Biomechanical Assessment of Pilot Hole Under Sizing on the Viscoelastic Behavior of Trabecular Bone A Finite Element Study

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INTRODUCTION: Screw stability in bone fixation is a critical concern in orthopedic surgery, significantly influenced by factors such as screw design, bone quality, and quantity, and the surgical techniques employed [1]. One such technique, the undersizing of the pilot hole, plays a pivotal role in enhancing screw stability by increasing the mechanical interlock between the screw and bone [2]. This technique, which involves drilling a pilot hole smaller than the screw's core diameter, can augment insertional torque, thereby potentially improving the initial fixation strength [3]. However, the increased friction and resistance that result from undersizing also elevate the prestresses within the bone and screw, presenting a delicate balance between achieving stability and risking bone damage, particularly in osteoporotic conditions [4]. Moreover, the viscoelastic behavior of trabecular bone, characterized by its time-dependent mechanical properties, adds another layer of complexity to screw stability [5]. The bone's ability to deform or relax under sustained load can influence both immediate and long-term fixation outcomes, with prestresses induced during screw insertion, further affecting stability [6]. Therefore, while under sizing the pilot hole can enhance the mechanical interlock and initial stability, careful consideration must be taken during surgery to avoid potential complications such as microcracks or fractures [3]. Surgeons must adapt their techniques to balance the benefits of increased stability against the risks associated with heightened prestresses, ensuring optimal surgical outcomes [7]. This study aims to utilize finite element analysis (FEA) to evaluate how pilot hole under-sizing influences the bone-screw system's stiffness while accounting for trabecular bone's viscoelastic properties.

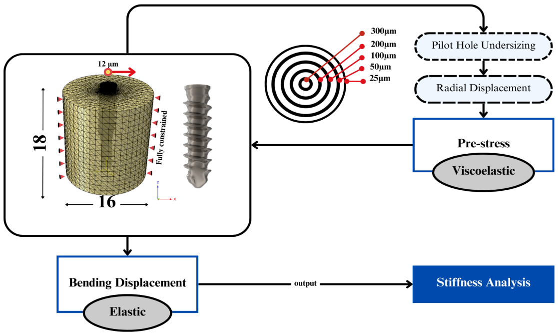

Figure 1: Flowchart illustrating the methodology employed in the current study.

METHODS: In this study, a finite element (FE) model of a screw inserted into trabecular bone was developed using ABAQUS software to simulate orthopedic screw fixation. The bone was assigned a bone volume fraction (BV/TV) of 0.26 [8], corresponding to an elastic modulus of 1.8 GPa [8]. It was modeled as a viscoelastic material to capture its time-dependent behavior [9]. The screw was treated as a rigid body due to its negligible deformation compared to the bone. Six different radial displacements (0, 25, 50, 100, 200, and 300 µm) were applied to simulate varying levels of pressure exerted by the screw threads on the bone during insertion. These changing radial displacements represent different pilot hole sizes in the experimental setup [10]. Pre-stress was introduced via radial displacement, followed by relaxation over four-time intervals: 1 second (0 s relaxation), 61 seconds (60 s relaxation), 121 seconds (120 s relaxation), and 181 seconds (180 s relaxation). For loading and boundary conditions, a horizontal displacement of 12 µm was applied to the head of the screw to simulate bending while the outer surface of the bone was fully fixed (Figure 1). The screw-bone interface was modeled using a surface-to-surface contact definition with a friction coefficient 0.2 to replicate realistic interfacial conditions during loading. The FE model utilized a mesh consisting of 559,309 nodes and 419,782 elements, with the bone represented by C3D10M elements and the screw by R3D4 and R3D3 elements. Using the static solver in ABAQUS, the primary output was stiffness, defined as the ratio of transverse force to the corresponding displacement. Stiffness was evaluated for each radial displacement across the specified time intervals (Figure 1). Additionally, the von Mises stress distribution was analyzed to assess the impact of radial displacement on the mechanical stability of the bone-screw interface.

RESULTS: The FEA results demonstrate the effect of radial displacement on the stiffness of the bone-screw system over various relaxation times (Figure 2), with stress distribution and deformation compared for the 1.5 mm and 2.05 mm pilot holes in Figures 2(A) and 2(B). The free-stressed (with no radial displacement) was calculated, and the stiffness was determined to be 4.61 kN/mm. The system's stiffness for a 2.05 mm pilot hole began at 6.29 kN/mm, slightly decreasing over time. The 2.0 mm and 1.9 mm pilot holes maintained stable stiffness values of 6.41 kN/mm and 6.45 kN/mm, respectively. The 1.7 mm pilot hole exhibited consistent stiffness at 6.43 kN/mm, while the 1.5 mm pilot hole started at 6.38 kN/mm and slightly increased with time (Figure 2(C)).

