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Fatigue Performance of Aluminum Alloy as a Biomaterial for Schanz Screws in Intertrochanteric Femoral Fractures: An Investigation Using Finite Element Analysis

Kadir GÖK[a,1] and Arif GÖK[b]
[a] Izmir Bakırcay University, Department of Biomedical Engineering, İzmir, Turkey
[b] Kutahya Dumlupinar University, Department of Industrial Design, Kutahya, Turkey
ORCiD ID: Kadir Gök, https://orcid.org/0000-0001-5736-1884
Arif Gök, https://orcid.org/0000-0003-2840-9601

Abstract. This study explores the relation between corrosion behavior and fatigue performance of Aluminum alloy as a biomaterial for intertrochanteric femoral fracture fixation using Schanz screws. Finite element analysis via ANSYS Workbench software revealed a fatigue life of approximately 6 months for the screws, with a safety factor of 1.66. The dynamic fatigue test results indicated favorable fatigue performance of the aluminum alloy. Despite this, biocompatibility and corrosion concerns remain regarding aluminum alloys. Hence, it is suggested to adopt a biomaterial with superior fatigue performance for Schanz screws to ensure fixator safety during patient mobilization. Additionally, proposing a real-time monitoring Digital Twin Model for aluminum alloy-based Schanz screws is recommended. Equipped with sensors, this model enables continuous data collection on corrosion, stress, and temperature, aiding healthcare professionals in early issue detection and predictive maintenance, thus enhancing long-term reliability and safety of orthopedic implant systems.

Keywords. Femoral intertrochanteric fracture, aluminum alloy, finite element analysis, biomechanics

1. Introduction

According to a report published in 2021, there were approximately 178 million new fractures reported in 2019, with 455 million cases of acute or long-term fracture symptoms reported, and 25.8 million categorized as "years lived with disability of fractures" [1]. Therefore, the careful selection of biomaterials such as implants, drill bits, plates, and screws for use in orthopaedic and dental surgeries is crucial to ensure proper stabilization and optimal fracture healing. Effective fracture management is critical, and the selection of appropriate fixation materials for optimal stability is a critical factor in achieving successful treatment outcomes [1]. Intertrochanteric femoral fractures are severe injuries that can result in complications such as pneumonia, pulmonary embolism, or even death. Therefore, it is essential to achieve high precision and stability when

[1] Corresponding Author: Kadir Gök, E-mail: kadir.gok@bakircay.edu.tr

treating these fractures. Surgeons use schanz screws with pertrochanteric fixator bodies or various implants to stabilize intertrochanteric fractures, but it should be noted that implants used for the fixation of fractures, such as pertrochanteric fixators (PTFs), are subjected to significant forces during walking [2]. Evaluating how durable Schanz screws are for pertrochanteric fractures is really important for helping patients get better. These fractures can cause serious health problems, and Schanz screws are super important for keeping external fixators stable. Knowing how strong these screws are helps prevent issues like the screws not working or problems during activities like walking. It also makes it easier for patients to start moving around sooner. This information helps doctors plan treatments better, so they can choose the right actions based on how the screws work. In the end, this makes managing fractures work better and helps patients recover faster.

Several studies have been conducted in the literature on implant design, implant materials, and the fatigue behavior of implants used in the skeletal system or dentistry. For instance, Sykaras et al. [3] conducted a review of the literature on the materials, designs, and surface topographies of endosseous dental implants. Additionally, several studies have employed three-dimensional analysis to investigate the mechanical interaction between a femoral stem and the femur in a hip arthroplasty [4-6]. Another study used a three-dimensional finite element model to conduct fatigue analysis of a hip implant [7]. Senalp et al. [8], modeled and analyzed four different stem shapes with varying curvatures for hip prostheses using the commercial finite element analysis code ANSYS. The effectiveness of the designed stem shapes was determined by examining their static, dynamic, and fatigue behaviors. Similarly, Kayabasi et al [9] investigated the static, dynamic, and fatigue behaviors of implants. Gok and Inal [10] used the FEA method to investigate the best stable fixation application by applying five different screw configuration types in a femoral neck fracture model.

