EXPERIMENTAL STUDY

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Biomechanical effect of medial cortical support and medial screw support on locking plate fixation in proximal humeral fractures with a medial gap: a finite element analysis

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Objective: This finite element analysis aimed to examine the effect of medial cortical support and medial screw support on loads at the implant-bone interface of locking plate fixation of proximal humeral fractures with a medial gap.

Methods: An intact humerus from a healthy volunteer was used as the basis for a 3-dimensional (3D) computer-aided design (CAD) model. The 3D CAD model of the locking plate system was based on information in the manufacturer's catalogue. The proximal part of the humerus was osteotomized to create standard three-part fractures, which were then divided into a –MSC group (which lacked medial cortical support, and in which fractures with a 5-mm medial bone gap simulated this lack) and +MCS group (which had medial cortical support, and in which fractures with medial cortical-to-cortical contact simulated this). Both fracture groups were respectively fixed with either +MSS (in which medial screw support was simulated by the addition of two calcar screws to the locking plate system), or with –MSS (in which the lack of medial screw support was simulated by absence of the two additional calcar screws to the locking plate system). All the modeling was conducted to represent 90° arm abduction.

Results: On the screw-bone interface, medial screw support and medial cortical support decreased maximum shear stress by 17% and 23% respectively. On the locking plate, medial screw support and medial cortical support decreased maximum von Mises stress by 11% and 22% respectively. However, a combination of these two appeared to decrease maximum shear stress by 56% for the screw-bone interface, and maximum von Mises stress by 54% for the locking plate.

Conclusion: Placement of calcar screws combined with good medial cortical contact in varus in locking plate fixation of proximal humeral fractures with a medial gap may provide optimal stability for the fixation.

Keywords: Biomechanics; finite element analysis; locking plate; shoulder fractures.

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Proximal humeral fracture accounts for 10% of all fractures,[1] and its incidence has been increasing by 15% per year.[2] It is the third most common fracture among the elderly, and a major cause of pain and disability.[3] While satisfactory results can be achieved with conservative treatment in 80% of cases,[4] surgical intervention is generally accepted in some unstable fractures, especially comminuted and osteoporotic cases, because of high nonunion rates (5% to 23%) in conservative treatment.[5] With the advent of locking-fixation, attention has turned to its use in repair of proximal humeral fractures.[6] Locking plates offer adequate mechanical support compared with conventional plating,[7] blade plating,[8] or intramedullary humeral nail,[9] and have shown superior outcomes over other means of fixation methods in patients.[10-12]

However, clinical studies evaluating the outcomes of patients treated with locking plates for proximal humeral fractures with medial cortex comminution have shown failure rates as high as 28.9%,[13-15] with one typical failure mode being subsidence of the fracture into varus with subsequent intra-articular screw penetration.[16,17] A lack of medial support may be one possible cause of this.[18,19] In fact, the presence or absence of medial support has been described as a significant predictor of loss of plate fixation.[20,21] There are two solutions to this problem. One is fracture fragments being fixed operatively in varus malreduction under surgeon control to obtain medial cortical-to-cortical contact, and thus medial cortical support.[22,23] The second is insertion of one or two screws, commonly referred to as calcar screws, to run tangentially to the medial curvature of the humeral surgical neck to obtain medial screw support.[24] Yet even with the use of additional calcar screws, screw penetration rates still range from 6% to 8%.[25]

To date, few biomechanical studies have been done on how these two forms of medial support can offer optimal stability of locking plate fixation in proximal humeral fractures with a medial gap. This finite element analysis (FEA) aimed to systematically examine the effect of medial cortical support and medial screw support on loads at the implant-bone interface of locking plate osteosynthesis for proximal humeral fractures with a medial gap.

Materials and methods

Finite Element Analysis

Computer-aided design (CAD) models– The intact humerus of a healthy volunteer aged 66 years and weighing 61 kg was fully scanned using a Siemens dual-source 64-slice spiral CT. The cross-sectional images were performed at 0.699 mm, saved in DICOM format, and then imported to Mimics Medical Imaging Software (The Materialise Group, Leuven, Belgium) for generation of the 3-dimensional (3D) model. Meanwhile, 3D CAD models of the locking plate system (PHILOS, Synthes, Oberdorf, Switzerland) were modelled using SolidWorks 2013 (SolidWorks Corp., Dassault Systemes, Concord, MA, USA).

