Trans Indian Inst Met (2024) 77(9):2711–2717
https://doi.org/10.1007/s12666-024-03371-3

ORIGINAL ARTICLE

# The Biomechanical Performance of Implant Screws with Different Biomaterials in Orthopedic Bone Fixation Procedures

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Received: 14 November 2023 / Accepted: 23 May 2024 / Published online: 5 June 2024


**Abstract** This study aimed to investigate the bone screwing process for stabilization following reduction of femur shaft fracture using M3.5 cortex screws made of four different materials: 316L stainless steel, Ti6Al4V, NiTi, and WC. The numerical analysis was performed using the finite element method and Deform-3D software, with loading and boundary conditions being accurately identified for each analysis. The screwing moment, screw wear, and temperature distributions in both the screw and bone material were evaluated for each material during the screwing process. The results showed that the lowest bone temperatures were achieved when using WC screws, followed by 316L, Ti6Al4V, and NiTi screws. The numerical simulations demonstrated good consistency across all four screw materials during the bone screwing process. The study used Finite Element Analysis to simulate screw insertion into sawbones. It employed tetrahedral elements for meshing, focusing on the hole area to mimic screwing accurately. Sawbones' lateral surfaces remained fixed, while the screw model experienced different spindle speeds and a constant feed rate. Contact between screw and sawbones was established using a master–slave algorithm, considering a friction coefficient of 0.42 to simulate frictional forces.

**Keywords** Biomaterials · Orthopedic surgery · Bone screwing · Finite element analysis

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## 1 Introduction

Human beings can experience various undesired traumas in their daily lives, resulting in fractures in the skeletal system. One common type of fracture is femur shaft fractures, which are usually treated with biocompatible plates and fixators, both external and internal, in orthopedic surgeries. During bone surgery, biocompatible plates and fixators are often attached using screws drilled into the bone with a surgical hand drill (Fig. 1). However, the drilling and screwing process generates heat due to the temperature difference between the screw and bone, which can result in thermal damage to the bone and surrounding tissues. Numerous studies have been conducted to determine the critical temperature value that causes irreversible damage to the bone. Hillery and Shuaib [1] found that serious bone damage occurs when the temperature rises above 55 °C in 30 s, while Eriksson et al. [2] reported that thermal necrosis occurred in the cortical bone of rabbits above 47 °C in 60 s. Augustin et al. [3] further suggested that temperatures could increase above 47 °C, causing irreversible osteonecrosis during bone drilling.

Biomechanics and biomaterials play a crucial role in orthopedics, especially in the selection of implants, drill bits, prostheses, and screws to effectively fix bone fractures, aiding the healing process. Various studies in the literature focus on the design and biomechanical performance of implant materials. For instance, Sykaras et al. examined materials and dental implant design, while Senalp et al. utilized three-dimensional analysis to assess different shapes of femoral stems for hip prostheses. Additionally, fatigue analysis of hip implants using Finite Element Analysis (FEA) has been conducted, along with investigations into the static, dynamic, and fatigue performance of implants. In a recent study, the biomechanical performance of four different screw

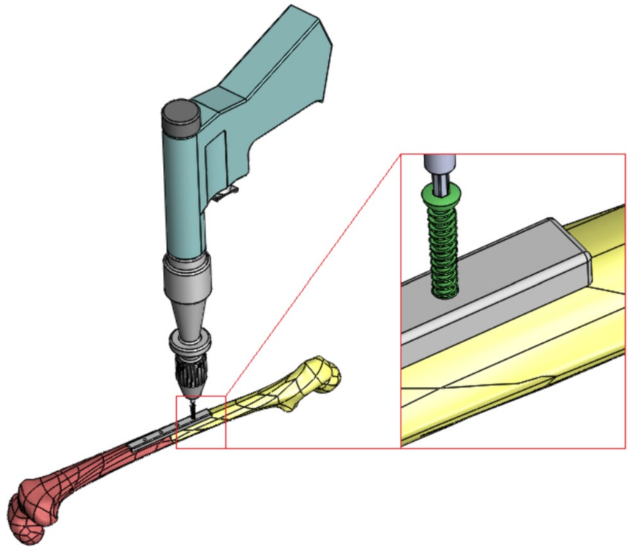

Fig. 1 The bone screwing process [19]

materials was analyzed for fixing pediatric epiphyseal fractures (Salter–Harris Type 4) under axial loading, aiming to determine the optimal material with the least stress on the epiphyseal plate and screws during loading. Gok et al. examined the use of computer-aided analysis to evaluate the biomechanical performance of Schanz screws made from different additive manufacturing materials (Ti6Al4V, 316L, Inconel 625, and Inconel 718) in a pertrochanteric fixator for the treatment of intertrochanteric femoral fractures [4–11].

