ASEC 2025 Conference

The 6th International Electronic Conference on Applied Sciences

09–11 December 2025 | Online

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CLEMSON UNIVERSITY

College of ENGINEERING, COMPUTING AND APPLIED SCIENCES

Application of Polymer Nanocomposites in the Design of Prosthetic Sockets that Feature Auxetic Meta-Structures

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INTRODUCTION & AIM

Background

- **2.3 million** people in U.S. live with limb loss, projected to **double** by **2050**.
- Prostheses are the standard of care, but **abandonment** rates remain high at **25-57%** due to **physical discomfort** and **poor fit**.
- Poor socket fit leads to **pressure concentration** ("hotspots"), skin irritation, and potential tissue damage (ischemia, abrasions).

Auxetic Structures and Polymer Nanocomposites

- Utilizes complex geometries (e.g., chiral) with a **negative Poisson's ratio**.
- When compressed, material flows **inward** to the point of pressure to provide adaptive, localized support.
- Polymer nanocomposites add tunable **stiffness** and **antimicrobial benefits**.

Objective

- Create an adaptive & comfortable socket, compare auxetic and non-auxetic sockets under compression and assess the effects of nanoparticle inclusions.

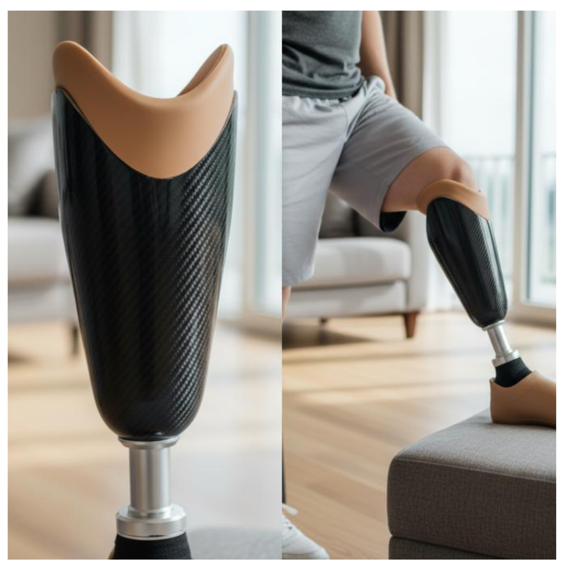

Fig. 1. Standard prosthetic socket

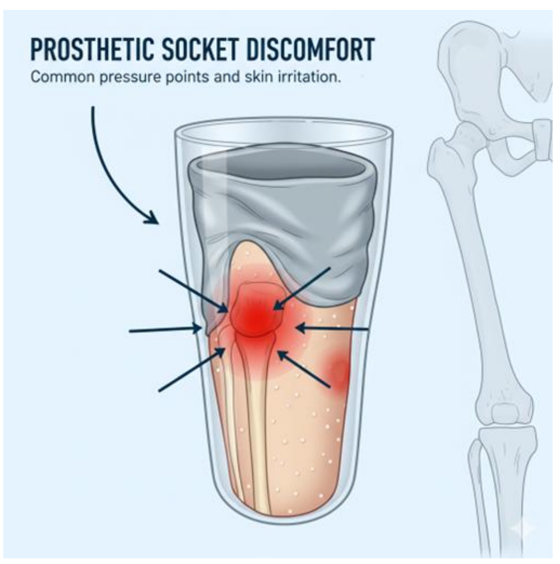

Fig. 2. Standard socket problems

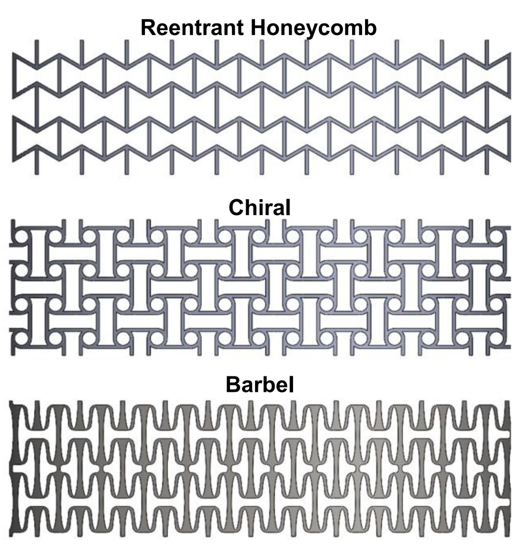

Fig. 3. Various auxetic meta-structures

METHOD

Materials and Design Overview

- We used polypropylene (PP) and ultra-high molecular weight polyethylene (UHMWPE) as base polymers and reinforced them with nanoparticles (TiO_2, ZnO, and Graphene) to enhance mechanical stiffness.
- **Materials Studied**: Polypropylene, UHMWPE, PP + 5% ZnO, PP + 5% TiO_2, UHMWPE + 0.5% Graphene nanoplatelets
- **Model**: 3 sockets - chiral, reentrant hexagon and hexagon (non-auxetic) + simplified limb (tibia, fibula, soft tissue) designed in **SOLIDWORKS**.
- Used **Finite Element Analysis** (FEA) to model 15 unique simulations (5 materials × 3 designs) under a realistic compressive load.

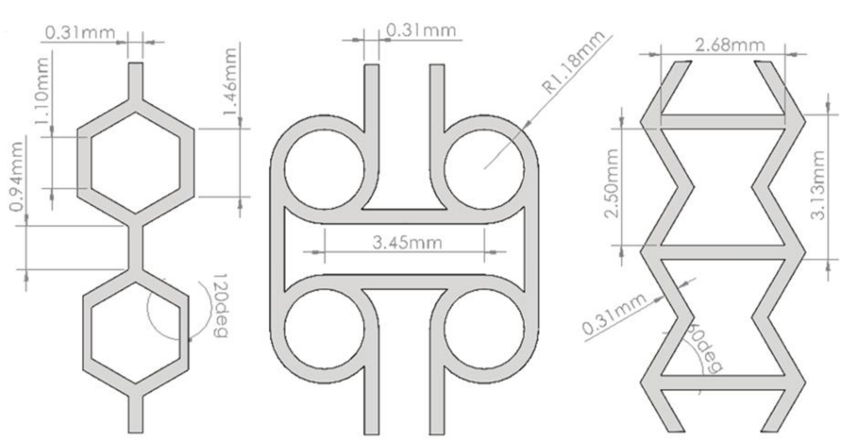

Fig. 4. Single unit of the meta-structures: hexagon, chiral, and reentrant hexagon

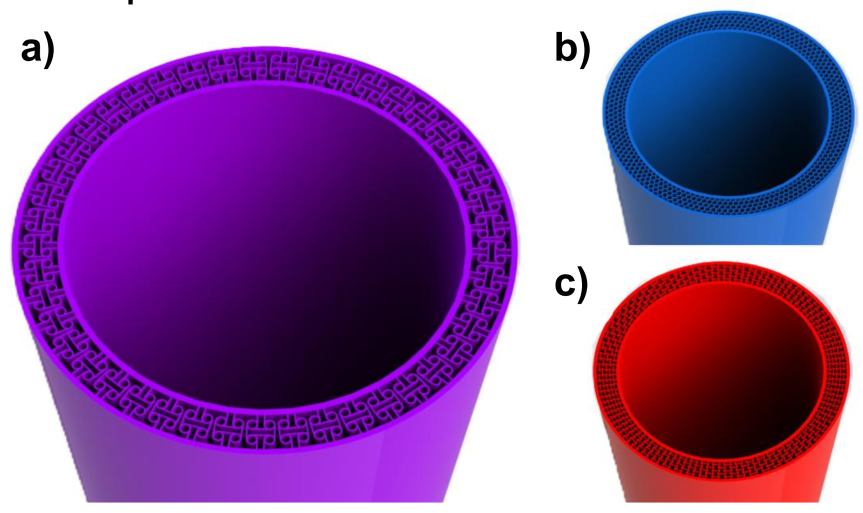

Fig. 5. Prosthetic sockets with meta-structure: a) Chiral. b) Hexagon. c) Reentrant hexagon.

