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Pull-out strength of screws in long bones at different insertion angles: finite element analysis and experimental investigations

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Abstract: Different types of plates are available to allow insertion of screws for internal fixation of long bone fractures. The aim of the study was to determine the effect of the insertion of screws at different angles on a long bone to the pull-out strength. Using 3D printed bone models, we tested the pull-out strength of screws in long bones at insertion angles between 0 and 40° with both finite element analysis and on printed models experimentally and compared the results. Test samples and cortical screws used were modeled with SolidWorks software and analyzed with Ansys software. As the screw insertion angle increases, the pull-out forces on the test specimens increase from 61.14 ± 3.5 N at 0° to 273 ± 6.8 N at 40° with an exception of a small drop between 15 and 20° from 235.4 ± 6.2 to 233 ± 6.9 N. Both methods showed an increase in the pull-out strength of screws as the insertion angle increases. This might be applicable in the clinical practice of bone fixation. Further studies on plate and screw fixation are needed to complement the findings.

Keywords: fibula fixation; pull-out strength; finite element analysis; additive manufacturing; experimental study

1 Introduction

Orthopedic surgeons frequently use fixation devices such as plate-screw systems and intramedullary nails in the treatment of long bone fractures [1]. Locked and nonlocking plate-screw systems are popular tools for fixation of some types of fractures, like fibula and tibia fractures [2]–[4]. Plate-screw systems aim to provide biomechanical stability and lead to fracture healing [5], [6]. However, factors such as screw toggling in the bone matrix, screw pullout, screw fracture by bending or torsion, and stress risers can lead to failure of fixation [7]–[9]. In plate-screw systems, the bond strength between the screw and the bone influences stability. Screw type, dimensions, thread width, insertion length, insertion angle, plate type, and bone properties are all important for the pull-out strength of the screw [10], [11]. Studies on pull-out strength of plate-screw system screw scan determine success of treatment [12].

Experimental and finite element analysis studies have investigated the factors affecting the screw pull-out strength [13]–[15]. One of those used polyurethane (PU) foam with insertion of cortical and cancellous screws, and it was observed that the pull-out strength increased when the foam density increased [16]. In another study 2 weeks after coating the titanium screws with bisphosphonate, the pull-out force increased by 32 % [17]. With regard to the effect of screw parameters (diameter, pitch, length) on the pull-out strength, it is known that large diameter is more effective than smaller one [18]. When pull-out tests are done, it is observed that friction is caused by bone sliding along a cylindrical surface around the outer circumference of the screw [12]. In many of these studies, cadaveric bone tissues or artificial materials with uniform properties so the different density distribution are used to mimic real-life conditions [12], [19]–[21]. Quality of bones taken from cadavers adversely affects test reliability. Moreover, given that the density and mechanical properties of the cortical and cancellous regions of the bone are different, tests with artificial materials cannot fully reflect reality [22], [23]. Tests with density of test samples similar to bone structure using Fused Deposition Modeling

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(FDM) type 3D printer may yield more consistent results. Poly Lactic Acid (PLA) is a cost-effective, biocompatible, thermoplastic material with a broad range of applications and produces quality products in 3D printers.

The aim of the study was to determine effect of insertion of screws at different angles on fixation strength. The effect of screw insertion angle on stability of the fixation was tested with pull-out analysis experimentally and using the finite element method. For this purpose, pull-out tests were performed by printing rectangular models shown in Figure 2 with 3D printers. The pull-out force values from the preliminary tests obtained were interpreted using the finite element method. The results obtained from both methods were compared (finite element method and experimental method).

2 Materials and methods

2.1 3D printing of test specimens

The test samples were fabricated using a 3D printer with a 1.75 mm PLA filament. The samples were modeled as 20 × 15 × 15 mm (screw insertion section) rectangles with SolidWorks Computer Aided Design (CAD) software. CAD model of test samples is shown in Figure 1. All test specimens were fabricated using a ZAXE brand FDM type 3D printer with a 0.4 mm nozzle at different wall thicknesses and occupancy repairs. Test samples were produced at 10, 20, and 30 % infill rates, similar to cortical and cancellous bone structure. In Figure 2, the test sample and hollow interior structure produced with FDM type 3D printer are shown. In Figure 2, the outer cortical structure and the inner cancellous region are shown in more detail. Initial trials with 10 % and 20 % filling rate interior structure did not give strong and stable results. Therefore, in the current study, we used 30 % filling rate for the purpose of this study (Figure 2).

