

QUANTIFYING DESIGN'S ROLE IN TOTAL HIP ARTHROPLASTY: MICRODAMAGE REDUCTION VALIDATES THE NEED FOR ADVANCED PATIENT-SPECIFIC IMPLANTS

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ABSTRACT

The advancement of additive manufacturing (AM) offers remarkable potential for enhancing orthopaedic implant longevity by enabling patient-specific design to mitigate stress shielding. However, the full quantitative impact of implant design on long-term outcomes is often secondary to the clinical emphasis on surgical technique. This study aims to provide foundational biomechanical evidence for the necessity of design optimization. A non-linear finite element analysis was conducted comparing a conventional collarless total hip arthroplasty stem against an identical design featuring a simple proximal collar modification. Microdamage formation at the bone-implant interface, a key predictor of aseptic loosening, was quantified by tracking solid element failures under loading. The collarless model exhibited heavy microdamage accumulation at the proximal fixation zone, indicating a high risk of early failure. In contrast, the collared design achieved a substantial reduction in element failures by 95.05% in compression and 91.60% in tension. This massive improvement, driven by a simple geometric change, confirms that design integrity is crucial to functional success. These findings validate the shift toward exploring the full optimization potential of patient-specific lattice structures and geometries enabled by AM for long-term clinical performance.

KEYWORD

Additive Manufacturing, Total Hip Arthroplasty, Finite Element Analysis, Implant Design, Bone Microdamage

INTRODUCTION

The advancement of additive manufacturing (AM), particularly metal 3D printing, is transforming orthopaedic surgery by offering the potential for near-perfect functional outcomes and longer implant lifespans in major procedures such as total hip arthroplasty (THA), total knee replacement, and spinal fusion. This technology provides unprecedented design flexibility, going beyond the limits of conventional manufacturing to enable implants that are truly patient-specific [1]. By using pre-operative imaging data such as computed tomography (CT), AM allows the precise creation of customized shapes that achieve an optimal fit for each patient's unique bone structure [2]. Importantly, AM also allows control over the implant's internal structure. Engineers can design complex porous architectures with adjustable density, enabling the implant's mechanical stiffness to be tuned to closely match that of the surrounding bone. This capability helps minimize stress shielding, a major cause of long-term implant failure, and promotes better bone healing and integration (osseointegration) [3].

Despite the revolutionary potential of additive manufacturing, achieving long-term clinical success depends on bridging the gap between surgical technique and implant design. In clinical practice, emphasis is often placed on surgical skill, while the mechanical influence of implant geometry on long-term bone adaptation remains less explored [4]. This study aims to provide biomechanical evidence that implant design plays a critical role in functional performance. To demonstrate this, a non-linear finite element analysis (FEA) was conducted to compare a

conventional collarless THA stem with an identical design that incorporated a simple proximal collar modification. The analysis focused on microdamage formation at the bone as a result from the design modification.

MATERIAL AND METHODOLOGY

An inhomogeneous finite element (FE) bone model was developed from CT images of a 61-year-old female patient (avascular necrosis, right femur), utilizing Mechanical Finder v.11 for all procedures, including 3D modelling, meshing, and fracture analysis. The 3D bone structure was reconstructed layer-by-layer. The internal cancellous and cortical bone was meshed using 2 mm tetrahedral elements, while the outer cortical layer used 2 mm triangular plate shell elements with 0.3 mm thickness.

Each element forming the bone structure was assigned specific mechanical properties based on the bone mineral density (BMD). The BMD was determined from the apparent density of the CT images in Hounsfield units (HU). The corresponding mechanical properties, i.e., Young's modulus and yield stress, were obtained from the BMD through linear relationships proposed by Keyak et al. [5] and Keller [6]. Consequently, every element within the bone structure had distinct mechanical properties, resulting in an inhomogeneous bone model.

Two identical femoral stems with design variations were used in this study. One model included a collar at the proximal stem region (collared), while the other was designed without a collar (collarless). Both stems were imported into the software in STL format for the reconstruction of the THA. The stem material was titanium alloy (Ti-6Al-4V, $E = 114\text{GPa}$, $\nu = 0.33$), and the femoral head was alumina ceramic (Al_2O_3 , $E = 370\text{GPa}$, $\nu = 0.22$). Non-bonded contact between the stem and bone was simulated using a friction coefficient of 0.4.

