**Structural behavior evaluation of prosthetic foot using the auxetic structure via finite element analysis**

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## Introduction

In the past years, the design of prosthetic feet has been widely studied for the lower extremity amputees. One of the critical design challenges is the impact reduction at the heel strike [1]. To carefully manage the impact load at the heel strike, a prosthesis design using a lattice structure was considered. The auxetic structure has received an attention due to its excellent mechanical properties, such as increased shear resistance and energy absorption [2]. Specifically, the re-entrant honeycomb structure exhibits an increased energy absorption capacity compared to the conventional honeycomb [3]. In this study, we propose the re-entrant structure for the prosthetic foot to enhance the energy absorption at the heel strike.

## Methods

Structural behavior analysis was conducted using ABAQUS (v6.14, ABAQUS Inc., Vélizy-Villacoublay, France). The foot shape was approximated as rectangular with a length of 250 mm and a width of 120 mm. The geometry was meshed with 8-node hexagonal elements and the material properties were set as acrylonitrile butadiene styrene copolymer (ABS). One of the design parameters is the relative density (RD) of a structure, which is the ratio of the volume of all struts in a unit cell to the apparent volume of the unit cell. The finite element analysis (FEA) was conducted using two types of foot with RD of 0.35 and RD of 0.55. In the FEA, the ankle connection part was constrained from moving in the x, y, and z directions. Then, the load was applied normal to the heel (red line in Figure 1 (b)) during the step time of 1 sec as pressure with the total force of 1,000N. All experiments were done numerically in the ABAQUS.

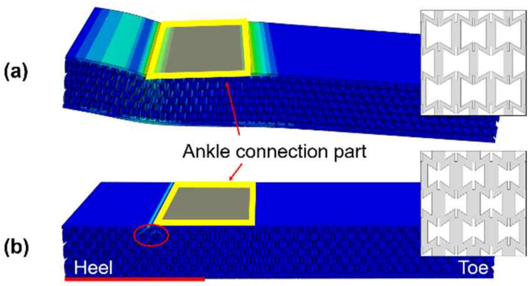


**Figure 1**: Stress analysis of the prosthetic foot at step time 1; (a) structure relative density of 0.35, (b) structure relative density of 0.55

## Results and Discussion

As a result of FEA, the stress distributions of the prosthetic foot are shown in Figure 1. The plastic deformation did not appear in both cases. The stress was evenly distributed in heel part of the foot with RD 0.35. However, in the foot with RD 0.55, the stress was largely concentrated in the area near the ankle connection part. Therefore, the local failure (e.g., brittle failure), not as an elastic deformation, would be expected in foot with RD 0.55. The instability deformations are further described as following.

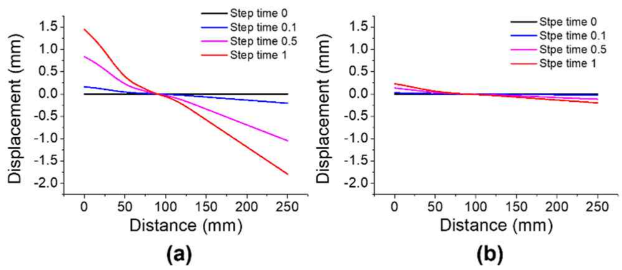


**Figure 2**: Displacement distribution of prosthetic foot according to the step time; (a) RD 0.35, (b) RD 0.55.

The displacement of the bottom surface of each foot is analyzed as shown in Figure 2. The distance in x-axis means the foot length (0 mm: the end of the hindfoot or heel, 250 mm: the end of the forefoot or toe tip). Under the same load condition, the foot with RD 0.35 deformed 6.3 times larger than the foot with RD 0.55. Also, the deformation of the forefoot was much larger in the foot with RD 0.33 than that of the foot with RD 0.55 due to the bending deformation. Through these deformations, the foot with RD 0.35 shows more stable energy absorption. This is because the re-entrant structures exhibit the significant energy absorption capacity at bending deformation [3]. However, with the higher RD (e.g., RD 0.55), the slenderness ratio of the strut increases, which makes the structure more brittle. The brittle properties of the foot with RD 0.55 can lead to instability behaviour, such as local failure due to stress concentration as shown in Figure 1. *Therefore, the decision of an appropriate RD is important to enhance the energy absorption behavior of the prosthetic foot for stable deformation at the heel strike.*

## Significance

The longer-term purpose of this study is to manufacture the prosthetic foot using 3D printing technology as a single part. This may make the manufacturing process simpler while enhancing the performance of the prosthetic foot. To achieve the shock-absorbing property at the heel strike, we applied the novel re-entrant structure to the prosthetic foot. Also, we investigated the effect of the structure's RD by comparing two different RD cases in the simulation. We expect that, via biomechanical studies of prosthetic walking, a stable heel strike can be achieved by using the proposed auxetic structure with optimal RD for the prosthetic foot.

## References

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