2.2 Screw pull-out test

For pull-out tests, PLA test specimens produced with FDM type 3D printer were drilled with 2.5 mm diameter drill and angles of 0°, 5°, 10°, 15°, 20°, 30°, and 40°. Then, 3.5 mm 316 L stainless steel cortical screws were used in pull-out tests [24], [25]. The screws, which have a total length of 26 mm, were inserted to the test specimens roundly in a dept. of 12 mm, while 14 mm of those were used to feed into the test machine (Figure 3). Tensile tests were performed using a SHIMADZU brand tester with a capacity of 50 kN (Figure 3). The screw

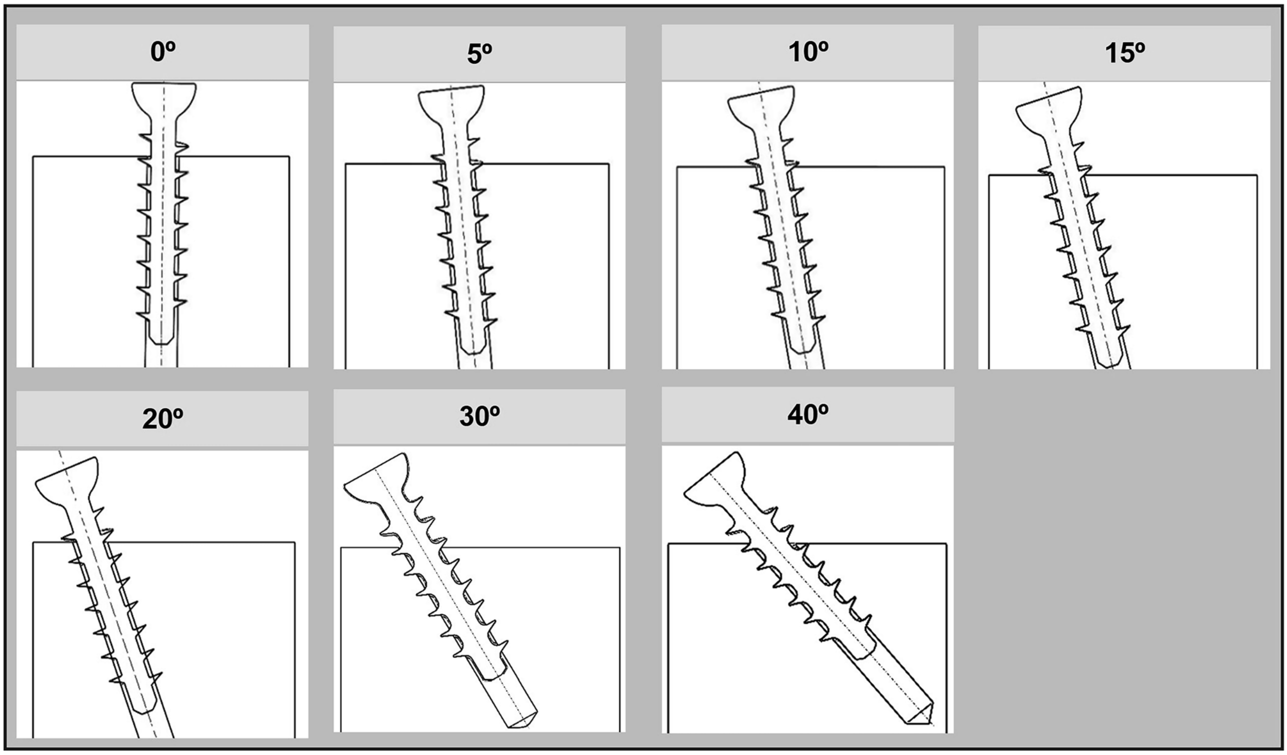

Figure 1: Screw fixation models designed at different angles.