DISCUSSION: The FE model was validated by comparing free-stressed results with those reported by Steiner et al. [11], who employed a detailed trabecular bone model with non-uniform material properties. An average structural stiffness of 4.28 kN/mm under bending loads was reported by Steiner et al., while stiffness of 4.61 kN/mm was predicted by our free-stressed model, showing a difference of about 7.5%. This close agreement, despite the variability in bone volume-to-total volume ratios (BV/TV = 27 ± 4) and the simplifications made in our model, suggests that the biomechanical behavior of the bone-screw interface was reliably predicted. It was observed that increasing radial displacement increased circumferential stress, leading to bone deformation and partial separation from the screw threads, as shown in Figures 2(A) and 2(B). This reduction in contact area was found to diminish force transmission, thereby lowering bone-screw system stiffness. Moreover, it was shown that stiffness initially increased with the radial displacement, reached an optimal size (pilot hole diameter equal to 1.9 mm with 100 µm radial displacement), and then decreased as the diameter increased further, Figure 2(C). This trend was consistent with previous experimental findings [10], where the optimal pilot hole size enhanced screw-bone interlock, while larger diameters weakened the bone's grip, reducing stiffness. While our study employed a relaxation period of only 3 minutes (180 seconds), we acknowledge this as a limitation. It is anticipated that longer relaxation times may significantly alter stiffness results, potentially highlighting the influence of viscoelastic behavior more prominently than observed in our findings. As the pilot hole diameter increased, the reduced moment arm diminished the impact of relaxation, allowing viscoelastic behavior to dominate. Conversely, at smaller diameters, the increased moment arm amplified its effect. Overall, it was observed that the impact of pilot hole diameter on stiffness outweighed the influence of viscoelastic behavior, with minimal differences seen between models with and without relaxation.

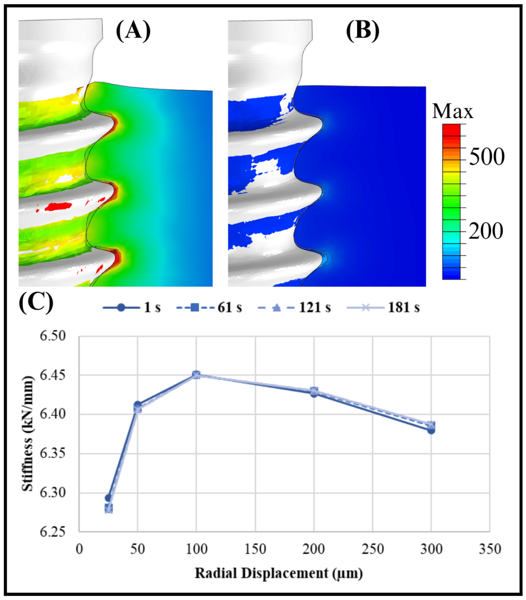

Figure 2: (A) Von Mises stress distribution for 300 µm radial displacement (1.5 mm pilot hole) and (B) 25 µm radial displacement (2.05 mm pilot hole) with Maximum value of 900 MPa, and (C) Stiffness of the bone-screw system as a function of radial displacement and relaxation time.

SIGNIFICANCE: The importance of our study lies in its detailed examination of the interplay between pilot hole undersizing and the viscoelastic properties of trabecular bone. By using finite element analysis to simulate realistic surgical conditions, our research provides critical insights into optimizing screw fixation techniques, which is essential for improving patient outcomes in orthopedic surgery. Our findings could guide surgeons in making informed decisions about pilot hole sizing, ultimately enhancing the longevity and effectiveness of orthopedic implants.

REFERENCES: [1] Li+, Front. Bioeng. Biotechnol. 2024; [2] Einafshar+, J. Orthop. 2024; [3] Oda+, Spine 2021; [4] Wu+, Spine 2015; [5] Yadav+, Med. Eng. Phys. 2022; [6] Ronderos+, Spine 1997; [7] Toossi+, Spine 2022; [8] Öhman+, J. Biomech. 2007; [9] Gersie+, J. Mech. Behav. Biomed. Mater. 2024; [10] Einafshar+, JOR SPINE 2022; [11] Steiner+, J. Orthop. Res. 2017.