Finite Element Simulation

- FEA conducted in **ANSYS Mechanical.**
- **Load:** 850 N static load (50th percentile of avg. US male body weight)
- **Boundary conditions:** Fixed socket, uniform load applied to tibia.
- **Metrics**: Contact (interfacial) pressure, strain energy (shock absorption), displacement (stiffness)

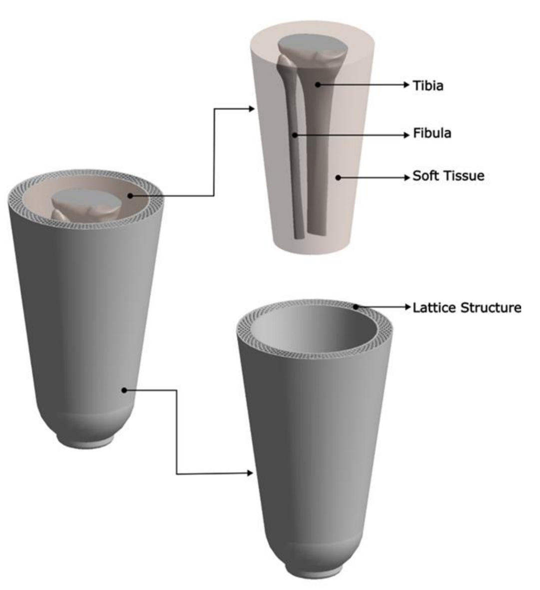

Fig. 6 Socket with residual limb (soft tissue and bone).

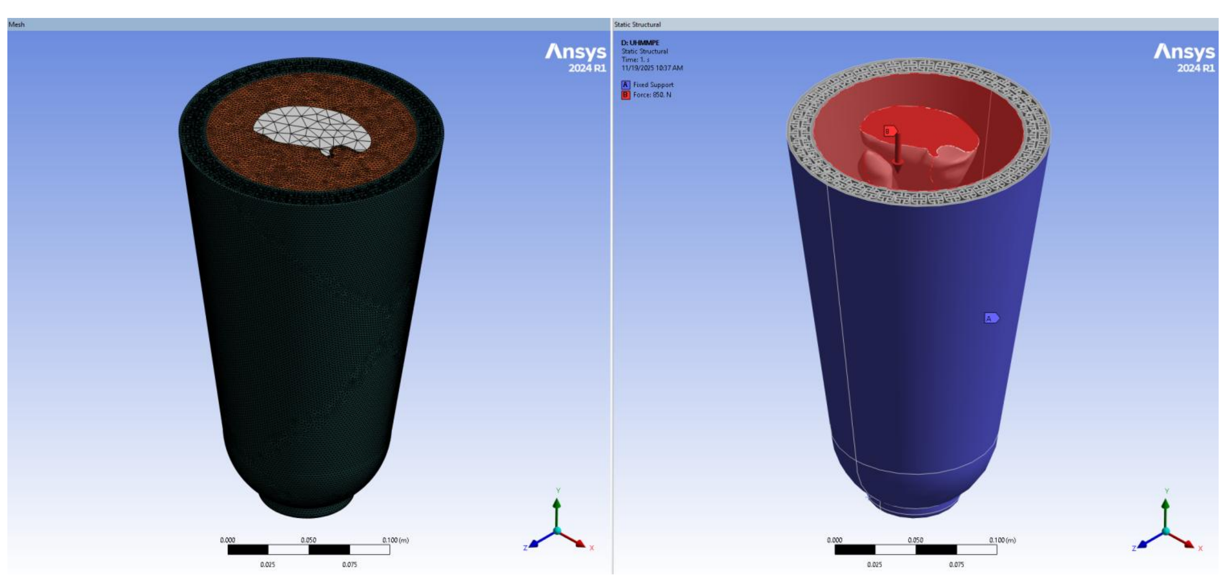

Fig. 7 FEA set-up of the socket model with tetrahedral mesh (left) and defined boundary conditions (right).