Although there have been many studies on bone stresses during dental procedures or bone drilling processes, there have been relatively few studies on bone screwing. Therefore, bone drilling processes have been extensively studied in the literature. Finite Element Analysis (FEA) is a reliable tool for validating experimental or analytical results and developing new surgical techniques. Several studies have investigated the orthopedic drilling process using FEA to optimize drilling parameters and prevent complications. Sezek et al. [12] measured temperature changes during drilling and optimized parameters to maintain a safe drilling temperature. Alam et al. [13] conducted a study in which they developed a FEA model of bone cutting and compared the results with experimental data. Gok et al. [14] conducted a new driller system to prevent osteonecrosis and optimized drilling parameters. Qi et al. [15] evaluated twist drill and hollow drill performance using FEA. Kuntu et al. [16, 17] used a computer program to study how bones react to heat and proposed a formula for estimating the highest temperature bones reach, while also comparing their findings with other computer simulations [18].

This study was to investigate the biomechanical performance of four different screw materials (316L stainless steel, Ti6Al4V, NiTi, and WC) during the bone screwing process for stabilization following reduction of femur shaft fracture using numerical method. The study aimed to provide insight into the screwing moment, screw wear, and temperature distributions in the screw and bone material during the screwing process for each material, to contribute to the development of new and improved orthopedic surgical techniques. To bridge this gap, this study employs FEA to evaluate screwing processes, providing valuable insights for the development of enhanced orthopedic surgical techniques. By addressing this research gap, this study contributes to the advancement of orthopedic surgery.

## 2 Computer-Aided Finite Element Analysis

The study inputted geometric and material models, as well as loading and boundary conditions, into the DEFORM-3D software. The analyses were then solved, and the bone screwing process was simulated using the FEM approach in the software.

### 2.1 Computer-Aided Modeling

The bone screw's design was created using the SolidWorks program, and finite element method drilling simulations were carried out in the most realistic physical environment, as depicted in Fig. 2. To develop a 3D model of the screw for simulation purposes, reverse engineering (RE) techniques were utilized. This involved scanning a physical screw and using RE techniques to generate a computer-aided design (CAD) model of the screw's external geometry. The resultant 3D model can be utilized in simulations to analyze the screw's performance in various circumstances, such as varying loads or temperatures. The application of the RE method ensured an accurate and efficient approach to create the necessary 3D model for simulations.

### 2.2 Loading and Boundary Conditions

The research study utilized Finite Element Analysis (FEA) through a simulation to investigate the process of inserting a screw into sawbones. The simulation involved a meshing process using tetrahedral elements, resulting in a complex mesh structure with a high number of nodes and elements for both the sawbones and the screw. Initially, the FEA meshing process was executed, utilizing tetrahedral elements. The mesh structure of the sawbones comprised 101,321 elements and 22,509 nodes, while the screw's mesh structure included 207,499 elements and 45,154 nodes. Given that the screwing process primarily transpires around the hole region in the sawbones, a higher mesh density was allocated to this area. Consequently, the size ratio of the mesh surrounding the hole was designated

