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

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RESEARCH HIGHLIGHT

- The effects of auxetic structure on the energy absorption at the heel strike of the prostheses was examined.
- Relative density (RD) of the auxetic structure played a significant role in the energy absorption at the heel strike.

INTRODUCTION

Prosthetic foot design

- Although the design of prosthetic feet has been widely studied for the lower extremity amputees, several fundamental challenges still remain [1].
- One of the critical design challenges in prosthetic feet is the impact reduction at the heel strike.

Required foot properties at heel-strike

- Human walking consists of several events: heel-strike, foot-drop, heel-off, push-off, and toe-off [2].
- At heel-strike, the impact has to be carefully managed to protect the other parts from damage.

Objective

Energy absorption at heel-strike

- To achieve the shock absorbing property at heel strike, we applied the novel re-entrant structure to the prosthetic foot.
- The prosthetic foot was designed to be manufactured as a single part using 3D printing technology.

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 [3].

Re-entrant honeycomb structure

- Specifically, the re-entrant honeycomb structure exhibits an increased energy absorption capacity compared to the conventional honeycomb [4].

Design parameters

- The geometric parameters of re-entrant structure are shown in Fig. 1.
- The relative density (RD) is the ratio of the volume of all struts in a unit cell to the apparent volume of the unit cell and can be described as followed:

\[ \rho_a = \frac{2l + 1.75ht + 2t^2}{3ht + 2h\cos\theta + 3l\sin\theta + 2t^2\sinh\theta} \]

Where:
- \( \rho_a \): density of bulk material
- \( \rho_s \): density of unit cell strut

Design parameters are shown in Table 1.

Material properties

- Material properties were set as acrylonitrile butadiene styrene copolymer (ABS).
- The mechanical properties of materials were considered to be elastic perfectly plastic, isotropic and homogeneous.

Numerical analysis

- Structural behavior analysis was conducted using ABAQUS/CAE (v6.14, ABAQUS Inc., Velizy-Villacoublay, France).
- The geometry was meshed with 8-node hexagonal elements.
- The ankle connection part was constrained from moving in the x, y, and z directions.
- The FEA was performed through two steps.
- In the first step, the 1,000 N load was applied to bottom of hind foot for 1 second.
- In the second step, the load applied in previous step was removed to check the residual stress in structure.

RESULTS

- The plastic deformation did not occur in both cases as shown in Fig. 4.
- In case of foot with RD 0.35, the stress was relatively evenly distributed in heel part compared to the foot with RD 0.55.
- The local failure (e.g., brittle failure), not as an elastic deformation, would be expected in a foot with RD 0.55 due to the stress concentration in the area near the ankle connection part.
- After the loading, the lattice structure with RD 0.35 showed elastic deformation (e.g., strut rotation), but strut deformation was barely found with RD 0.55.

CONCLUSIONS

- 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.
- Foot with RD 0.35 showed 6 times higher deformation than the foot with RD 0.55 under the same loading condition.

FUTURE WORKS

- Systematic experiments using 3D printed foot with different structure RD will be conducted.
- It is expected that optimal RD structure will provide optimal energy absorption with more stable deformation for the powered transfemoral prosthesis.
- It is also expected that optimal RD structure will provide better biomechanical properties during the prosthetic walking.

Acknowledgments

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References


Fig. 2 The prosthetic foot filled with re-entrant structure modeling for FEA: (a) fixed boundary condition at ankle connection part; (b) foot with RD 0.35; (c) foot with RD 0.55.

The foot shape was approximated as rectangular with a length of 250 mm and a width of 120 mm.

The two types of foots with different relative density of structure were used to investigate the RD effect on the energy absorption; RD 0.35 and RD 0.55 in Fig. 2.

Table 2 ABS material properties used for prosthetic foot FEA.

<table>
<thead>
<tr>
<th>Young’s modulus, E</th>
<th>Yield strength, σy</th>
<th>Poisson’s ratio, ν</th>
<th>Density, ρ</th>
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<td>ABS</td>
<td>2.2 GPa</td>
<td>31 MPa</td>
<td>0.35</td>
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</table>

Table 1 The design parameters with respect to the relative density of re-entrant structure.

<table>
<thead>
<tr>
<th>RD</th>
<th>l</th>
<th>h</th>
<th>s</th>
<th>t</th>
<th>θ</th>
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<td>0.35</td>
<td>3.75 mm</td>
<td>9.8 mm</td>
<td>2.45 mm</td>
<td>0.6 mm</td>
<td>-30°</td>
</tr>
<tr>
<td>0.55</td>
<td>3.75 mm</td>
<td>9.8 mm</td>
<td>2.45 mm</td>
<td>1.1 mm</td>
<td>-30°</td>
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</table>

Table 2 ABS material properties used for prosthetic foot FEA.

Fig. 3 The schematics of the boundary conditions applied in the first step of the FEA and the defined distance for deformation check.

Fig. 4 Stress analysis results of the prosthetic foot during the first step: (a) with a structure relative density of 0.35, (b) with a structure relative density of 0.55. Yellow lines indicate the ankle connection part and the red line represents the part where the load was applied.