Axial compressive load (1764 N, approximately 3 bodyweight) was applied along the femoral axis ($\alpha = 180^\circ$ and $\beta = 0^\circ$) to simulate peak loading. Microdamage was determined using an asymmetrical strain criterion where element failure occurred when the minimum principal strain exceeded $-10,000$ microstrain under compression or ultimate tensile stress exceeded of the compressive yield stress. Upon failure, element stiffness was reduced to zero to model local loss of load-bearing capacity. The total number of failed elements was recorded for both models to quantify the influence of stem design. Figure 1 summarizes the modelling and analysis workflow of this study.

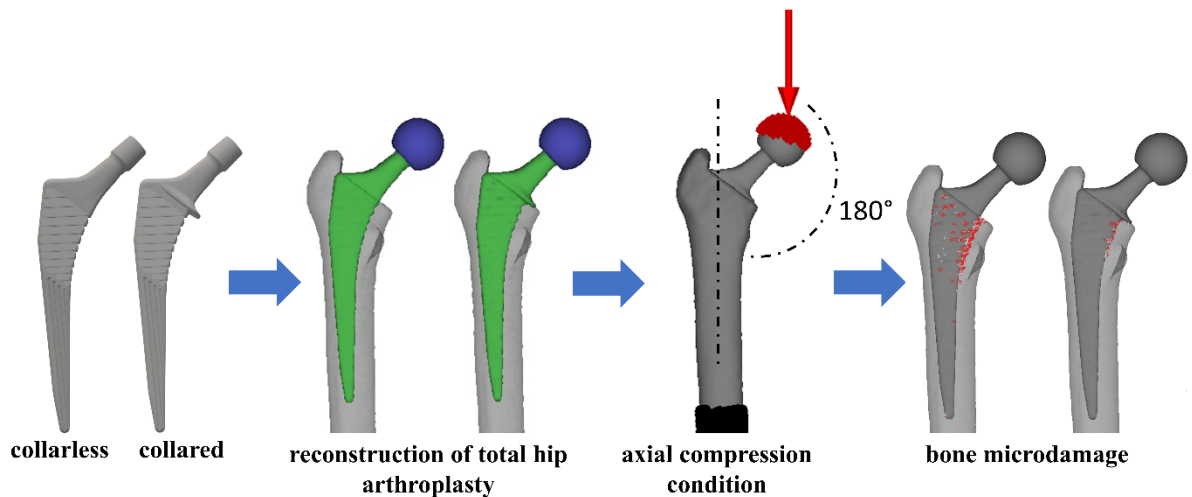


Figure 1: Workflow of the finite element analysis procedure.

RESULT AND DISCUSSION

The FEA results provide compelling evidence that even minor design adjustments, such as the inclusion of a proximal collar, yield profound biomechanical benefits especially at the critical bone-implant interface. Figure 2 (a) illustrates the qualitative distribution of microdamage, represented by solid element failures (compressive in red, tensile in white), around the collarless and collared THA stems following a simulated subsidence event. In the collarless stem model, a heavy concentration of microdamage is clearly accumulated at the proximal fixation point, specifically where the load-bearing cortical bone meets the tapered stem surface. Damage localized in this crucial region suggests that the necessary mechanical stability and uniform load transfer required for successful long-term osseointegration are compromised [7]. Since the integrity of the proximal bone surrounding the stem is crucial for ensuring stable initial fixation and preventing micromotion, this high concentration of damage is a strong indicator of increased risk for early and late-stage implant loosening [8].

Conversely, the collared stem exhibits a near-complete elimination of element failures in the critical proximal zone, confirming that the collar effectively acts as a proximal load-bearing platform. This load transfer mechanism prevents excessive stress concentration at the bone-implant interface that precipitates microdamage formation [9]. This visual difference is quantitatively supported by the data presented in Figure 2 (b), which tracks the total number of solid element failures as a function of applied BW.