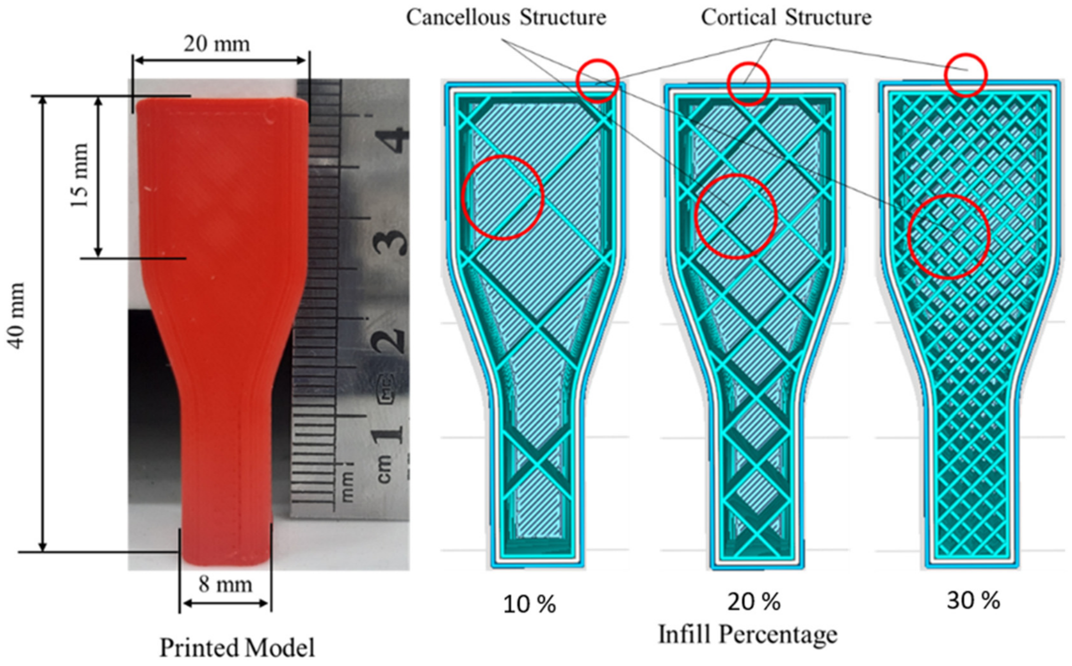

Figure 2: 3D printed and internal structures (rectangular lattice structure) of the samples used in pull-out tests.

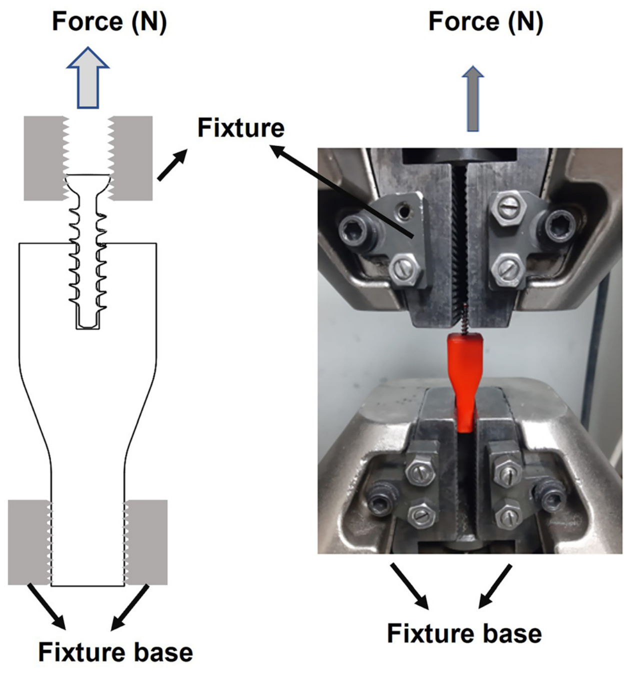

Figure 3: Pull-out tests.

head is fixed to the upper jaw of the pulling device, while the test specimen is placed in the lower jaw of the pulling device. Tensile tests were carried out at a tensile speed of 1 mm/s. In order to minimize the experimental errors, three of each sample were produced and tested, and the results were evaluated by taking the average of the results.

