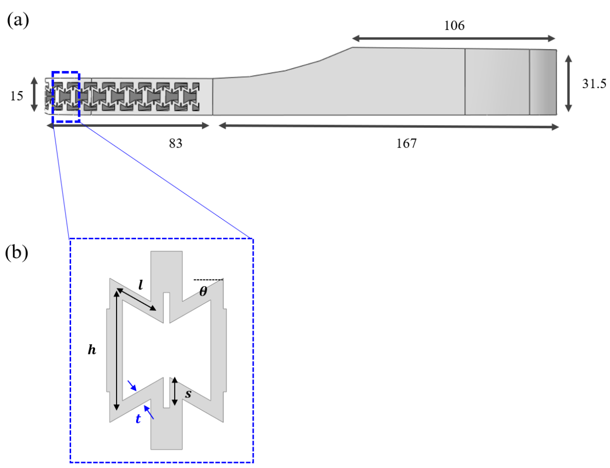

Fig. 2. (a) The dimension of prosthetic foot used in this study and (b) geometrical variables of re-entrant unit cell.

C. Toe design of prosthetic foot

Auxetic structures are a kind of special lattice structures that have negative Poisson's ratio. Among the auxetic structures, re-entrant honeycomb structure was applied in toe joint design as shown in Figure 2. The re-entrant honeycomb structure has received an attention due to its excellent mechanical properties, such as increased energy absorption capacity and shear resistance than conventional honeycomb structure [8]. Also, they have variable stiffness characteristics when compressive or shear deformed. Therefore, the auxetic structures, i.e., re-entrant honeycomb structure, were applied in the toe for the springiness feeling and variable stiffness and compared.

The prosthetic foot dimension used in this study is shown in Figure 2(a). The overall length and height were set based on the dimension of AMPRO II, a robotic transfemoral prosthesis developed at Texas A&M University [16]. The re-entrant honeycomb unit cell was exhibited in Figure 2(b) and there are five geometrical variables. The relative density (RD) is the ratio of the area of all strut in unit cell (A_s) to the apparent area of unit cell (A). The RD can be calculated using geometrical variables as followed [15], [17]:

$$\frac{A_s}{A} = \frac{2lt + 1.75ht + 2t^2}{3ht + 2hl\cos\theta + 3lt\sin\theta + 2l^2\sin\theta\cos\theta} \qquad (1)$$

III. FINITE ELEMENT ANALYSIS

A. Simulation model

The toe stiffness properties were analyzed through finite element simulation. The finite element analysis (FEA) models were established as shown in Figure 3. The reference model without any structure was called solid foot (see Figure 3(a)). In Figure 3(b), the re-entrant structure was applied in the forefoot part. In FEA, the two different materials were used and the material properties are shown in Table I [15], [18]. The acrylonitrile butadiene styrene copolymer (ABS) is widely used filament as 3D printing material. The onyx is the short carbon fiber reinforced nylon filament produced by Markforged (Watertown, MA, USA). The both materials

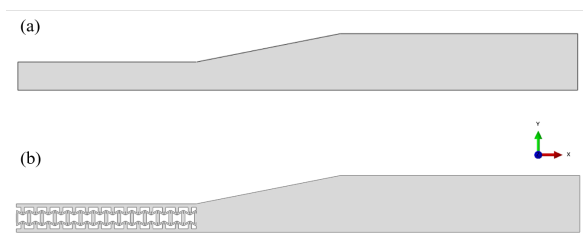

Fig. 3. Finite element model (a) solid foot, (b) re-entrant structure foot.

TABLE I

MECHANICAL MATERIAL PROPERTIES OF ABS AND ONYX FILAMENT FOR FEA [15, 18]

	Young's modulus, E	Yield strength, σ_y	Poisson's ratio, ν	Density, ρ
ABS	2.2 GPa	31 MPa	0.35	1.05 g/cm^3
Onyx	1.4 GPa	36 MPa	0.33	1.2 g/cm^3

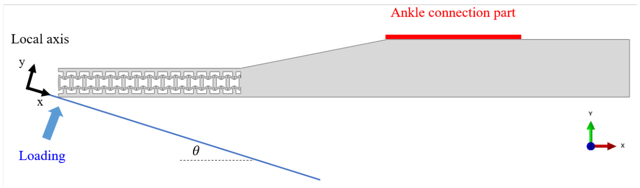

Fig. 4. The boundary condition and loading condition for the FEA of prosthetic foot.

were considered to be elastic perfectly plastic, isotropic and homogeneous.

B. Simulation setup

All numerical simulation was performed with ABAQUS (v6.14, ABAQUS Inc., Vélizy-Villacoublay, France). The toe bending simulation was conducted from HO to TO. For this, a rigid plate was placed at the bottom of the foot with angle θ and it approached gradually to the foot model as shown in Figure 4. The surface-to-surface contact was set between the rigid plate and foot bottom. And the force of 1 kN was applied to the rigid plate in the direction normal to the rigid plate (y direction in local axis). This load was set based on the maximum vertical ground reaction force generated when pushed off for a 100 kg adult male [19]–[21]. Since the designed prosthetic foot will be bolted to the ankle, the ankle connection part is set to a fixed condition as indicated by the red line in Figure 4.