Aluminum alloys are commonly used as biomaterials in many areas, such as orthopedic implants, artificial hip joints, ankle implants, dental implants, and other medical devices. However, due to aluminum's high potential for toxicity, it is not suitable for long-term use in the body. The effects of aluminum on human health are still being studied. When parts of aluminum alloys are implanted in the body, the corrosion products of the alloys can release aluminum ions due to electrochemical reactions and other factors. Aluminum ions can cause toxic effects by disrupting the normal functions of cells. Therefore, it is not recommended to keep them in the body for a long time. Implants such as Schanz screws are usually manufactured in stainless steel or titanium alloy.

This study aimed to analyze the fatigue performance of schanz screws made of aluminum alloy, which were used to fix femoral intertrochanteric fractures. The study also aimed to evaluate the suitability of this material in biomechanical applications. In addition to these, this model suggests the development of a real-time monitoring Digital Twin Model equipped with sensors to detect corrosion, stress, and temperature variations. This model facilitates early issue detection and predictive maintenance, enhancing the safety and reliability of orthopedic implant systems. Digital twin models of Schanz screws will use strain gauge sensors for real-time monitoring of their fatigue behavior and performance during mobilization. This approach allows observation of corrosion effects and other factors in a virtual environment.

2. Materials and methods

The process of creating a femoral intertrochanteric fracture model and its associated components (such as schanz screws and a fixator) involved using the SolidWorks program, as depicted in Fig. 1. Subsequently, the resulting models and components were exported into ANSYS Workbench to conduct Finite Element Analysis (FEA).

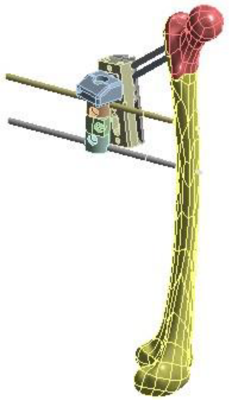

Figure 1. Femoral intertrochanteric fracture model

2.1. Computer aided finite element analysis

The computer aided FEA was performed in AnsysWorkbench to determine the fatique performance of schanz screws having aluminyum alloy in intertrochanteric fractures. The tetrahedrons element type was prepared to obtain the best mesh process as shown in Fig. 2. There are 189436 nodes and 105360 elements. The contact types were determined for FEA. The frictional contact was chosen between implant – bone (0.42) and bone – bone (0.46) [11]. The loading and boundary conditions were applied as Fig. 3. This study conducted based on a subject with a mass of 70 Kilograms (kg) [8, 12, 13]. All materials used for PTFs are structural steel and they were taken from the ANSYS Material Library.

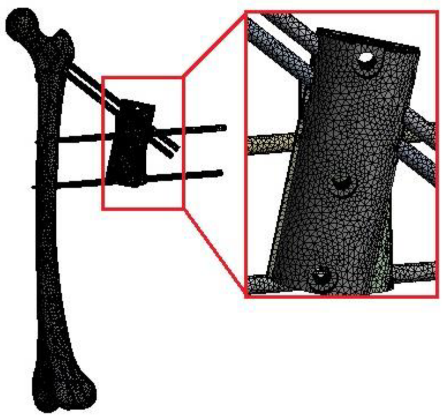

Figure 2. The mesh process.

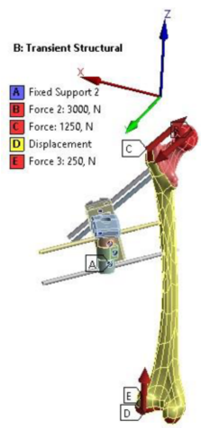

Figure 3. Types of forces exerted on pertrochanteric fixators and femur

An abductor muscle load of 1.25 kN showed as label C in Fig. 3 is applied at an angle of 20° to the proximal area of the greater trochanter. Distal end of the femur is constrained not to move in horizontal direction showed as label D in Fig. 3 [8, 13]. An iliotibial-tract load of 250 N showed as label E in Fig. 3 is applied to the bottom of the femur in the longitudinal femur direction. All materials used for PTFs were stainless steel from the ANSYS Material Library.