RESULTS & DISCUSSION

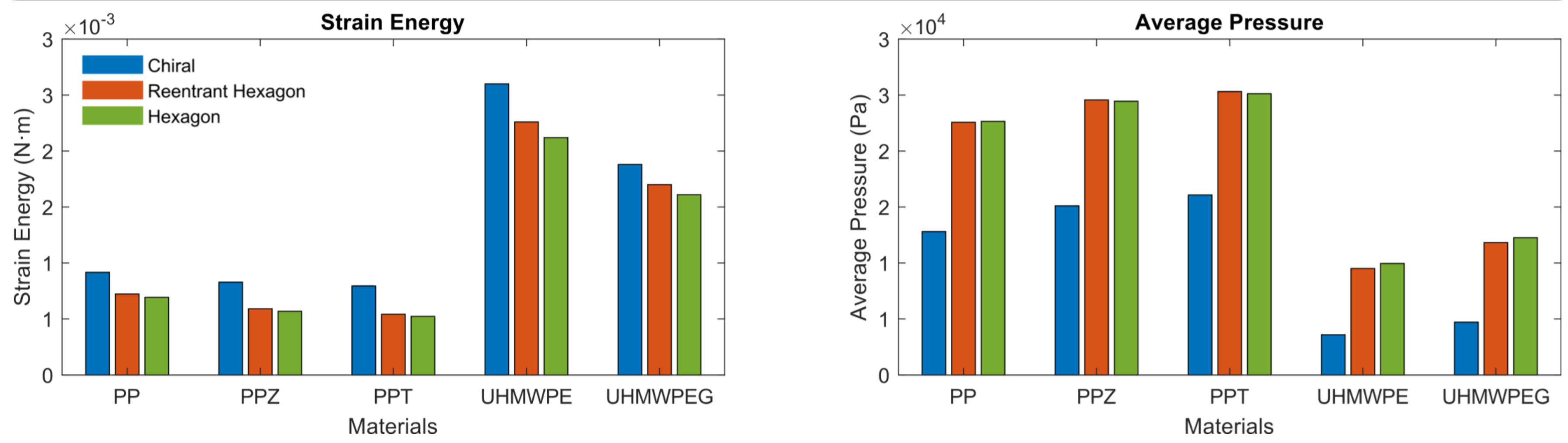

Fig. 8. Comparison of strain energy and avg. pressure of the three sockets modeled using PP, PP+5% ZnO, PP+5% TiO_2, UHMWPE and UHMWPE+0.5% Graphene nanoplatelets.

- The chiral design stored the most strain energy, indicating **better shock absorption**. This was achieved with a comparable stiffness (displacement) to the non-auxetic design.
- The chiral design consistently shows the **lowest** average interfacial pressure. The chiral UHMWPE socket was the overall best performer.
- The chiral socket, across all materials, demonstrated a **44.6% reduction** in average interfacial pressure compared to the non-auxetic hexagon socket.