2.3 Finite element analysis

ANSYS software is used to simulate the pull behavior of test samples fabricated with the FDM type 3D printer. Test samples and the cortical screws used in pull-out experiments are modeled with the SOLIDWORKS software. Stresses in the structure are determined by the FEA method, applying a pull-out force of 100 N in the vertical direction, considering the pull-out forces obtained from the experimental studies. The cortical screw model and dimensions are shown in Figures 4 and 5 illustrates the FEA model and boundary conditions.

3 Results

3.1 Pull-out strength

Figure 6 shows the pull-out forces that occur when screws are placed at 0°, 5°, 10°, 15°, 20°, 30°, and 40° angles. The pull-out strengths of the test specimens vary depending on the screw insertion angle. As the screw insertion angle increases, the pull-out forces on the test specimens increase. While the highest force was obtained in the screw placed axially at an angle of 40°, the lowest force was obtained in the test specimens placed vertically at an angle of 0°. Figure 7 shows the damaged test specimen as a result of the pull-out test. When the test sample is examined, it is seen that the

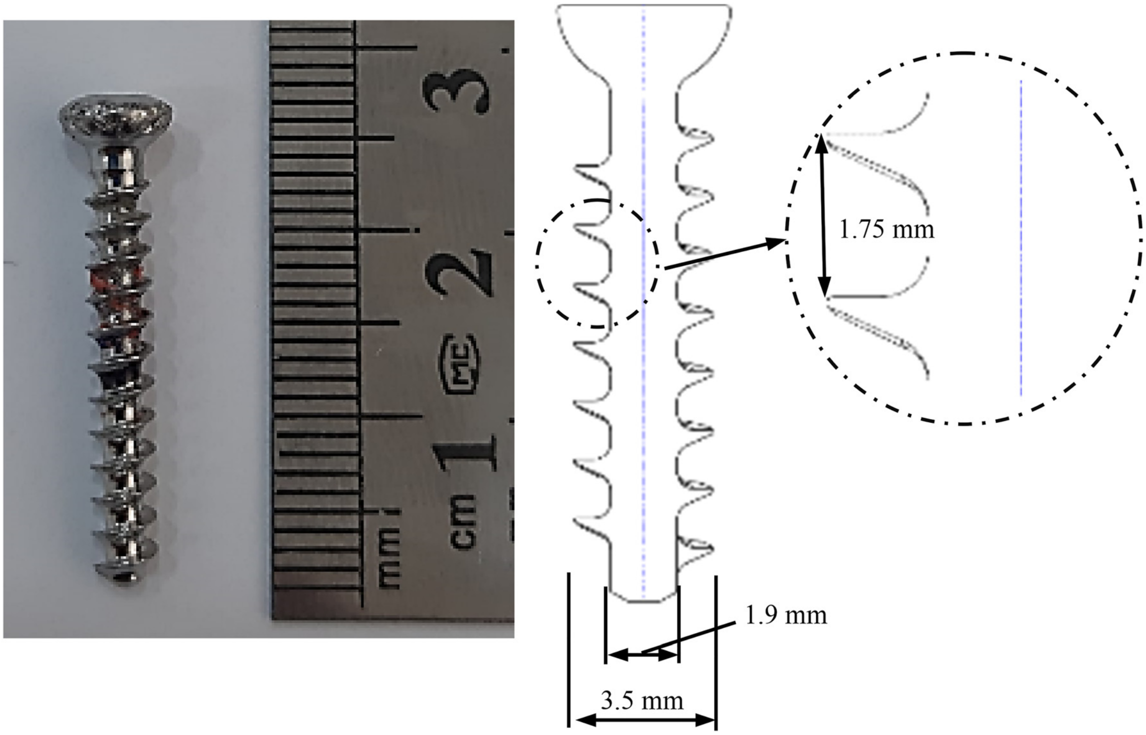

Figure 4: Screw dimensions.

