PATIENT-SPECIFIC BONE PLATES: DESIGN STRATEGIES AND BIOMECHANICAL PERFORMANCE

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Introduction

Slipped capital femoral epiphysis (SCFE) is a prevalent hip disorder among adolescents. The possible causes include obesity, endocrine disorders, and heightened mechanical stress on the growth plate [1]. A corrective surgical procedure, Imhäuser osteotomy, comprising of realignment of the femoral head and shaft via femoral head-neck osteotomy, followed by stabilization using an orthopedic plate, is performed to restore hip motion and mechanics while limiting the incidence of avascular necrosis [2]. The present study endeavors to enhance the biomechanical performance of SCFE-patient-specific proximal femur fixation plates through the integration of computational modeling and topology optimization into the plate's functionality under physiological loading conditions through experimentally validated finite element (FE) analysis. The objective is to support medical engineers in fabricating reliable and optimally sized patient-specific SCFE plates.

Methods

The aim of this study was to develop a patient-specific proximal femur fixation using computer-aided design (CAD) and topology optimization (TO) techniques. The case under consideration was a patient with SCFE (ethical approval no. WO20.057) who underwent Imhäuser osteotomy and fixation using patient-specific Ti-6Al-4V plating and screws. The design procedure commenced with imaging and clinical evaluation, followed by the creation of a 3D bone model. Virtual proximal femur osteotomy was executed, and the CAD plate was generated using SolidWorks by a instrumentmaker at the OLVG hospital. The TO plate was developed through the definition of an initial design domain and iterative TO process. The FE model was validated against experimental data obtained from the CAD plates using digital image correlation (DIC), and was extended to incorporate a musculoskeletal system to simulate more complex physiological loading conditions (*i.e.*, two-leg stance and walking). Compression tests and cycling loading were performed to evaluate the long-term mechanical function of the plates (Figure 1a).

Results

The FE results (Figure 1b) indicate that the CAD plate experienced high levels of stress near its most lateral proximal screw during two-leg stance and walking scenarios. The maximum stress values recorded during these conditions were 233.0 MPa and 762.0 MPa, respectively. However, these levels of stress exceeded the designated safety margin while walking, thereby posing a risk of further plate fractures. On the other hand, the TO plate exhibited a more evenly distributed stress pattern that remained within the safety limit. Furthermore, the TO plate was 18.1% shorter and had a maximum thickness around the fracture gap that was doubled that of the CAD plate.

The results from the compression tests further revealed that all 3D-printed TO constructs failed at loads greater than walking loading condition. Meanwhile, three out of the four CAD constructs failed at lower loads compared to the maximum walking load. Additionally, the TO constructs demonstrated a 25.5% higher ultimate load value, 41.6% higher ultimate displacement, and 79.8% higher stored strain energy compared to the CAD constructs. The TO plate was also characterized by a reduced design area, a unique screw arrangement, and a 23.1% increase in weight as compared to the CAD plate.

Conclusion

These results highlight the biomechanical efficacy of patient-specific orthopedic plate design strategy using CAD and TO.

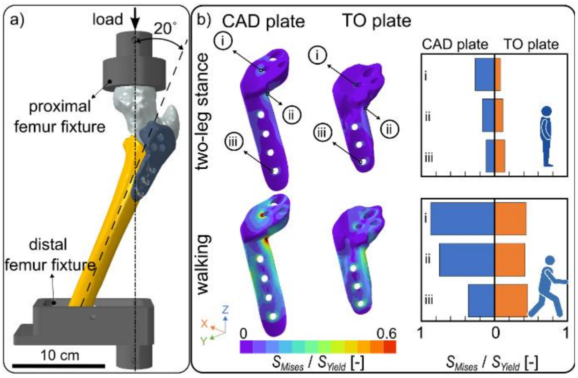

Figure 1: a) Experiment setup, b) FE results for CAD and TO plate under physiological loading conditions

References

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