IV. RESULT AND DISCUSSION

The Figure 5 shows the FEA results of the solid and re-entrant structure model with onyx material. The stiffness (i.e., slope of FD curve) of the solid foot was not changed and it showed linear behavior during gait cycle as shown in Figure 5(a). On the other hand, the structure foot showed nonlinear stiffness behavior (see Figure 5(b)). In addition, the solid foot only deformed 14 mm, whereas the structure foot showed a larger amount of 15 mm deformation at HO step. It means that the re-entrant structure foot can be bent more than the solid foot. In both cases, the maximum strength did not exceed the yield strength of onyx as shown in Figure 5(c) and (d).

To analyze the toe joint characteristics according to the material, the FE simulations was performed by varying materials (i.e., ABS and onyx) for the same re-entrant structure. As shown in Figure 6(a), the linear behavior of FD curve was found when using the ABS material whereas nonlinear behavior was found for the onyx. Also, when the

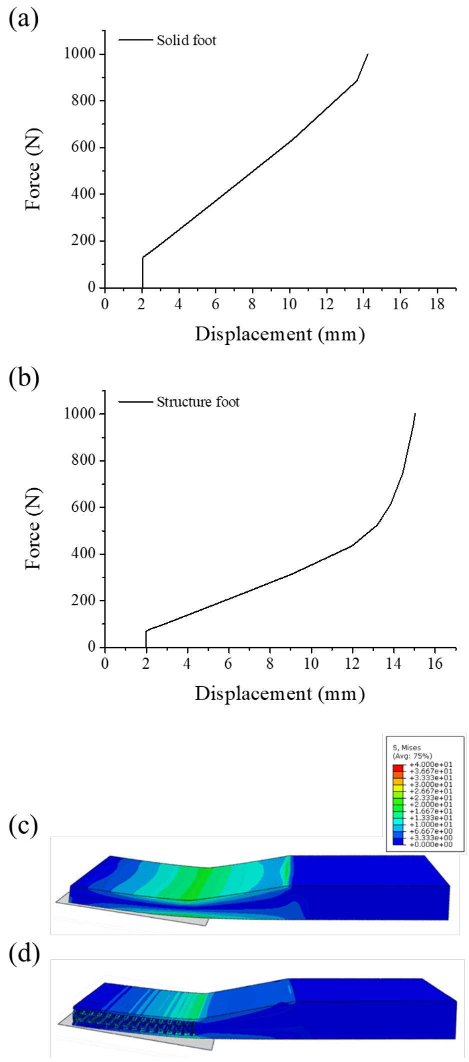

Fig. 5. The force-displacement (FD) curve as a result of FE simulation; (a) solid foot (b) re-entrant structure foot. The stress distribution according to the foot type; (c) solid foot, (d) re-entrant structure foot.

ABS material was used, the amount of deformation was also smaller than that of the onyx case, which means that the bending deformation of the toe joint does not occur properly. Moreover, the ABS with smaller yield strength than the onyx showed higher maximum Von Mises stress, whereas the onyx with higher yield strength showed relatively lower maximum Von Mises stress (see Figure 6(b)). Since the onyx has higher elasticity and mechanical strength, various stiffness change properties could have been performed in the stress range lower than the yield strength.

In human toe torque-angle behavior as shown in Figure 1, the maximum toe torque value is about 15 Nm, and the toe angle ranged from 20 to 10 degrees while transitioning from HO to TO. Therefore, the toe joint behavior in the range of human toe joint angle was compared using the result of prosthetic foot simulation applying the re-entrant structure. The toe torque-angle result of the designed foot simulation was exhibited in Figure 7. The apparent difference compared

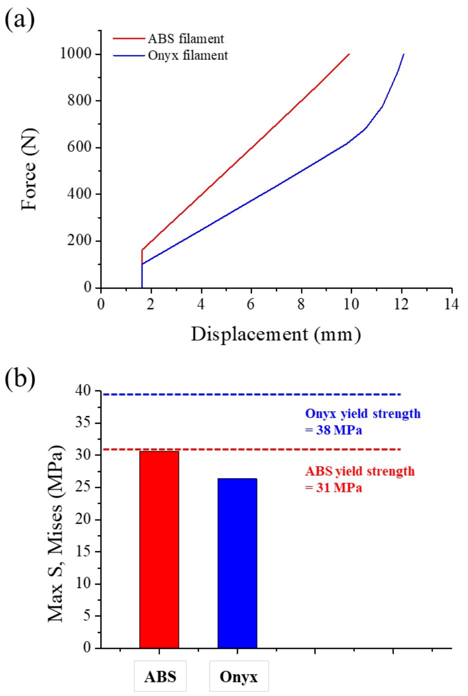

Fig. 6. The FEA results of the re-entrant structure foot with respect to the materials: (a) Force-displacement graph; (b) maximum Von Misses stress.