The mechanical properties of the materials were given in Table 1. Fig. 4 presents the S-N curve for the Schanz screw materials used in this study for fatigue calculations, plotted on a logarithmic scale to show the relationship between the alternating stress and the number of cycles.

Table 1. Mechanical properties of bone and screws used in FEA [14, 15]

Parameters	Aluminum alloy	Bone
Denstiy (kg.m-3)	2770	2100
Elasticity modulus (MPa)	71000	17000
Tensile Yield Strength (MPa)	280	135
Tensile Ultimate Strength (MPa)	310	148
Poisson Ratio	0,33	0.35

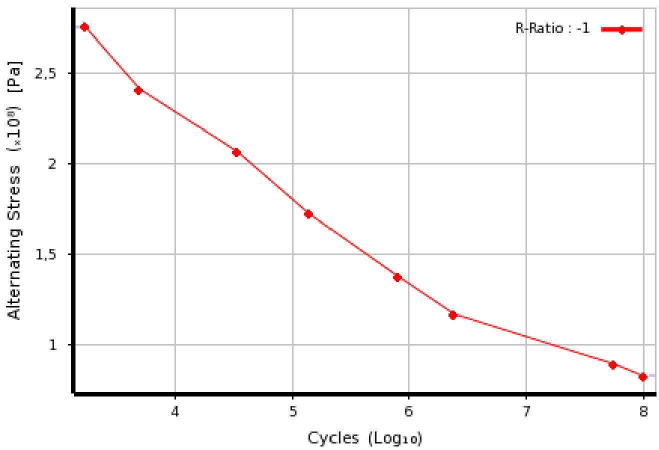

Figure 4. S–N curves of schanz screws having aluminum alloy [14]

2.2. Fatigue analysis

The fatigue performance of schanz screws made of aluminum alloy for fixing femoral intertrochanteric fractures was analyzed through computer-aided analyses using ANSYS Workbench. The Equivalent (von-Mises) stress was used as the basis for the analyses. Fully Reversed loading type was chosen for the fatigue life, as shown in Fig. 5. The analysis type was Stress Life, and the Mean Stress Theory was None. The design life for the schanz screws was set as 109 seconds to calculate their fatigue life. It should be noted that 1 cycle is equal to 1 second.

A digital twin is a virtual representation of a real-world physical product, system, or process (referred to as a physical twin). It functions as an essentially identical digital counterpart for practical purposes, including simulation, integration, testing, monitoring, and maintenance. Since its inception, the digital twin has been designed to serve as the fundamental foundation for Product Lifecycle Management [16]. With the growing significance of simulation in medicine, the vision for future precision medicine includes delivering personalized diagnoses and treatments to individual patients. The realization of this customization is expected to be facilitated by the advancement of digital twin technology [17].