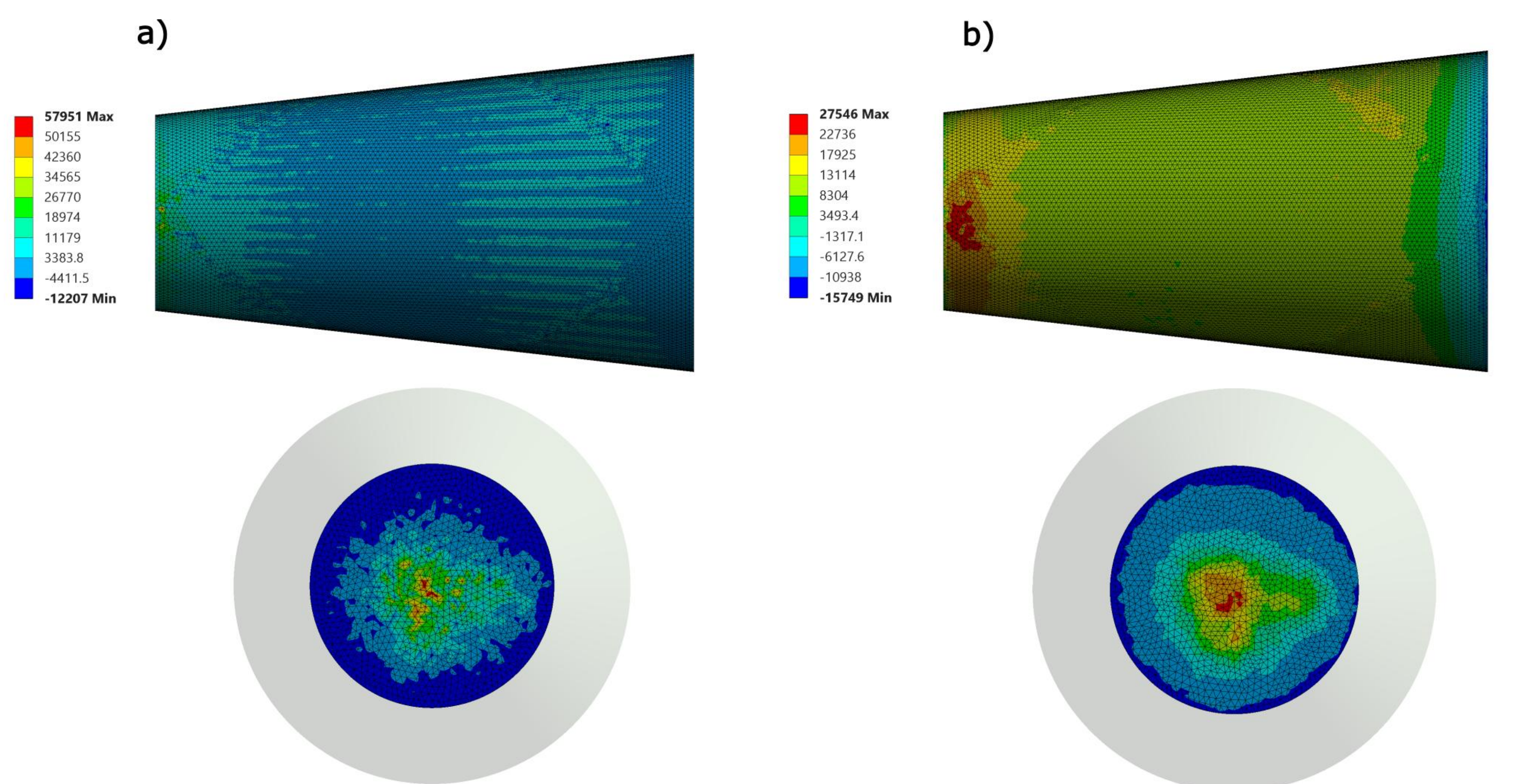

Fig. 9. Contact pressure distribution for two socket designs (UHMWPE). (a) Chiral socket: top (side view) & bottom (top view). (b) Hexagon socket: top (side view) & bottom (top view).

- The auxetic Chiral design (a) shows a broad, **uniform pressure distribution** across the socket's inner surface.
- In contrast, the non-auxetic Hexagon design (b) concentrates the load in a few **hotspots**, which can lead to **pain** and **tissue damage**.
- Clinically, a lower **average** pressure and uniform distribution is far more important than a lower **peak** pressure.

CONCLUSION

- Chiral auxetic sockets provide a **superior** pressure profile, **reducing** average interfacial pressure by **44.6%**, **improving** pressure distribution.
- Chiral + UHMWPE was the **optimal** combination found for minimizing average pressure.
- Nanocomposites are a viable tool for tuning socket stiffness for patient-specific sockets that **reduce discomfort** and may **lower** prosthesis **abandonment** rates.

FUTURE WORK / REFERENCES

- Experimental validation to verify these simulation results.
- Analysis of dynamic (gait) and torsional loads.
- Use of anatomically accurate residual limb models.

REFERENCES

1. J.A. Rivera, K. Churovich, A.B. Anderson, B.K. Potter, Estimating Recent US Limb Loss Prevalence and Updating Future Projections, Archives of Rehabilitation Research and Clinical Translation (2024) 100376. https://doi.org/10.1016/j.arrct.2024.100376.
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