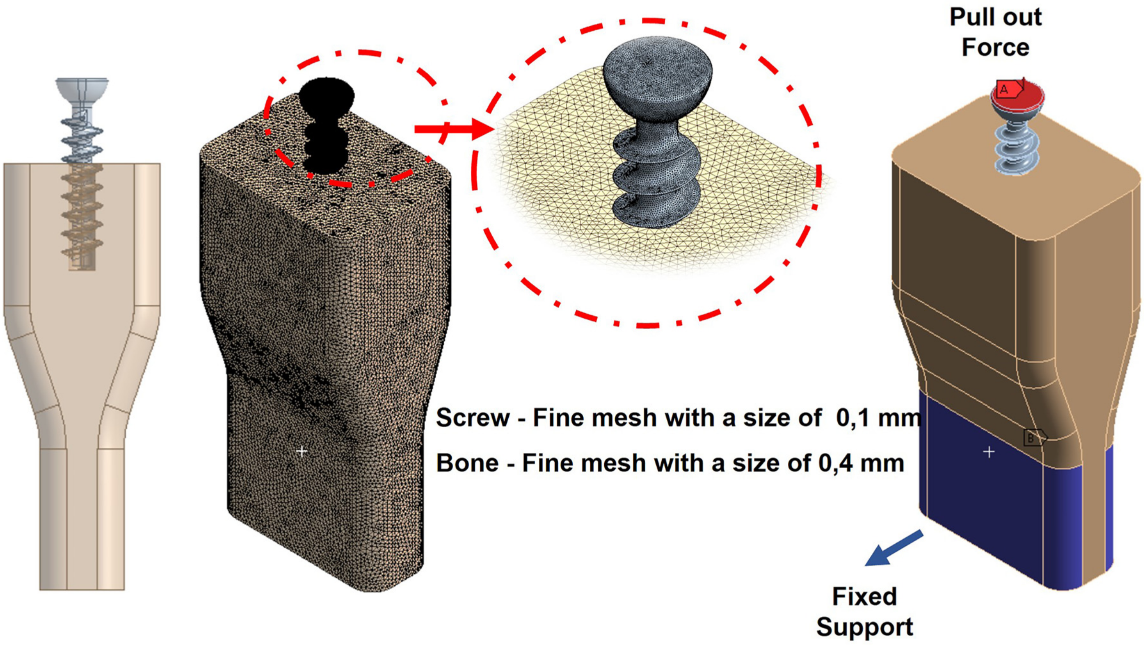

Figure 5: FEA model and boundary conditions.

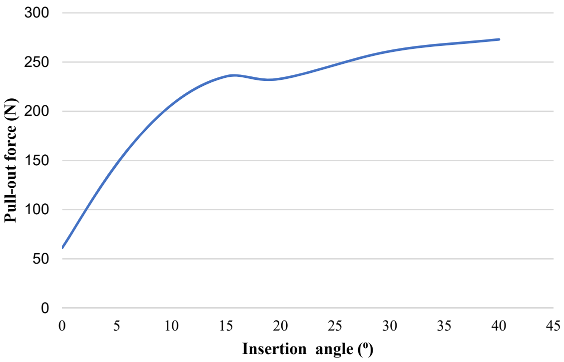

Figure 6: Experimentally obtained pull-out forces for screws inserted at different angles.

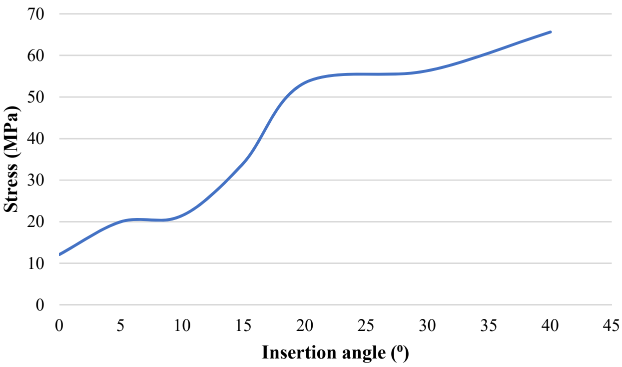

Figure 8: Stress results are obtained when pulling-out force is applied in the vertical direction for screws placed at different angles.

screw threads break the connections in the lattice internal structure and cause damage.