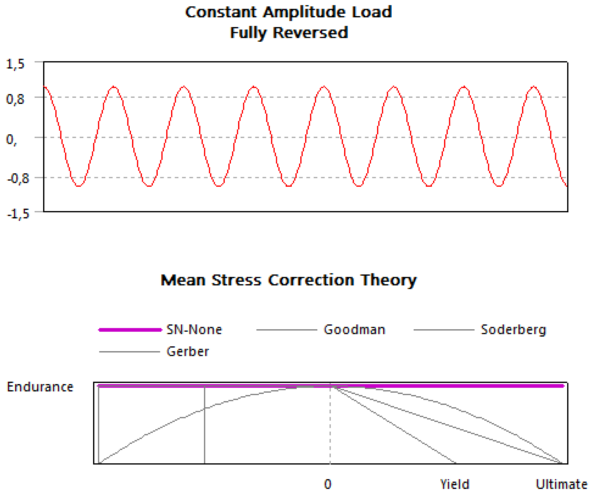

Figure 5. Fully reversed for loading type and mean stress theory

3. Results and discussion

The von-Mises stress and life of schanz screws were calculated using the computer aided fatigue analyses in Fig. 6. The minimum fatigue was calculated as 1,9223e+014 seconds on the upper schanz screws just in front of the fixator body having aluminum alloy. During the mobilization of the patient, the maximum equivalent stress on the shaft portion of aluminum alloy shaft screws was calculated as 166,12 MPa due to the muscle forces in the hip joint and the effect of the patient's body weight. It was found that the aluminum alloy, which has a yield strength of 280 MPa, can withstand these combined forces under static load. In addition, it is also apparent from the calculation results of the computer-aided dynamic fatigue test that this material can show very good fatigue performance. Additionally, titanium alloy may be preferred in these applications.

Corrosion is the chemical or electrochemical dissolution or wearing a way of a material. This process causes the metal atoms on the material surface to react with compounds in their environment, resulting in their dissolution and conversion to corrosion products. There are many causes of corrosion, but it is often related to environmental factors to which the material is exposed (such as humidity, temperature, chemicals, etc.). Fatigue, on the other hand, is the damage that occurs to a material because of exposure to cyclic loads. Such loads increase the stress level on the material and can eventually lead to cracks and fractures in the material over time. The relationship between corrosion and fatigue is often independent events. However, in some cases, corrosion can cause cracks or other damage to occur on the material surface. These damages can then lead to fatigue and increase the stress level on the material, resulting in fractures and other damages. Therefore, the relationship between corrosion and fatigue is important in some cases for material strength and durability. Corrosion-fatigue is the result of the combined action of alternating or cycling stresses and a corrosive environment. The fatigue process is believed to cause rupture of the protective passive film, which accelerates corrosion. If the metal is simultaneously exposed to a corrosive environment, the failure can occur at even lower loads and after a shorter time. In a corrosive environment, the stress level at which a material is assumed to have infinite life is lowered or completely removed. Unlike pure mechanical fatigue, there is no fatigue limit load in corrosion-assisted fatigue. Corrosion fatigue and fretting are both examples of this type of failure. Significantly lower failure stresses and shorter failure times can occur in a corrosive environment compared to a non-corrosive environment where the alternating stress is present [18].

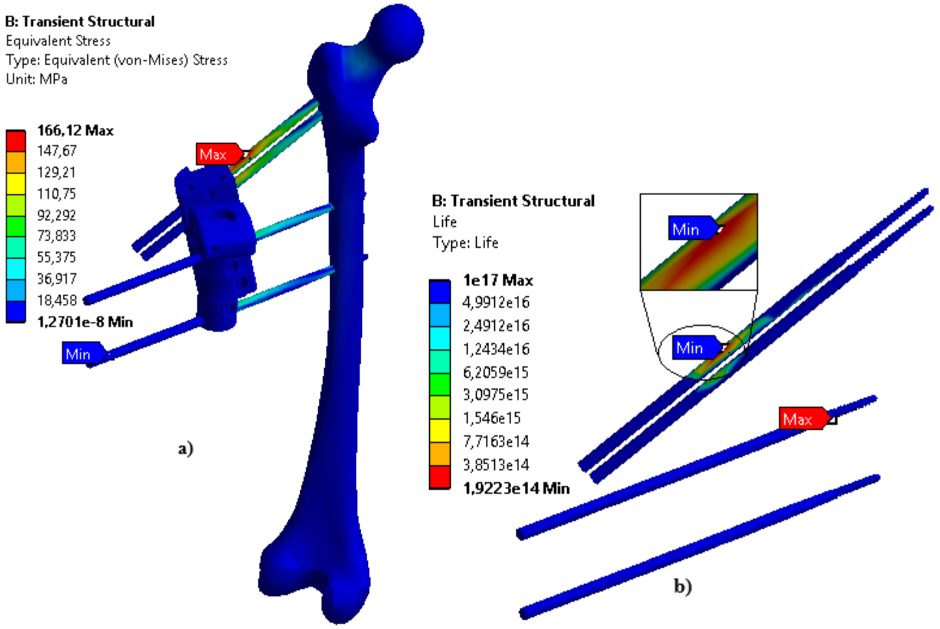

Figure 6. The fatigue analyse results. (a) the maximum equivalent stresses of schanz screws, (b) the life of schanz screws