The addition of the simple collar achieved a microdamage percentage reduction of 95.05% in compression, and 91.60% in tension. This massive reduction demonstrates that small geometric changes can decisively alter the local mechanical environment and significantly reduce the pathological formation of microdamage that ultimately leads to periprosthetic bone loss and aseptic loosening [10].

The significance of this finding confirms the main argument of this study that mechanical design is not secondary to surgical technique but is, in fact, equally important in determining the long-term biological response of the bone. Since a simple, non-customized collar modification provides such significant improvement, exploring patient-specific geometries and lattice structures enabled by additive manufacturing (AM) represents an essential direction for future research and clinical application.

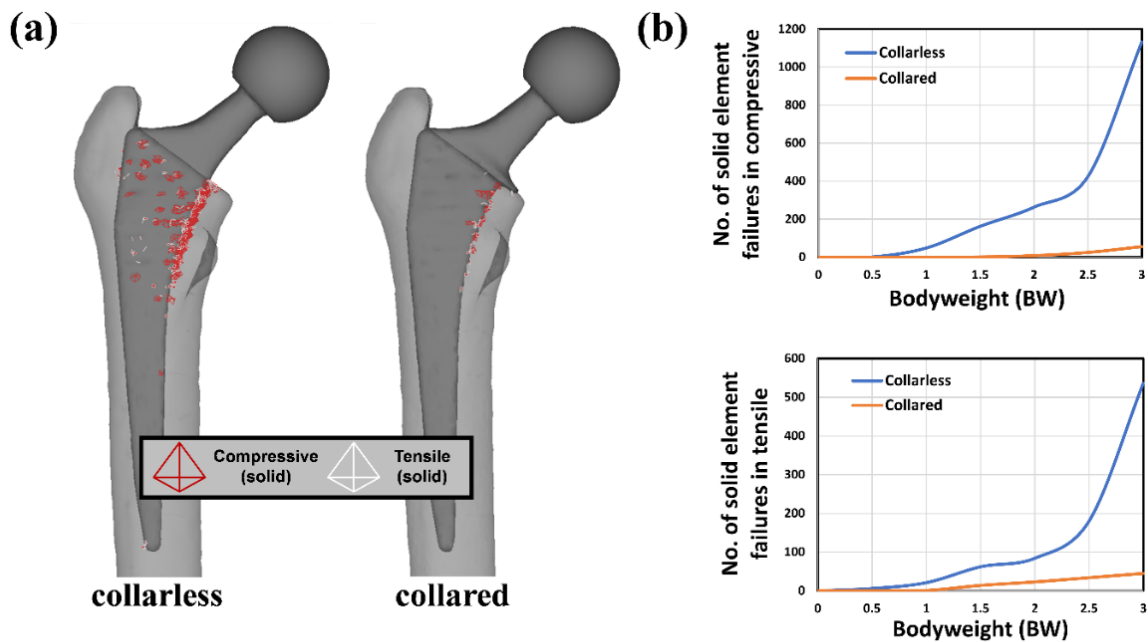


Figure 2: (a) bone microdamage formation and (b) quantitative comparison of solid element failures in compressive and tensile states

CONCLUSION

This study utilized a non-linear FEA to provide essential biomechanical evidence supporting the critical role of implant design in THA longevity. Contrary to clinical tendencies that emphasize surgical technique, our findings demonstrate that even a simple geometric modification i.e., the inclusion of a proximal collar, can profoundly enhance mechanical performance at the bone-implant interface. The collared design achieved a dramatic reduction in microdamage formation, registering fewer solid element failures in compression and fewer in tension compared to the collarless stem under simulated loading. This significant improvement strongly validates the premise that design integrity is a crucial determinant of long-term biological outcome and aseptic loosening mitigation. Ultimately, this work serves as a foundational justification for the paradigm shift toward advanced manufacturing. Since basic design changes yield massive benefits, the precise control over stiffness and geometry offered by patient-specific AM is essential for achieving the near-perfect functional outcomes required for the next generation of orthopedic implants.

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