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3D PRINTING IN PEDIATRIC SURGERY: A SYSTEMATIC REVIEW AND IN VITRO EVALUATION OF 3D-PRINTED NUSS IMPLANTS

INTRODUCTION

Three-dimensional (3D) printing was first introduced approximately 39 years ago as a form of rapid prototyping intended for the fabrication of 3D objects. This technology is now employed across a broad spectrum of healthcare applications, including the development of patient-specific medical devices and implants, the enhancement of medical education and clinical training, surgical planning and simulation, as well as ongoing biomedical research.

This study aimed to conduct a systematic review of 3D printing applications in pediatric populations, focusing on the thoracic cavity, upper limbs, and spine, and to design, fabricate, and evaluate 3D-printed Nuss implant models for treating Pectus Excavatum through in vitro mechanical testing.

METHOD

Step 1.0

Systematic literature analysis of the use of 3D printing technologies, with a focus on applications in the thoracic cavity, upper limbs and spine in pediatric population.

Step 2.1

Literature review of the primary characteristics and **design parameters** of Nuss implants used in the surgical correction of Pectus Excavatum.

Methods used: P1S 3D printer (BambuLab); BambuSlicer software (BambuLab).

Step 2.2

3D fabrication and *in vitro* testing of custom Nuss implant models to assess their mechanical properties.

Methods used:

1. 3D-printed implant samples were mechanically loaded to measure displacement and stiffness.
2. A three-stage COMSOL model was constructed to identify effective material parameters based on experimental data.
3. Fatigue behavior was evaluated using two approaches:
    1. stress–life method using the experimental loading curve;
    2. stress-based fatigue method applying the maximum normal stress criterion.

Materials used:

1. PLA
2. PETG
3. ASA
4. TPU

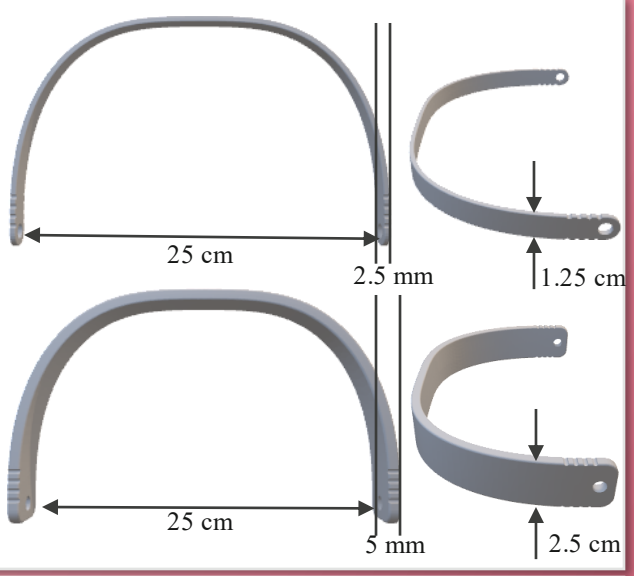
RESULTS

Step 1.0

A total of 136 pediatric patients were included across 20 selected studies. 3D printing was primarily applied in diagnostic and preoperative planning, particularly for congenital respiratory anomalies (36.8%), Pectus Excavatum (31.6%), and spinal deformities (10.5%). Therapeutic applications most frequently addressed tracheobronchomalacia (88.9%), spinal fractures (5.6%).

Step 2.1

Based on our literature review and internal discussions regarding biomechanical requirements, we designed implants with the following dimensions: length 25 cm, width 1.25 cm, and thickness 2.5 mm, with an arc angle of 170 degrees. Accordingly, we revised the implant design, increasing the width to 2.5 cm and thickness to 5 mm to enhance volume and structural integrity.



Step 2.2

Parameter identification

In experimental study, 3D-printed implant models were subjected to compression testing with forces ranging from 0 to 250 N in 10 N increments. Maximum displacements for the remaining filaments were: TPU – 42.28 mm, ASA – 19.79 mm, PETG – 19.35 mm. and PLA – 11.96 mm.