The analysis reveals that the aluminum alloy demonstrates resilience against combined forces in static conditions and displays commendable fatigue performance. Despite these positive attributes, it is ephasized that the crucial consideration of the interplay between corrosion and fatigue to ensure the material's long-term durability and reliability. The potential advantages of the alternative aluminum alloy may encompass its effective resistance to both static and dynamic loads, as indicated by its favorable fatigue performance. Moreover, the common use of aluminum alloys in biomaterial applications is attributed to their favorable mechanical properties, including high strength, low density, and light weight. Nonetheless, the text also draws attention to the challenges associated with aluminum's elevated toxicity potential, urging caution in its prolonged use within the body. A comprehensive assessment of the alternative aluminum alloy's benefits compared to standard Schanz pins would necessitate additional details regarding its specific strengths and applications.

Several articles have been examined under various conditions, focusing on the fatigue behaviors of aluminum alloys. It was determined that the fatigue strength of 2024-T4 aluminum alloy decreases at high temperatures [19]. The decrease in fatigue strength of the 2024-T4 aluminum alloy at high temperatures raises concerns about situations where medical implants may be exposed to body temperature. This scenario is crucial for understanding how the fatigue performance of materials intended for use in biological environments can vary under different temperature conditions. Moreto et al. [20] evaluated the fatigue crack lifetimes of AA2198-T851 and AA7081-T73511 alloys in a saline environment, emphasizing the detrimental effects of saline solution treatment. It emphasizes the effects of saline solution treatment on the fatigue behavior of aluminum alloys. This illustrates how the corrosion resistance and fatigue strength of materials intended for use in biological environments can be affected, considering situations where implant materials are exposed to bodily fluids. Esmaeili et al. [21] demonstrated that subjecting Al-7075 aluminum alloy to Equal Channel Angular Pressing (ECAP) increases its fatigue strength, but the extent of this improvement varies with the number of ECAP passes. This suggests situations where material strength and durability are critically important in biomedical implants. Imam et al. [22] showed that heat treatments of aluminum alloys can significantly increase their fatigue lifetimes and delay crack formation. In all articles, the effects of process conditions and environmental factors on the fatigue behaviors of aluminum alloys are emphasized. In this context, the impact of heat treatments, saline environments, and specific processing techniques on the fatigue performance of alloys is compared and examined. These studies contribute to understanding the optimized conditions for enhancing the reliability and performance of aluminum alloys in industrial applications. This has the potential to explain investigations focused on the development of materials with increased reliability and durability for upcoming biomedical applications.

4. Conclusions

In conclusion, computer-aided fatigue analysis shows that the aluminum alloy in Schanz screws can handle static loads well and has good fatigue performance. However, corrosion can significantly reduce failure stresses and shorten failure times, making it crucial to address corrosion in cyclic loading applications to avoid failures and ensure material safety. Although aluminum alloys are used in biomaterials like orthopedic implants, their potential toxicity limits their long-term use in the body. Corrosion can release toxic aluminum ions, affecting cell function. Therefore, aluminum alloys for biomaterials should be designed with high strength, low density, and improved biocompatibility through coatings and surface treatments.

Additionally, a Digital Twin Model for real-time monitoring of aluminum alloy-based Schanz screws could enhance intertrochanteric femoral fracture fixation. This model would use sensors to track corrosion rates, stress distribution, and temperature changes, allowing for early issue detection and predictive maintenance, thereby improving patient outcomes and implant reliability.

Digital twin models of Schanz screws will be established in real-time using strain gauge sensors, allowing the monitoring of their fatigue behavior during the mobilization process in a virtual environment. This approach provides insights into the screws performance and longevity, enabling the observation of the effects of corrosion and other factors in a simulated setting.

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