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 prosthesis 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

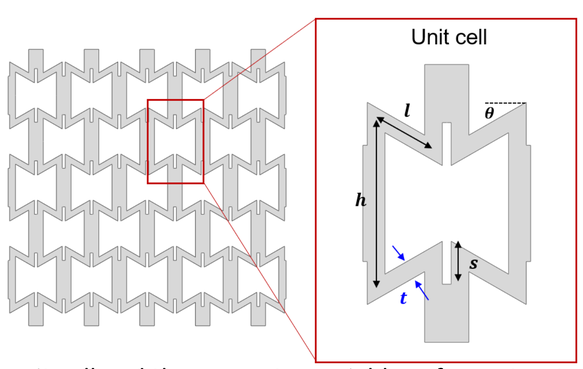

Fig. 1 The unit cell and the geometry variables of re-entrant structure.

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:

$$\frac{\rho}{\rho_s} = \frac{2lt + 1.75ht + 2t^2}{3ht + 2hl\cos\theta + 3lt\sin\theta + 2l^2\sin\theta\cos\theta}$$

ρ: density of bulk material

ρ_s: density of unit cell strut

	l	h	s	t	θ
RD 0.35	3.75 mm	9.8 mm	2.45 mm	0.6 mm	-30 °
RD 0.55	3.75 mm	9.8 mm	2.45 mm	1.1 mm	-30 °

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

Prosthetic foot design

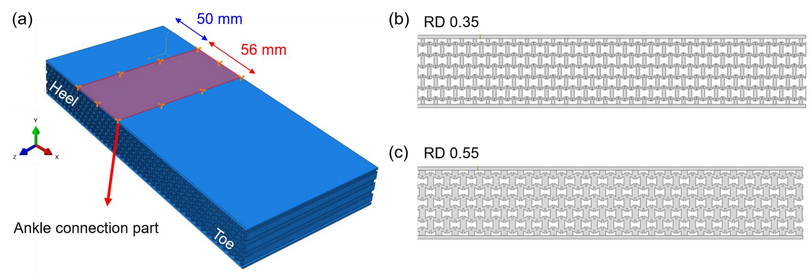

Fig. 2 The prosthetic foot filled with re-entrant structure modelling for FEA; (a) fixed boundary condition at ankle connection part; (b) foot with RD 0.35; (c) foot with RD 0.55.

- 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.

Finite element analysis

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.

	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/cm³

Table. 2 ABS material properties used for prosthetic foot FEA.

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.

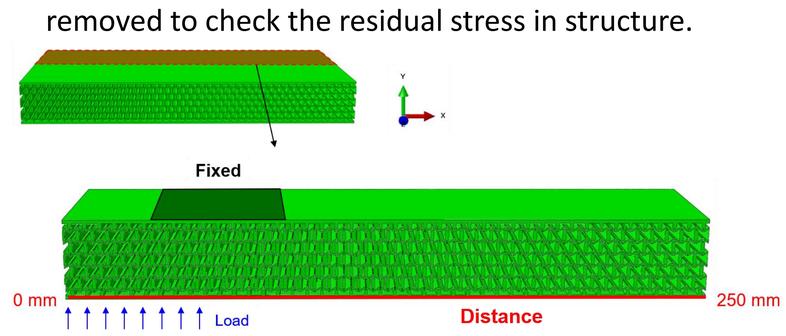

Fig. 3 The schematics of the boundary conditions applied in the first step of the FEA and the defined distance for deformation check.

RESULTS

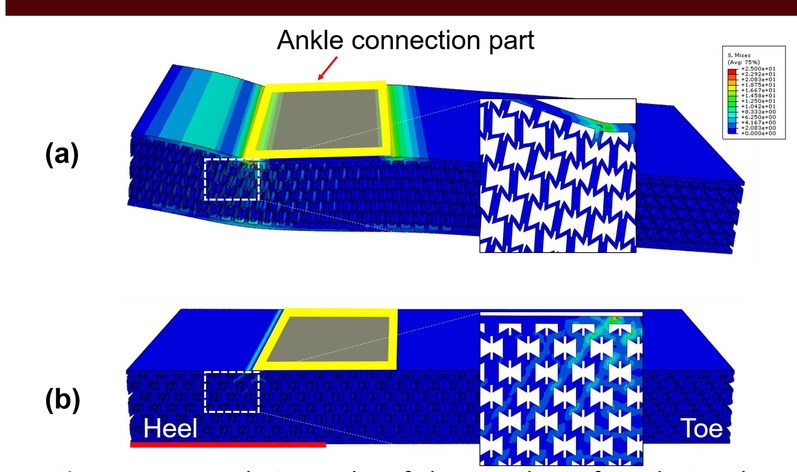

Fig. 4 Stress analysis results of the prosthetic foot during the first step; (a) with a structure relative density of 0.35, (b) with a structure relative density of 0.55. Yellow lines indicate the ankle connection part and the red line represents the part where the load was applied.

- 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.

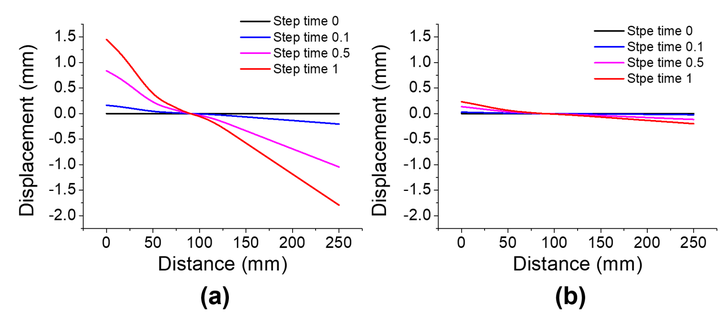

Fig. 5 Displacement distribution of prosthetic foot according to the step time; (a) RD 0.35, (b) RD 0.55.

- Under the same load condition, the foot with RD 0.35 deformed 6.3 times larger than the foot with RD 0.55.
- The deformation of fore foot was much larger in the foot with RD 0.35 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.
- With the higher RD (e.g., RD 0.55), the slenderness ratio of the strut increases, making the structure more brittle.
- The brittle properties of the foot with RD 0.55 can lead to instability behavior, such as local failure.

CONCLUSIONS

It was observed that

- 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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