3.2 Pull-out simulation with the finite element method

While performing the structural analyses, the experimental conditions were taken as basis and FEA analyses were carried out by applying the same conditions as the experimental study. Figure 8 shows the stress values obtained in the test samples as a result of the analysis. Considering the results of the analysis, the lowest stress value was obtained 12.12 MPa in the test specimen placed at an angle of “0”. As the screw insertion angle increases, the stress on the test specimens increases. The stresses were obtained as 19.99, 21.46, 34.12, 53.42, 56.32, and 65.63 MPa in the test specimens with screw insertion angles of 5°, 10°, 15°, 20°, 30°, and 40°, respectively. Figure 9 shows the stress distributions (MPa) obtained when vertical tensile force is applied to the screws installed at different angles.

In this study, the effect of screw insertion angle on the pull-out force is investigated by experimental and finite element methods. In many other studies on pull-out, the effect of screw size and material quality on pull-out strength has been examined by different methods [12], [18]–[20], [26]. In the literature, bone from cadavers or artificial bones with homogeneous density and mechanical properties were used [27], [28]. In this study, test specimens produced from PLA by FDM type 3D printer were used, producing models with an outer shell similar to the cortical bone and the inner region similar to the cancellous bone.

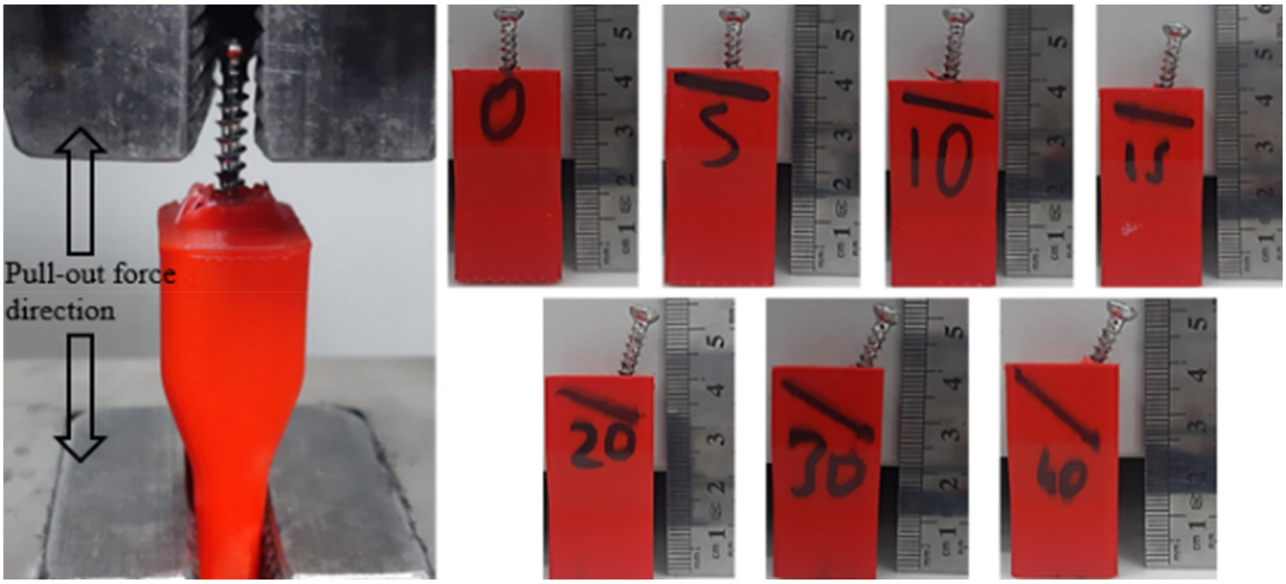

Figure 7: Test specimen damaged as a result of pull-out test and test specimens with screws placed at different angles.