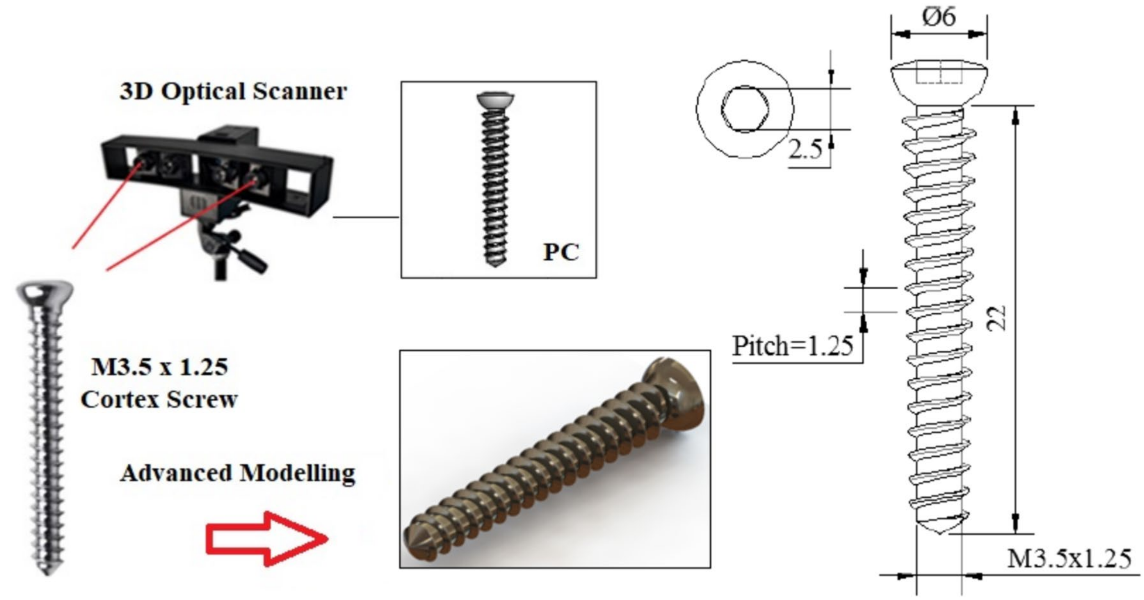


**Fig. 2** Three-dimensional model of M3.5 1 1.25 cortex screw

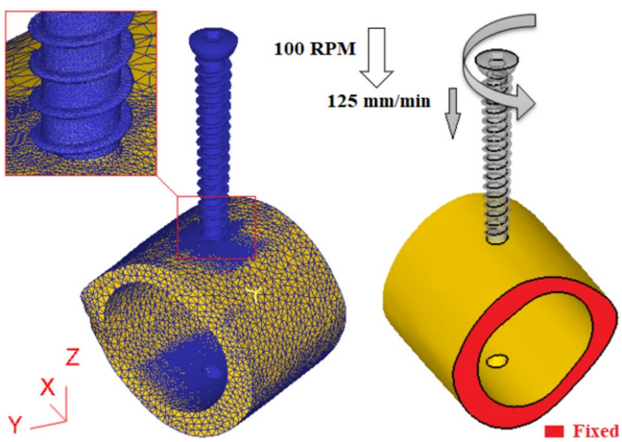


**Fig. 3** The mesh generation, loading, and boundary conditions in the analysis

**Table 1** Thermal conductivities of materials [21, 23]

| Material | (W/mK) |
|---|---|
| 316L stainless steel | 14.0–15.9 |
| Ti6Al4V | 6.70 |
| NiTi | 10.0 |
| WC | 110 |

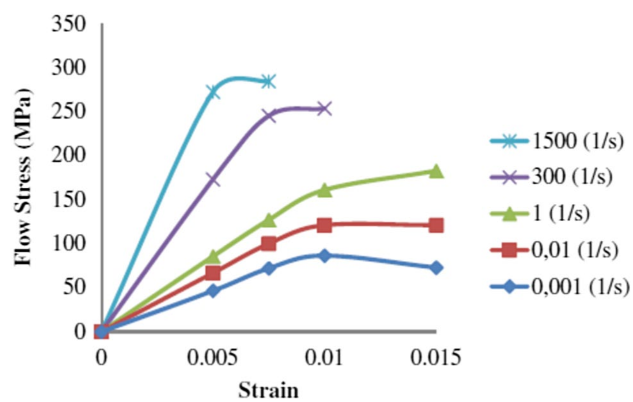


**Fig. 4** The flow stress curves for the bone model [22]

as 0.01. The lateral surfaces of the sawbones model were fixed, while the screw model was subjected to various spindle speeds and a consistent feed rate in the *Z*-axis direction, as shown in Fig. 3. To establish contact between the screw and the sawbones, a master–slave algorithm was utilized, with the screw model designated as the master and the sawbones model as the slave. A friction coefficient of 0.42 was used in the simulation to account for the frictional forces present during the screwing process [20]. The analyses were repeated three times.

