3D-Printable Prosthetic Foot with Human Toe-Joint Property

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Introduction

In designing a prosthetic foot, the relationship between the mechanical properties (e.g., stiffness and damping) and the gait biomechanics should be considered to have human-like ambulation. One of the critical factors is the toe joint stiffness, which can provide a general feeling of springiness in toe-off step. Several studies have attempted to implement the toe stiffness in the prosthetic foot design; however, their designs were complex to be manufactured [1], [2]. Also, the aforementioned designs usually require an additional mechanical part for the toe joint, leading to the heavier weight of the foot. In this study, we propose the 3D printable foot structure (i.e., re-entrant and honeycomb structure [3]) to mimic human foot characteristics, specifically the toe stiffness. We also propose a composite material, called "onyx", to enhance the elasticity and strength.

Methods

To analyze the toe stiffness properties, two finite element analysis (FEA) models (a: re-entrant, b: re-entrant honeycomb) were established (Figure 1). In Figure 1(a), the re-entrant structure was applied in the forefoot. To investigate the effect of the foot material, two different materials (i.e., ABS and onyx) were compared using the identical structure in the simulation. On the other hand, in Figure 1(b), the combined structure of the re-entrant and honeycomb was applied in the forefoot to release stress concentration of the re-entrant model. Then, to analyze toe bending characteristics, a simulation was conducted with and without the bending zone (BZ). For a toe bending simulation, a rigid plate was placed at the bottom of the forefoot and approached gradually with 10° inclination in the re-entrant model, and 15° inclination in the re-entrant honeycomb model to confirm reinforcement of the latter model. All numerical simulation was done with ABAQUS (v6.14, ABAQUS Inc., Vélizy-Villacoublay, France).

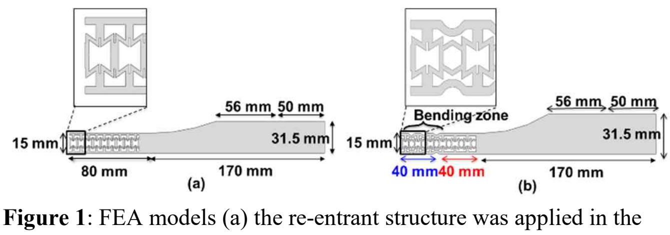

Figure 1: FEA models (a) the re-entrant structure was applied in the forefoot; (b) the combined structure of the re-entrant, honeycomb, and BZ was applied in the forefoot

Results and Discussion

Figure 2 shows the FEA results of the re-entrant model. As it is shown in the force-displacement (F-D) graph (Figure 2(a)), the stiffness (i.e., slope of F/D curve) of the onyx increased while that of the ABS was constant. Note that the nonlinearly increasing toe joint stiffness is desired for the prosthetic foot due to the human gait biomechanics. In addition, the onyx showed lower maximum stress and higher yield strength than the ABS (Figure 2(b)). Since the onyx has high elasticity and strength, it may have performed variable stiffness characteristics while having a proper strength characteristic.

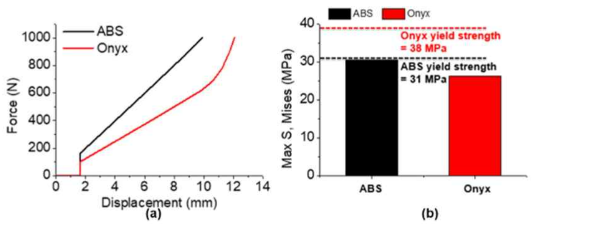

Figure 2: The FEA results of the first model: re-entrant structure (a) F-D graph; (b) maximum stress

However, when the toe bending angle was over 15°, the maximum stress of the re-entrant structure exceeded the yield strength. For this reason, the re-entrant honeycomb model was designed to reduce the maximum stress. Since it resulted in a deterioration of the stiffness characteristics, BZ was used to compensate it. The FEA results are depicted in Figure 3. The characteristics of the stiffness and the strength were enhanced when the BZ is considered. The curved surface of the BZ released the stress concentration, resulting in the enhancement of the bending characteristics.

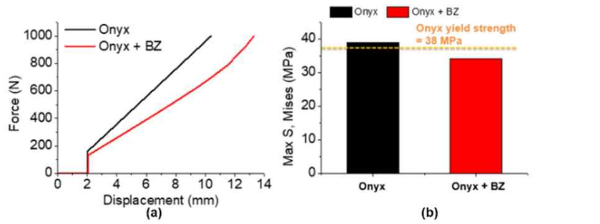

Figure 3: The FEA results of the second model: re-entrant honeycomb structure (a) F-D graph; (b) maximum stress

Significance

This study shows that numerous mechanical properties can be obtained by modifying the structure of the prosthetic foot. Further, the desired characteristics can be obtained by the optimization process. Since the proposed foot is 3D printable, it is easy to manufacture the prosthetic foot while considering individuals' characteristics. We expect that the proposed re-entrant honeycomb structure and onyx will lead to simplicity in manufacturing, the reduction of the cost and the weight, and enhancement of gait biomechanics.

References

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