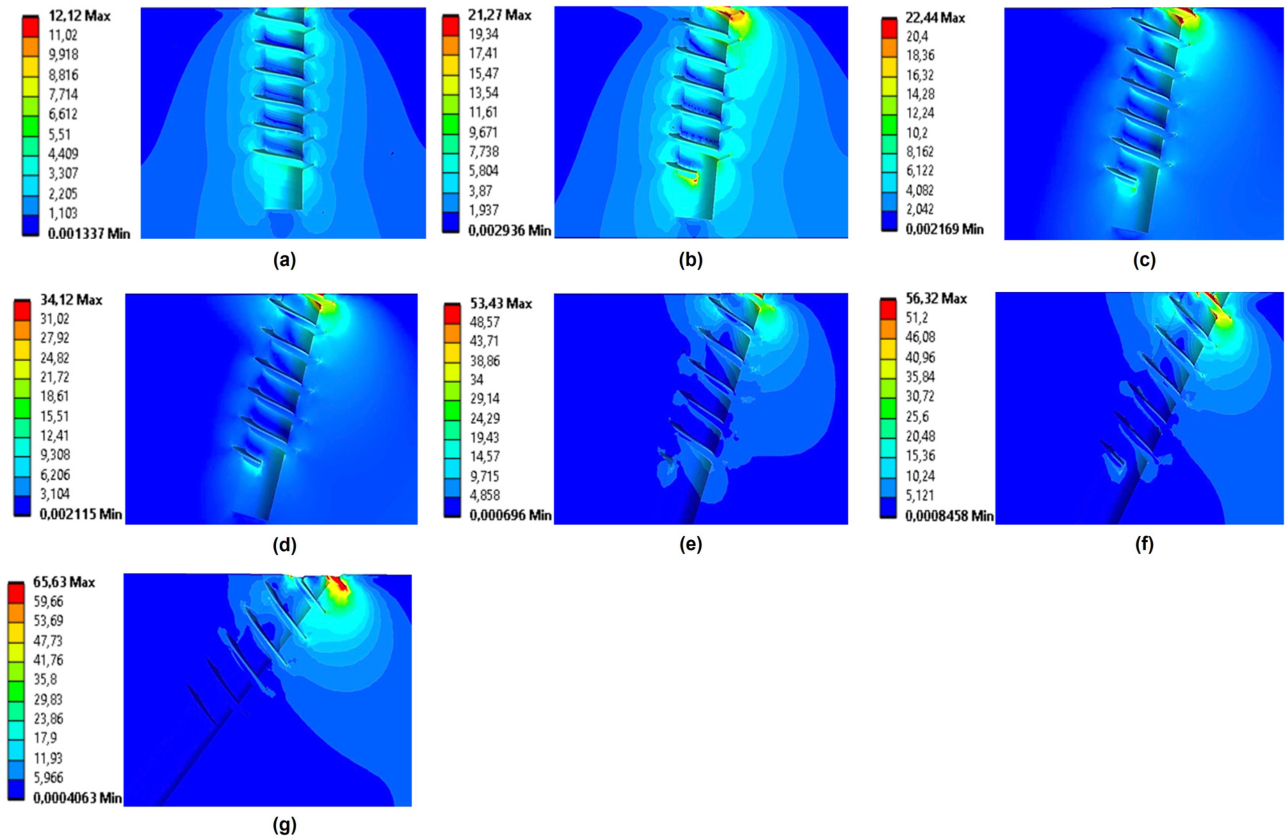

Figure 9: Stress distributions (MPa) obtained in the case of applying a pull-out force in the vertical direction on screws inserted at different angles are a) 0°, b) 5°, c) 10°, d) 15°, e) 20°, f) 30°, and g) 40°.