### 2.3 Material Model

The mechanical and thermal properties of the bone model are given in Table 1 from [18]. The mechanical and thermal properties of 316L stainless steel, Ti6Al4V, NiTi, and WC screws were taken from [21]. The flow stress curves [22] for the bone are presented in Fig. 4. The flow stress $\overline{\sigma}$ in Eq. (1)

was chosen to show correct material performance as a role of the effective plastic strain ($\overline{\varepsilon}$), effective strain rate ($\dot{\overline{\varepsilon}}$), and temperature ($T$). Table 1 presents the thermal conductivities of materials.

$$\overline{\sigma} = (\overline{\varepsilon}, \dot{\overline{\varepsilon}}, T) \quad (1)$$

## 3 Results and Discussion

The study aimed to investigate the biomechanical performance of four different screw materials during the bone screwing process for stabilization following reduction of femur shaft fracture using numerical methods. The findings of the study showed that different screw materials have distinct biomechanical performance during the screwing process. Specifically, the study provided insights into the screwing moment, thrust force, wear, and temperature distributions in the screw and bone material during the screwing process for each material. These insights can be utilized to develop new and improved orthopedic surgical techniques for femur shaft fracture stabilization. Therefore, this study is valuable in advancing the field of orthopedic surgery and improving patient outcomes. The bone model temperature variation has been shown for Ti6Al4V screw in Fig. 5a. The temperature variation in screwing process using Ti6Al4V is shown in Fig. 5b. The same for the wear zone of screw is shown in Fig. 5c.

The bone model and screw temperatures, screwing moment, and screw wear values were numerically obtained during the bone screwing process using the FEA with Deform-3D software. These features are critical for screwing operations, particularly the temperature values in the bone model during screwing or drilling, which can cause necrosis if they exceed 47 °C, leading to irreversible damage to the sawbones and surrounding tissues. Figure 6 illustrates the FEA results.

The lowest bone and screw temperatures during the bone screw insertion process were observed with WC screws. Additionally, the amount of wear generated with different screw materials was also observed to be the lowest with WC screws. As shown in Fig. 6, the lowest bone temperatures were achieved in the screwing process with WC, 316L, Ti6Al4V, and NiTi screws, respectively. This can be attributed to the thermal conductivity coefficients of the screw materials. As shown in Table 2, WC has the highest thermal conductivity coefficient, which implies that heat is rapidly dissipated from the screwing region. Therefore, both the bone model and screws (for WC) exhibited the lowest temperatures.

The biomechanical performance of stainless steel, titanium alloy, cobalt–chromium, and NiTi alloy has been compared for fixation in Salter–Harris Type 4 fractures by Gok et al. [24]. The optimal material was identified under axial loading conditions. It was observed that screws made of NiTi alloy exhibit lower stress loads. However, despite the advantages observed with titanium alloy, NiTi screws are not commonly utilized in orthopedic surgery, leaving room for exploration from various perspectives [24]. Titanium alloys outperform stainless steel and Co–Cr–Mo biomaterials in biomechanics, with lower Young's modulus and excellent corrosion resistance. They also offer a superior balance between strength and ductility. For example, the commonly used Ti alloy ($\alpha+\beta$) has a Young's modulus of around 110 GPa, half that of 316L. Recent advancements, like β-type Ti–29Nb–13Ta–4.6Zr (TNTZ), exhibit excellent

