Structural design for energy absorption during heel strike using the auxetic structure in the heel part of the prosthetic foot

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***Abstract*— In designing prosthetic foot, the function that can absorb the shock during the heel strike should be considered for the user's convenience and safety. For this, we designed a 3D printable prosthetic foot that absorbs energy by applying an auxetic structure to the heel part. Through the Finite Element Analysis, the heel strike conditions were established, and energy absorption and maximum stress loaded on the structure were analyzed with respect to the direction and dimensions of the auxetic structure. In addition, the stress concentration that may occur on the upper plate of the heel part according to the round shape design was analyzed. As a result, the designed structure had energy absorption of 3.16 J and the maximum stress of 37.92 MPa, showing that the designed prosthetic foot is practically applicable in the rehabilitation field.**

I. INTRODUCTION

In the past years, the design of prosthetic foot has been widely studied for the lower extremity amputees [1], [2]. Although the design of prosthetic foot has been widely studied for the lower extremity amputees, several fundamental challenges still remain. One of the critical design challenges is the impact reduction at the heel strike [3]. Human walking consists of several events: heel-strike, foot-flat, heel-off, and toe-off as shown in Figure 1 [4]. At heel-strike, the impact has to be carefully managed to protect the electromechanical parts from damage and to mitigate the discomfort. To carefully manage the impact load at the heel strike, a prosthesis design using a lattice structure was considered. The auxetic structure has received a considerable attention due to its excellent mechanical properties, such as increased shear resistance and energy absorption [5]. Specifically, the re-entrant honeycomb structure exhibits an increased energy absorption capacity compared to the conventional honeycomb [6]. In this study, we propose 3D printable design for the prosthetic foot to enhance the energy absorption at the heel during the heel strike. For this, onyx material that has high mechanical properties (e.g., elasticity, strength) and is used as a printing material was used. The auxetic structure was applied to the heel for energy absorption during the heel strike. In addition, heel part was designed by applying a round-shaped structure that disperse the stress concentration so that the maximum stress does not exceed the yield strength of the onyx.

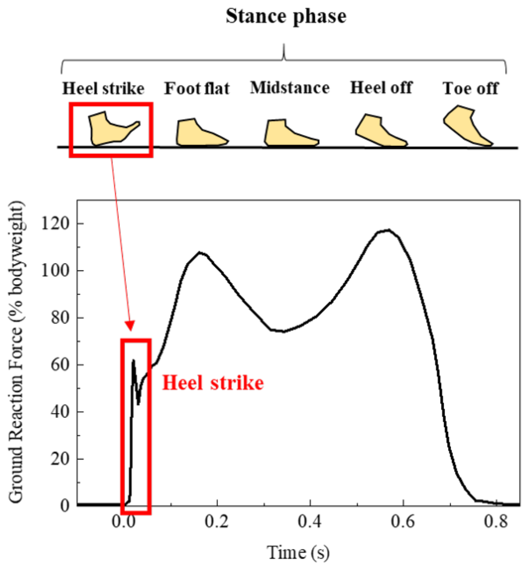

Fig. 1. The gait cycle of human walking and the ground reaction force according to the vertical direction

II. METHODS

A. Finite Element Analysis

Structural behavior of the prosthetic foot was analyzed via the FEA using the commercial ABAQUS software (ABAQUS Inc., Vélizy-Villacoublay, France). The foot model was designed as a 2D surface model and meshed with plane strain elements CPE4R to reduce the calculation time. The prosthetic foot was designed based on the dimensions of the previously implemented foot of a custom-built powered prosthesis, AMPRO II, as shown in Figure 2(a) [7], [8]. The total length of the foot was 250 mm, the height of hind foot was 63 mm and the heel part for structural design was 125 mm, which is half of the total foot length as shown in Figure 2(b). The tip of the heel part was designed in a curved shape to induce the energy absorption into the structure during heel strike. Considering the 3D printing, the onyx that has higher mechanical properties than the conventional plastic 3D filaments was used for the design of the prosthetic foot.