The screws positioned at an angle the axial direction have higher pull-out forces than the vertical one. The highest force is determined at 273 ± 6.8 N on the model when screws are inserted at the highest angle (40°). The pull-out force was 61 ± 3.5 N in the test specimen inserted vertically in the axial direction and increased by approximately 240 % to 146 ± 4.2 N in the test specimen inserted at an angle of 5°. The pull-out force increased to 206 N when the screw is placed at an angle of 10°. Patel et al. similarly, in the pull-out study conducted by polyurethane (PU) foam ($d = 0.16$ g/cm^3), found that 120 N pull-out force was obtained when the screw insertion angle was 0°, while a 200 N force was obtained in the test specimen where the screw was placed at 10° angle. In the study, it was concluded that a decrease in the pull-out force was observed due to the breaks in the foam at higher screw placement angles [16]. The rate of increase in pull-out force in test samples fabricated with FDM type 3D printer is high at 10° screw insertion angle. However, the rate of increase in pull-out force decreases at insertion angles above 10°. While the pull-out force was 261 ± 7.1 N in the test specimen inserted at an angle of 30°, the pull-out force increased to 273 ± 6.8 N when the screw insertion angle was is 40°. When the experimental results in Figure 5 are examined, it is seen that the axially angled placement of the screws increases the applied pull-out force. Increasing the pull-out force of the screw will positively affect the stability of the fixation.

When the analysis results shown in Figures 8 and 9 are examined, it is seen that the stress values increase with increasing screw insertion angle. In the test specimen inserted at an angle of 0°, the stress is concentrated at screw thread's contact with bone, while as the angle increases, the stress shifts to the base of the thread and body of the screw. Examining the points of concentration of stress in angular models with vertical tensile force applied, it is seen that there is a compression force between the screw body and the model. In this case, it is seen that higher force is needed for the screw to pull-out. Moreover, angled placement of the screws increases the rigidity of the fixation by increasing the area in contact with the cortical bone [10].

Although there are not many studies on this subject in the literature, references to pull-out forces have been made in plate and screw application and studies with various angles. Bekler et al. reported that screws applied to the plates as divergent and convergent (at 15 and 30°) can be more stable [29]. In addition, in studies with locked versus nonlocking plates and angled versus nonangled screws, it has been seen that the pull-out force in variable angle locking screw applications is more resistant to rotation than parallel and fixed angle applications [30], [31]. In the study of Robert et al., pull-out resistance decreased at 10 and 20°, while fixation strength increased at 30° [32]. In our study, however, as the screw angle increased, the pull-out force increased relatively, a decrease was observed at only 20°, and increased again in the following 30 and 40° angles. It could be meaningful for clinicians to consider the insertion of screws at an angle to the plate rather than perpendicularly, which might increase stability and fixation strength of the fixation.

There are some limitations to this study. First, we used models with screws but no plates/screw constructs with locking and nonlocking screws at different angles so results could potentially differ. In the next stage of our study, screw application through locking and nonlocking plates will be tested. Second, the effect of bicortical versus unicortical screw application, screw length and number of cortices involved, to the pull-out strength, has not been tested as it could affect biomechanical behavior, which will be tested in the next stage.

4 Conclusions

Both methods of FEA and 3D printed model testing showed increase in pull-out strength of screws as the insertion angle increases. The tensile force applied during the pull-out test affects the body as well as the screw threads. We believe that long bone fracture fixation with plate and screws constructs, inserting the screws at an angle will increase the stability of the fixation.

Research ethics: Not applicable.

Author contributions: Osman İYİBİLGİN: Finite element analysis and manuscript writing preparation; Engin GEPEK: Finite element analysis and experiments; Levent BAYAM: study planning and Manuscript writing preparation; Efstathios Drampalos: Writing the article and making corrections and comments; Amer Shoaib: Writing the article and making corrections and comments.

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Data availability: The raw data can be obtained on request from the corresponding author.

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Amer Shoaib

Amer Shoaib is a consultant orthopedic surgeon at Manchester University Hospital NHS Foundation Trust, UK, specializing in surgery and conditions of the foot and ankle. His practice centers around foot and ankle surgery from bunions to ankle arthritis. He uses keyhole surgery for bunions, ankle pain, and Achilles tendon injuries. He also deals with complicated limb injuries and deformities with circular frame external fixators. He teaches courses run by the British Orthopedic Foot and Ankle Society and gives lectures for the British Limb Reconstruction Society. He has also worked in several war zones for charities to treat casualties.