Finite Element-Optimized Biomechanical Framework for Angulated Implant Placement in Severely Resorbed Posterior Mandibular Ridges Using Platform-Switched Zirconia Abutments

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Abstract. Severely resorbed posterior mandibular ridges present significant biomechanical challenges for osseointegrated implant systems, particularly regarding crestal bone stress distribution and long-term marginal bone stability. This study developed and validated a finite element analysis (FEA)-optimized placement protocol for angulated titanium implants (15°–25° off-axis) coupled with platform-switched zirconia abutments in class V–VI Cawood–Howell defect configurations. Forty-eight three-dimensional mandibular models were reconstructed from cone-beam computed tomography datasets and subjected to oblique and axial occlusal load simulations (150–400 N). Results demonstrated a statistically significant reduction in von Mises stress concentrations at the implant–abutment interface ($p < 0.001$) and a 31.4% decrease in periimplant cortical bone microdeformation compared to conventional non-angulated protocols. The proposed framework provides clinicians with quantitative angulation thresholds and abutment geometry parameters to optimize load distribution and minimize marginal bone resorption risk.

Keywords: finite element analysis dental implants, angulated implant placement, platform switching zirconia abutments, posterior mandibular bone resorption, osseointegration biomechanics, crestal bone stress distribution, cone-beam computed tomography implantology, Cawood-Howell ridge defect classification, implant-abutment interface microstrain

Introduction

Posterior mandibular atrophy resulting from prolonged edentulism, periodontal disease, and tooth extraction-associated alveolar remodeling remains one of the most diagnostically and surgically demanding conditions encountered in contemporary implant dentistry. As global population aging accelerates through 2024–2026, the prevalence of moderate-to-severe mandibular ridge resorption classified under the Cawood–Howell system (Classes IV–VI) is projected to increase substantially, placing intensified demand on predictive biomechanical planning tools that transcend traditional empirical implant positioning protocols. The anatomical constraints imposed by severely resorbed ridges—including proximity to the inferior alveolar nerve canal, compromised buccolingual bone width, and reduced vertical crestal height—frequently preclude straightforward axially aligned implant insertion, necessitating deliberate angular compensation strategies that introduce complex off-axis loading vectors at the implant–abutment–bone complex. Titanium endosseous implants subjected to non-axial occlusal forces transmit concentrated stress gradients to the periimplant cortical bone envelope, a phenomenon directly implicated in progressive marginal bone loss, peri-implantitis susceptibility, and prosthetic component fatigue failure. Despite considerable advances in implant surface topography—including sandblasted acid-etched (SLA) and anodized hydrophilic surfaces—the mechanical consequences of angulated placement remain insufficiently characterized at the microstructural level. Concurrently, the emergence of high-strength monolithic zirconia (Y-TZP) as an abutment material has introduced new variables into implant-prosthetic biomechanics, given its distinct elastic modulus (approximately 200 GPa) relative to titanium alloy (Ti-6Al-4V, ~114 GPa), with implications for interfacial micromovement, bacterial microleakage, and cortical bone strain shielding. Finite element analysis has established itself as the gold-standard computational methodology for quantifying stress distribution within complex craniofacial bone–implant assemblies, enabling parametric investigation of geometric, material, and loading variables without ethical or logistical constraints of in vivo experimentation. However, existing FEA-based implant studies have largely failed to integrate angulation-specific protocols with platform-switching geometry optimization under clinically representative oblique and combined loading conditions across anatomically accurate, patient-derived mandibular models. This gap represents a critical limitation in translating computational findings into actionable clinical placement guidelines. The present study addresses this deficit by developing a validated, FEA-optimized biomechanical framework that systematically characterizes von Mises stress fields, cortical microdeformation indices, and implant displacement magnitudes across a matrix of angulation angles (0°, 15°, 20°, and 25°) and platform-switching offset configurations in Class V–VI resorbed posterior mandibular ridges. Cone-beam computed tomography (CBCT)-derived three-dimensional models were employed to preserve patient-specific cortical–trabecular bone architecture, enhancing the clinical translational fidelity of simulation outputs. The article is organized as follows: Section 2 details the CBCT acquisition parameters, three-dimensional model reconstruction methodology, material property assignments, and boundary condition definitions; Section 3 presents the quantitative FEA results stratified by angulation group and abutment configuration; Section 4 provides a critical biomechanical interpretation of stress distribution patterns relative to established marginal bone loss thresholds; and Section 5 proposes an evidence-based clinical decision algorithm for angulated implant placement in atrophic posterior mandibles.

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