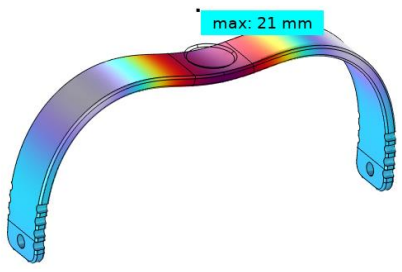


Figure. 1 Model for finding effective material parameters

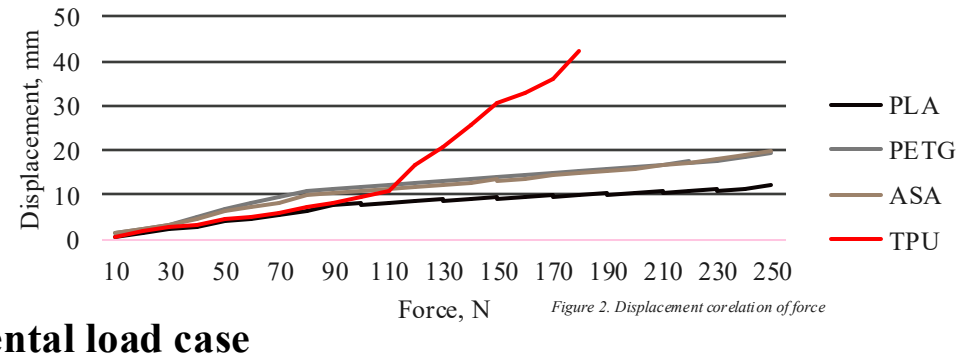


Figure 2. Displacement corelation of force

Fatigue under experimental load case

ASA and PETG showed the longest predicted fatigue life, with PLA performing moderately and TPU failing early due to high strain accumulation.

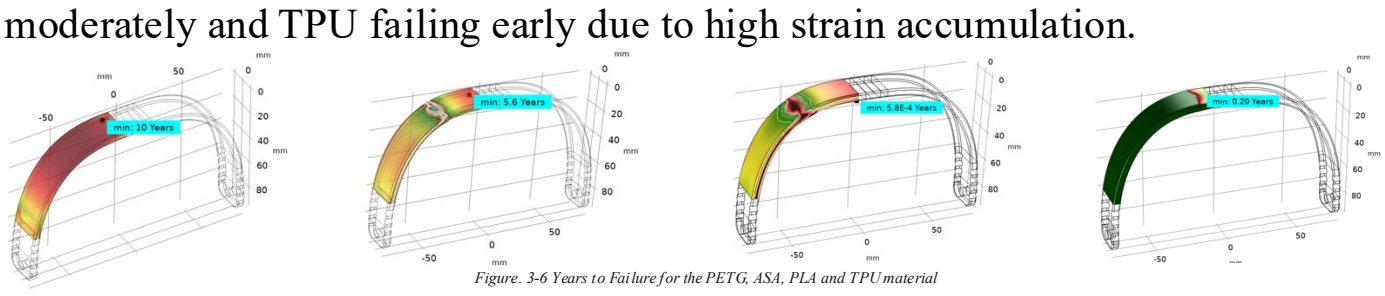


Figure. 3-6 Years to Failure for the PETG, ASA, PLA and TPU material

Fatigue under implant-representative load

ASA demonstrated the lowest Fatigue Usage Factor along the implant line, indicating the highest resistance to cyclic degradation. PETG remained acceptable but inferior to ASA, PLA approached its fatigue limit, and TPU failed even when the loading was reduced by an order of magnitude (25 N).

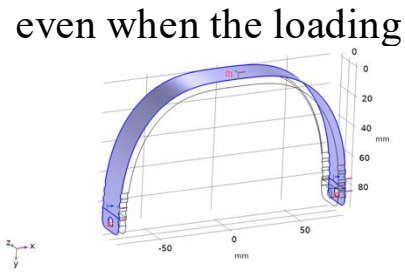


Figure. 7 Boundary load 250 N according Y axes

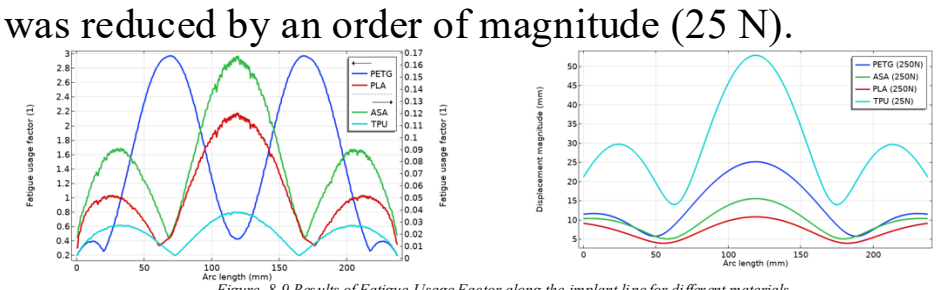


Figure. 8-9 Results of Fatigue Usage Factor along the implant line for different materials

DISSCUSION AND CONCLUSION

3D printing shows strong potential for use in pediatric thoracic surgery. Among the tested materials, ASA demonstrated the most reliable mechanical and fatigue performance under implant-like loading conditions. These results support the feasibility of custom 3D-printed Nuss implants and justify further preclinical and clinical investigation.

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