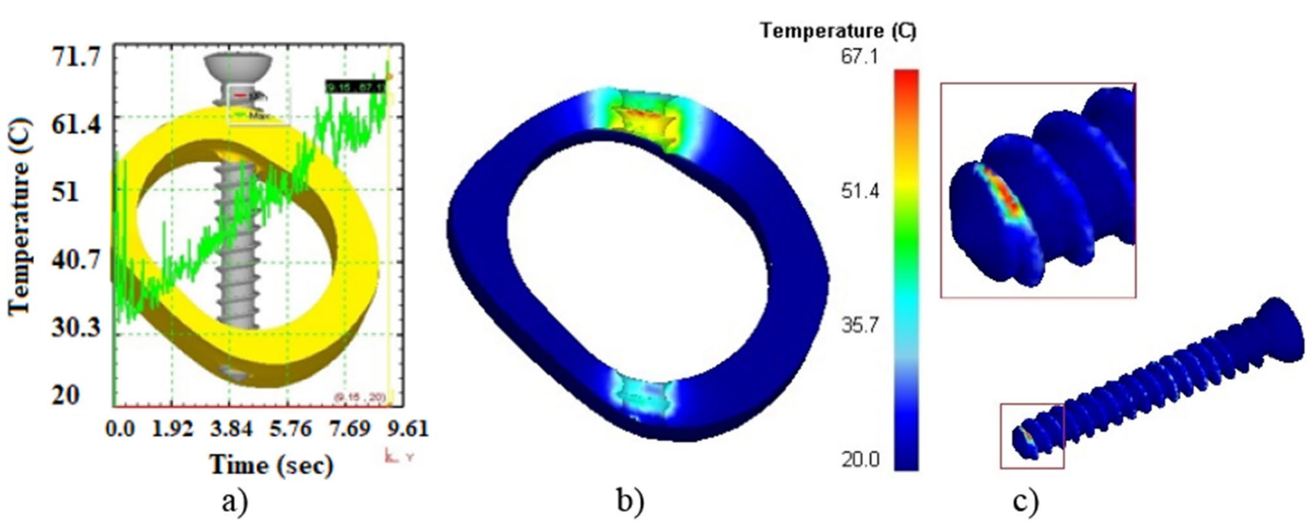


**Fig. 5** **a** The bone model temperature variation, **b** color variation, and **c** wear value of screw

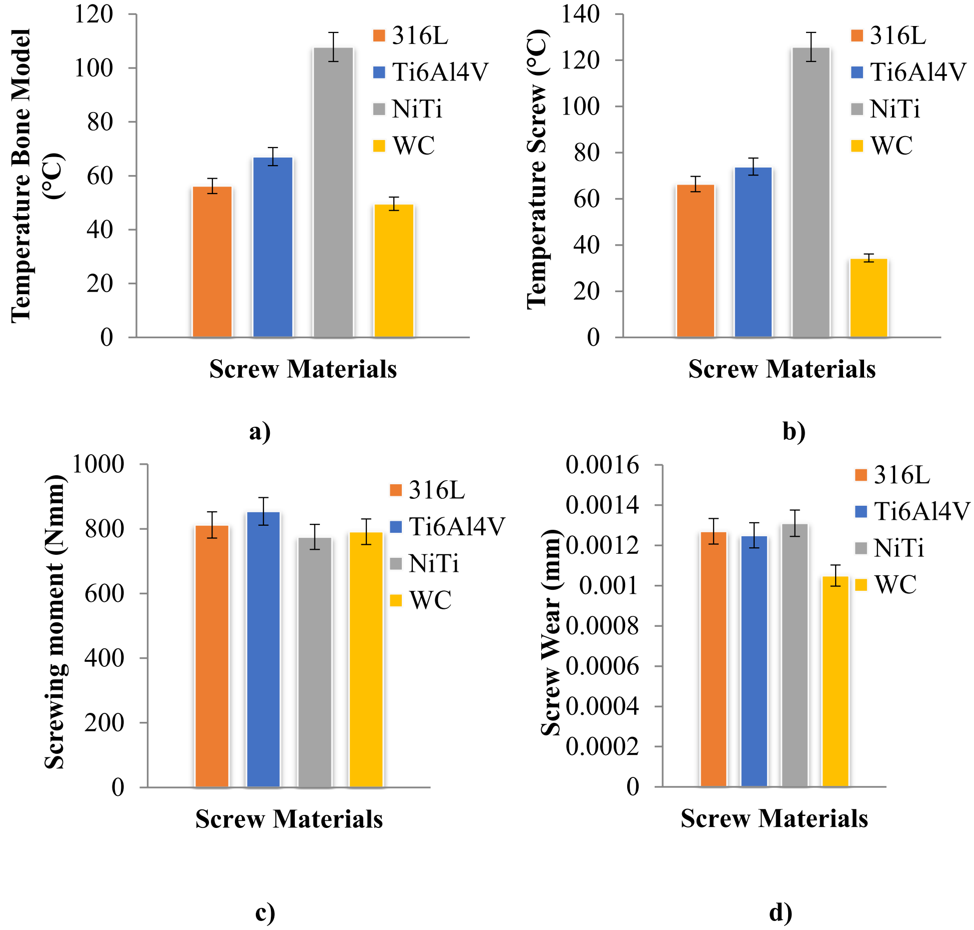


**Fig. 6** FEA results, **a** temperatures of bone model, **b** temperatures of screw, **c** screwing moment, and **d** screw wear in bone screwing process

**Table 2** The mechanical properties of four different implant materials [32]

| Properties | Stainless steel | Titanium alloy | Nitinol |
|---|---|---|---|
| Strength | Medium (300/560 Mpa) | High (880/950 Mpa) | High (500/1400 Mpa) |
| Stiffness | High (200 Gpa) | Moderate (90 Gpa) | Very low (25 Gpa) |
| Fatigue | Good in load control | Good in load control | Good in strain control |
| Corrosion | Good $Cr_2O_3$ (500 mV) | Excellent $TiO_2$ (800 mV) | Excellent $TiO_2$ (800 mV) |

mechanical properties, corrosion resistance, biocompatibility, and a low Young's modulus of ~ 60 GPa, similar to bone [25–30]. Ultrasound-assisted powder compaction successfully created Zn–WC nanocomposites by Guan et al. [31]. Zn–10WC showed a 48% hardness increase, unchanged after 14 days of biodegradation testing. Evaluation revealed that WC nanoparticles did not affect Zn ion release, and no detectable tungsten ion release occurred. These results suggest that Zn–WC nanocomposites retain Zn's favorable biodegradation for bioabsorbable implants while enhancing mechanical properties.

The mechanical properties of four different implant materials were analyzed using Finite Element Analysis (FEA) and von Mises analysis. Additionally, a comparative study was conducted on four implant materials (stainless steel, Ti alloy, and NiTi) to assess both mechanical and metallurgical properties. The mechanical properties are presented in Table 2.

The study investigated the biomechanical performance of four screw materials during bone screwing for femur shaft fracture stabilization. Findings revealed distinct performances among materials, particularly in screwing moment, thrust force, wear, and temperature distributions. Results indicate that WC screws exhibit lowest temperatures and wear. Titanium alloys, despite advantages, are not widely used in orthopedics, leaving room for exploration. Recent advancements show promising materials like TNTZ with low Young's modulus. Zn–WC nanocomposites enhance mechanical properties while retaining favorable biodegradation for implants.

The study lacks detailed exploration of potential confounding variables that could influence biomechanical performance, such as bone density variations or surgical techniques. Future research could investigate these factors to provide a more comprehensive understanding of screw material performance. Additionally, longitudinal studies tracking patient outcomes following orthopedic procedures involving different screw materials would offer valuable insights into the long-term efficacy and complications associated with each material. Furthermore, expanding the study to include a broader range of fracture types and surgical scenarios would enhance the generalizability of the findings.

## 4 Conclusion

In conclusion, this study has demonstrated that the biomechanical performance of screw materials during the bone screwing process for femur shaft fracture stabilization varies significantly. The findings have highlighted the distinct differences in screwing moment, thrust force, wear, and temperature distributions in the screw and bone material during the screwing process for different screw materials. The numerical analyses based on FEM and Deform-3D software have provided valuable insights into the bone and screw temperatures, which are crucial for preventing necrosis during the screwing or drilling process. The results suggest that WC screws have the lowest bone and screw temperatures, as well as the lowest wear generation among the four screw materials investigated. Therefore, these findings have important implications for the development of new and improved orthopedic surgical techniques, which can ultimately lead to better patient outcomes.

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**Funding** There is no funding.

**Declarations**

**Conflict of interest** There is no conflict of interest.

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