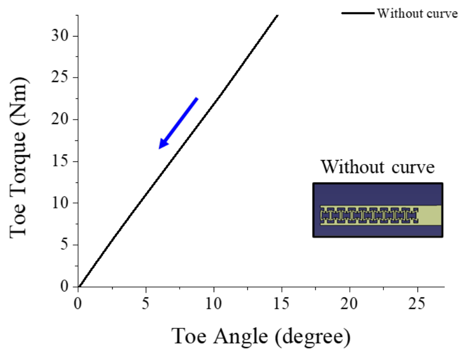

Fig. 7. Toe torque-angle curve as a result of the finite element simulation for re-entrant structure foot.

to human behavior is that the maximum toe angle is less than 15 degrees in the HO state when the toe joint is fully flexed, and the toe angle is 0 degrees in the TO state when the toe lifts off the ground. Also, the maximum torque value is higher than that of human toe, which is required to be modified the toe joint structure.

To reduce the maximum toe torque and to induce stiffness change behavior according to the angle of the human toe, the shape of the toe part has been changed from flat to curved. Also, the bending space was introduced right after the last re-entrant structure (see Figure 8(a)) to improve the bending properties of the toe joint. As a result, bending deformation of toe joint occurred more than 20 degrees, and the toe angle was also about 10 degrees instead of 0 degrees at the TO stage. Therefore, by introducing the bending space

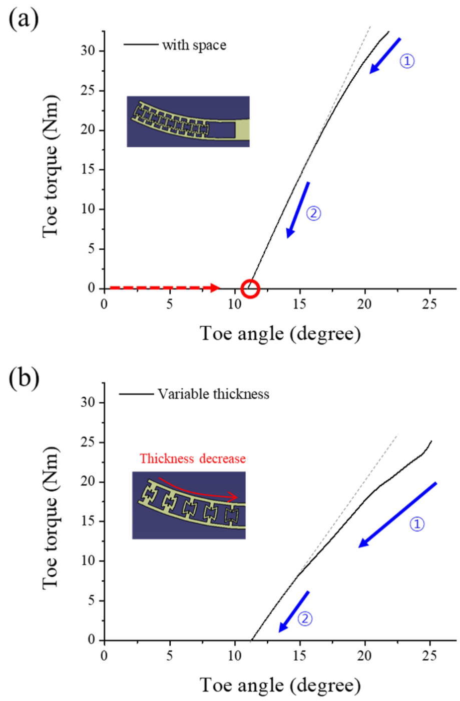

Fig. 8. The toe torque-angle graph as a result of the finite element simulation: (a) for the curved shape foot with bending space; (b) for the designed foot with variable thickness structure.

and curved shape, the toe joint angle behavior during HO to TO was improved. Moreover, it can be seen that the toe joint stiffness change occurred after HO (① in Figure 8(a)). However, the stiffness change occurred at a relatively large toe angle of about 17 to 18 degrees. In addition, since the toe stiffness was mostly maintained at a high level during the gait behavior as exhibited by ② in Figure 8(a), the tendency of the toe stiffness change shown in Figure 1 was not clearly indicated.

Therefore, to further improve the toe joint characteristics, a thickness-varying structure was applied to the toe part. When the push off proceeds after the toe joint is fully flexed, the human toe stiffness increased as shown in Figure 1. Therefore, from the toe tip to the center of the foot, the thickness of re-entrant structure was reduced by 0.2 mm from 1.5 mm to 0.5 mm. The toe torque-angle graph of foot with variable thickness structure is shown in Figure 8(b). Compared to the previous structure, the maximum toe angle increased and the maximum toe torque value decreased, resulting in a similarity to human toe behavior. In addition, the toe joint stiffness increased more apparently as it progressed from HO to TO. The toe stiffness changed when the toe angle was less than 15 degrees. However, there still exist limitations such as the higher toe torque value at HO step and different stiffness change behavior in toe torque-angle graph. Therefore, optimization of geometry, e.g., the dimension of the re-entrant structure and the bending space, is required to further mimic the human gait motion.

V. CONCLUSION

In this study, the toe joint of prosthetic foot was designed to implement the variable stiffness characteristics observed in human walking between HO and TO. The auxetic structure and bending space were applied to the prosthetic foot to mimic the human gait behavior without additional electromechanical parts such as motor and control systems. The toe joint behavior was analyzed through FEA using ABAQUS software. The two materials (i.e., ABS vs. onyx) were used for the prosthetic foot. The ABS material, which is widely used in 3D printing area, could not implement the nonlinear behavior of toe joint compared to the onyx material even with the same structure. Therefore, the onyx material was more appropriate to design prosthetic foot because it has excellent elasticity and high yield strength. The FE simulation was conducted in range of human toe angle by applying the curved foot shape and bending space. As a result, toe stiffness change was implemented by using variable toe structure thickness. Therefore, it was confirmed that the toe joint behavior with a change in stiffness can be realized through the design of prosthetic foot structure using only a single material.

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