

Optimal Fixation of 3D-Printed Patient-Specific Implant for Femoral Replacement in Osteosarcoma

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INTRODUCTION: Osteosarcoma is a rare malignant bone tumor with highly variable location and size. After tumor resection, fixation using 3D-printed patient-specific implant (3D-implant) produced by additive manufacturing has emerged as a promising solution. Two major challenges remain. First, there is no established guideline for optimal screw fixation in 3D-implant, particularly in osteosarcoma cases where limited residual bone and low bone density near joints make stable fixation difficult. While screw placement and type have been widely studied in fracture cases, their biomechanical performance in tumor-related 3D-implant fixation, especially comparing compressive and locking screws in extreme skeletal reconstruction, has not been clarified. Second, stress shielding must be avoided by ensuring that mechanical load transfer to the bone is neither excessive nor insufficient. Therefore, this study compares the biomechanical performance of compressive and locking screws in 3D-implant for osteosarcoma and proposes a methodological framework to balance fixation stability and load transfer, thereby supporting successful 3D-implant fixation.

METHODS:

Image Segmentation and 3D Reconstruction: A 3D bone model was generated from CT DICOM images of a female patient with osteosarcoma, using the contralateral healthy bone as reference. CT images were obtained under IRB approval. Since female bone typically exhibits lower bone density compared with male cases, this approach allowed us to simulate a more extreme fixation scenario. After image segmentation and 3D reconstruction, two conditions were established: a long bone stock (substantial bone preservation case) and a short bone stock (limited bone preservation case). The 3D-implant was designed to conform to each model. In the short bone stock case, five screws were modeled with either compressive or locking fixation. In the long bone stock case, one proximal and five distal screws were used, producing four configurations with different screw types.

Finite Element Modeling: Bone heterogeneity was represented by assigning elastic modulus values to each element based on CT-derived Hounsfield units. 3D-implant and screws were modeled as Ti6Al4V. Boundary conditions included 330 N pretension for compressive screws and bonded contact for locking screws. A 700 N axial load along mechanical axis was applied, with the 3D-implant upper surface constrained.

Analysis: Von Mises stress was calculated to examine the overall stress distribution in bone and to assess potential failure in the 3D-implant and screws. Strain energy density was measured to evaluate the stress shielding effect. From this, a stress shielding signal was derived, and its ratio to that of normal bone was determined. The resulting values were then classified into three regions: bone loss, dead zone, and bone gain.

RESULTS SECTION: In the short bone stock model, maximum Von Mises stress was 5.67 MPa with compressive screws and 0.89 MPa with locking screws, showing substantially higher stress in the compressive configuration. In the long bone stock model, stresses ranged from 1.36 MPa with only locking screws to 5.7 MPa with distal compressive-proximal locking screws, while the configuration with distal locking-proximal compressive screws produced a markedly elevated value of 40.54 MPa at screw #6 (proximal screw). Strain energy density analysis showed that in the short bone stock model, only the locking screw configuration placed screw #2 (distal screw, upper row middle screw) in the bone loss region. In the long bone stock model, screw #6 was in the bone loss region in all cases except the configuration with distal locking-proximal compressive screw.

DISCUSSION: In the short bone stock model, compressive screws produced higher stresses (11–18 MPa at screw heads) and showed insufficient fracture safety compared with the yield strengths of cortical (148 MPa) and trabecular bone (8 MPa). Locking screws reduced stress, providing greater fracture stability but with a potential risk of bone loss due to stress shielding. In the long bone stock model, stresses around distal screws were within safe limits, although screw #6 in the proximal cortical region reached 74 MPa, still acceptable relative to cortical bone yield strength. Stress shielding analysis indicated that the configuration with distal locking-proximal compressive screw avoided the bone loss region and was identified as the most biomechanically favorable. Overall, this study demonstrated that in extreme conservation scenarios, the exclusive use of either compressive or locking screws is biomechanically insufficient. In cases with relatively greater fixation potential, placing locking screws in the distal region and the compressive screw in the proximal cortical region provided the most favorable biomechanical performance.

SIGNIFICANCE/CLINICAL RELEVANCE: For successful 3D-implant fixation, it is essential to avoid excessive stress that compromises initial stability while simultaneously providing sufficient mechanical stimulation to prevent stress shielding, which is critical for long-term osseointegration. The framework proposed in this study offers a methodological basis for achieving this delicate balance and it can be applied to other anatomical locations.

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