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TABLE I

MECHANICAL MATERIAL PROPERTIES OF ONYX FILAMENT FOR FEA

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

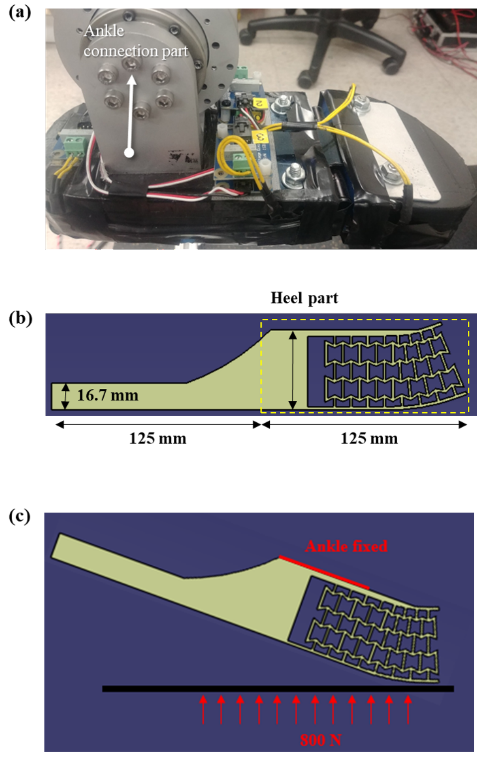

Fig. 2. (a) AMPRO II which was used in the previous study; (b) Overall dimensions of the prosthetic foot; (c) Simulation conditions for the heel strike.

The mechanical properties of the onyx are depicted in Table I [9]. The mechanical properties were assumed to be elastic perfectly plastic, isotropic and homogeneous. For the heel strike simulation, a rigid plate was placed at the bottom of the heel part and approached gradually with 20o inclination with the total force of 800 N as shown in Figure 2(c). The ankle connection part was constrained from moving in the x,y and z directions.

B. Auxetic Structure

Auxetic structures are a kind of special lattice structures with negative Poisson's ratio. It has received an attention due to its excellent mechanical properties, such as increased shear resistance and energy absorption [5]. Specifically, the re-entrant structure exhibits an increased energy absorption capacity compared to the conventional honeycomb [10]. Therefore, the re-entrant structure was applied to the heel part to absorb energy during heel strike. The geometric parameters of re-entrant structure are shown in Figure 3(a). After that, energy absorption with respect to the direction of the re-entrant structure was compared as shown in Figure

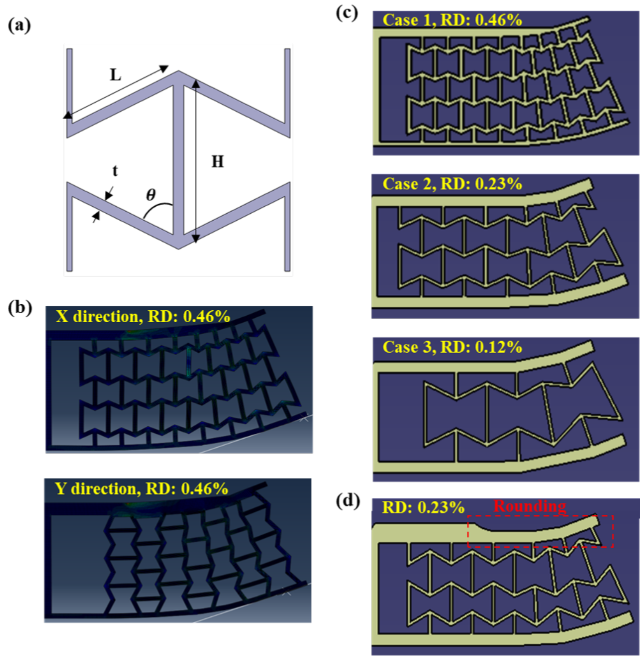

Fig. 3. (a) Geometric parameters of the re-entrant structure unit cell; Heel part design with respect to the, (b) direction of the re-entrant structure and (c) dimensions of the re-entrant structure; (d) Round shape design in the upper plate of the heel part.

3(b). Then, three cases in which different number of structures were applied vertically to the heel were compared as shown in Figure 3(c). The structure was changed to have the same aspect ratio according to the number of the structures. Also, a rounding design was analyzed to the upper plate of the heel part to disperse the stress concentration due to the fixed ankle area as shown in Figure 3(d) [11], [12]. For the comparison, the relative density (RD) for each case was calculated. The relative density (RD) is the ratio of the area of all the lattice structure (A) to the apparent area of the unit cell (A_s) and can be calculated as the following equation (1):

$$\frac{A_s}{A} = \frac{t(h+2l)}{2l\cos\theta(h+l\sin\theta)} \tag{1}$$

Where, t, h and l are the geometric parameters of re-entrant structure as shown in Figure 3(a). The RD of the structures in Figure 3(b) is 0.46%, and the RDs for cases 1, 2 and 3 are 0.12%, 0.23%, 0.46%, respectively. Then, the energy absorption and the maximum stress of the structure with respect to the RD were compared.

C. Energy Absorption

The energy absorption (W) can be derived by force-integral method [13]. The force-integral method calculates the energy absorption by numerically integrating the ground reaction force vector F over the foot-ankle deformation S as the following equation (2):

$$W = \int F\, dS \qquad (t_0 \leq S \leq t_e) \tag{2}$$

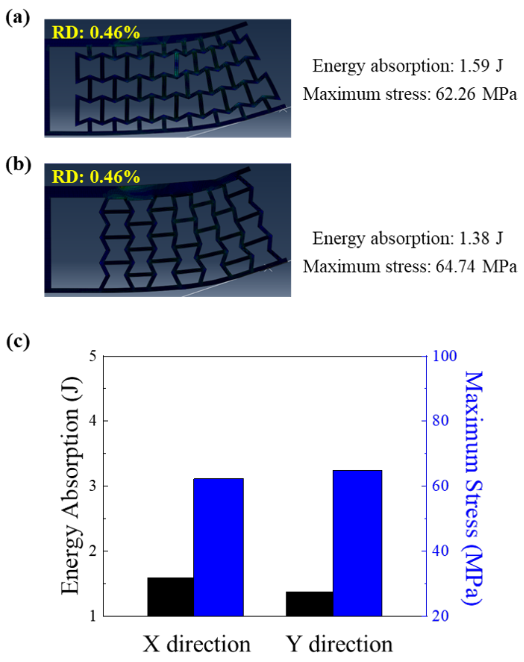

Fig. 4. The FEA results of the re-entrant structure with (a) X direction and (b) Y direction, and (c) the energy absorption and maximum stress.

where, t_0 is the time when the heel strike starts and t_e is the time when the heel strike ends. By deriving the normal contact force and the displacement of the designed foot from the FEA, the energy absorption was calculated.

III. RESULT AND DISCUSSION

To apply the structure suitable for energy absorption in the heel part, the energy absorption and maximum stress with respect to the direction and dimensions of the structure were analyzed using the FEA. Figure 4 shows the energy absorption and maximum stress values according to the direction of the re-entrant structure. The energy absorption was higher when the re-entrant structure was applied in the X direction (see Figure 4(a)) than when the structure was applied in the Y direction (see Figure 4(b)). From this result, it can be seen that the re-entrant structure in the X direction functions more effectively on compression deformation (see Figure 4(c)). However, the energy absorption of 1.59 J was too low for the value of 3.6 J that is required for human foot. The maximum stress applied to the structure was also 64.74 MPa, which is higher than the yield strength of the onyx (36 MPa, see Table I). Since the structure's RD of 0.46% was too high, the bending deformation in the structure did not occur significantly, and the energy absorption did not occur smoothly [6], [14]. As a result, it is necessary to select a re-entrant structure with appropriate number of structure in order to increase the energy absorption of the structure.

Figure 5 shows the simulation results derived from each case with different number of the structure. In the case 1, the energy absorption was 1.59 J, which is generally much lower than the 3.60 J required for the actual human foot (see

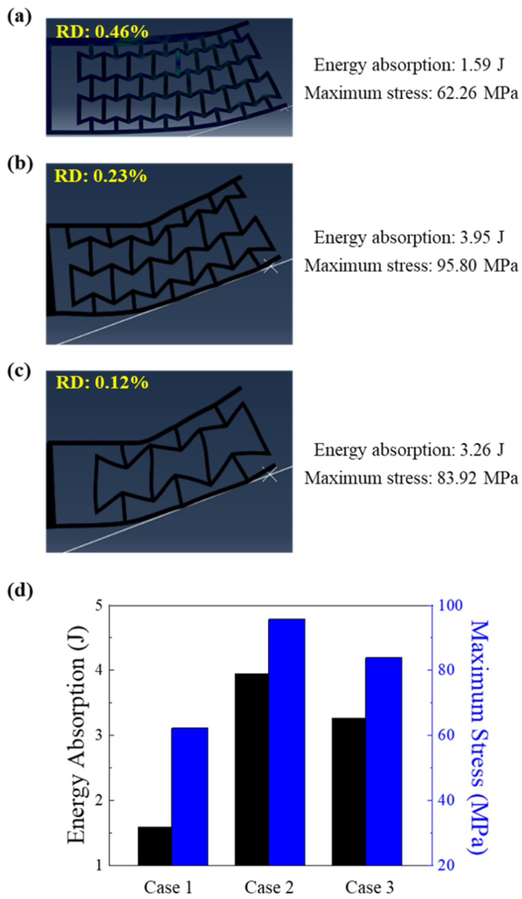

Fig. 5. (a-c) The FEA results of the re-entrant structure with respect to the number of structure and (d) the comparison of the energy absorption and maximum stress.

Figure 5(a)). In contrast, case 2 showed more stable energy absorption value of 3.95 J (see Figure 5(b)). The re-entrant structures exhibit the significant energy absorption capacity at bending deformation [6]. Since the RD of the structure in the case 2 (0.23%) is lower than in the case 1 (0.46%), more bending deformation occurs, absorbing more energy. In the case 3, the energy absorption increased to 3.26 J , and then the structure was destroyed during the simulation (see Figure 5(c)). This is because the structures consist of only one layer, so it cannot function as re-entrant structure. Also, the structure is brittle since the structure's RD of 0.12% is too low, leading to instability such as local failure due to stress concentration [6], [14]. Therefore, the decision of an appropriate number of structure is important to enhance the energy absorption behavior of the prosthetic foot for stable deformation at the heel strike. In this paper, the structure of the case 2 is the most appropriate for a given foot dimensions (see Figure 5(d)).

However, the maximum stress of the structure is too high, exceeding the yield strength of the onyx (36 MPa, see Table I). In the distribution of stress applied to the prosthetic foot, it was confirmed that a stress concentration occurred in the middle part of the upper plate as shown in Figure

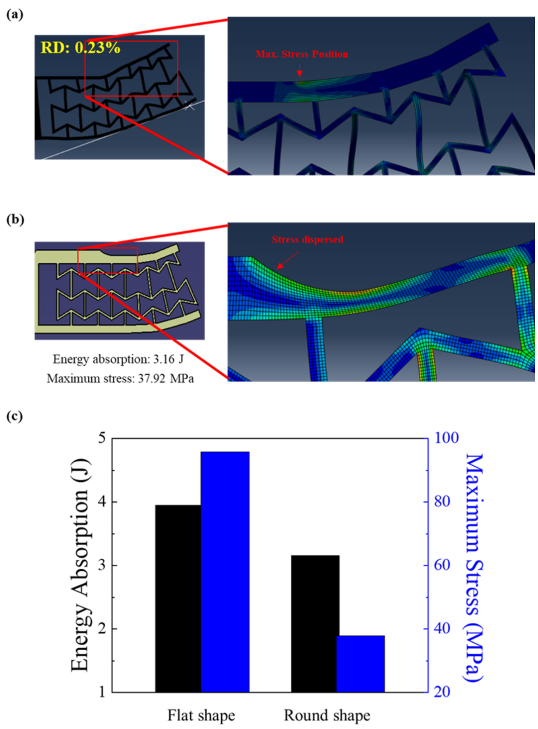

Fig. 6. (a) The stress concentration occurred in the middle part of the upper plate; (b) The FEA results of the structure with and without round shape in the upper plate and (c) the comparison of the energy absorption and maximum stress.

6(a). This is because deformation occurs significantly at the corresponding position due to the fixed condition of the ankle. To relieve the stress concentration, the upper plate of the heel part was rounded as shown in Figure 6(b). Since the round shape distributes the stress to the plate and the structures, the maximum stress greatly reduced to 37.92 MPa (see Figure 6(c)). On the other hand, due to the additional deformation of the rounded part, the energy absorption in the re-entrant structure was reduced to 3.16 J. Although the energy absorption was reduced to 3.16 J by the rounded structure, it was possible to design an effective heel structure through the disperse of the stress concentration.

IV. CONCLUSION

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. Then, we investigated the effect of the structure by comparing different directions and dimensions of the re-entrant structure in the simulation. Also, we analyzed the effect of the round shape in the heel part to disperse stress concentration. We expect that, via biomechanical studies of prosthetic walking, a stable heel strike can be achieved by using the proposed auxetic structure with optimal dimensions for the prosthetic foot.

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