Assembly of component parts– The 3D CAD models of the intact humerus were exported to SolidWorks CAD software, and the proximal part of the humerus was osteotomized to create a three-part fracture involving the surgical neck and greater tuberosity. In order to explain the biomechanical effect of presence or absence of medial cortical support on the locking plate for proximal humeral fractures with a medial gap,[23] we had this 3D model of a 3-part humeral fracture re-modelled as a +medial cortical support (+MSC) group of 3-part humeral fractures, in which there was medial cortical-to-cortical support, and a –medial cortical support (–MCS) group of similar fractures, in which a 5 mm medial bone gap simulated a lack of medial support. In each construct described above, a fracture repair was implemented using a locking plate with nine screws (six proximal screws anchored in the humeral head, and three distal screws). The plate fixations were then divided into two different constructs as follows: 1) the +medial screw support (+MSS) construct, in which there is locking plate fixation with two additional calcar screws, and 2) the -medial support screw (–MSS) construct, in which there is locking plate fixation only. For this study, the screws were modelled as smooth, conically-tipped cylinders of diameter 3.5 mm. The length of the screws was adjusted individually so that the screw tip lay exactly 2 mm within the surface of the humeral head, thus simulating optimal surgical fixation. In order to improve solution time, the range of the distal cancellous bone and cortical bone was removed. An illustration of the four different fixation models is shown in Fig. 1. All four models were then imported to ANSYS Workbench 14.0 (ANSYS, Inc., Canonsburg, PA, USA) for FEA.

Meshing and material properties– All the assembled fixation models were meshed using the Solid 187 element of the ANSYS software. The Solid 187 element, a 10-node tetrahedral element, was shown to be accurate in modelling 3D geometries of irregular shape. A test to gauge the mesh sensitivity for the assembled models was conducted by studying the response of a series of meshes of increasing refinement under the same applied load. The refinement was performed using the 'relevance' utility in ANSYS Workbench. Mesh relevance values

Fig. 1. 3D computational models of four different repair nodes: **(a)** Fracture repair node lacking both medical cortical support (–MCS) and medial screw support (–MSS). **(b)** Fracture repair node with medial screw support (+MSS), but lacking medial cortical support (–MSS). **(c)** Fracture repair node with medial cortical support (+MCS), but lacking medial screw support (–MSS). **(d)** Fracture repair mode with both medial cortical support (+MCS) and medial screw support (+MSS). [Color figure can be viewed in the online issue, which is available at www.aott.org.tr]

range from 0% (coarse mesh) to 100% (very fine mesh). A mesh with a relevance of 95% was chosen as optimal, since it provided marginal change in stress and strain values of less than 1%. The current study used 1 mm as the mesh planning element size (Fig. 2). The total nodes and elements were: 392071 and 235483 (model A), 418020 and 246599 (model B), 406455 and 244122 (model C), and 426825 and 255872 (model D). The humerus was modelled as isotropic, linearly elastic, heterogeneous material with material properties for cortical bone (E=12 GPa, v=0.3) and cancellous bone (E=0.8 GPa, v=0.3).[26] The locking plate system was made from titanium alloy (E=110GPa, v=0.3).

FEA boundary conditions– Contact interactions between the humeral shaft and the greater tuberosity fragment, the humeral shaft and the articular fragment, and between the greater tuberosity and the articular fragment were defined using surface-to-surface finite sliding with a coefficient of friction of 0.3.[27] To mimic the commercially designed "locking plate", contact interactions were defined as no movement along the interfaces of screw and surrounding bone; screw and plate; and cortical bone and cancellous bone.

The boundary condition of each fixation model was to define all the nodes on the cross- section of the distal end of the humerus, and to set all their degrees of freedom at zero, with the assumption that the distal end was fixed. All models were inclined 52.5° to the vertical and a distributed load of 543 N was applied to the articular surface (Fig. 3). These boundary conditions replicated physiological loads on the proximal humerus at 90° abduction.[28] After the analysis model described above was solved, shear stresses were considered in order to provide a complete description of stress in the bone and screw.

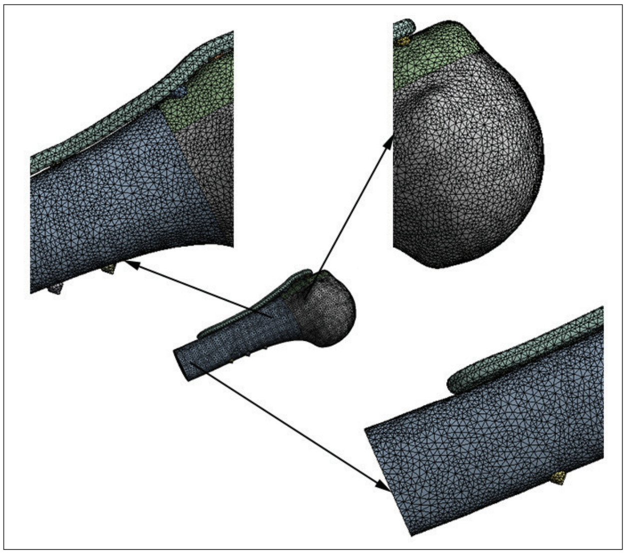

Fig. 2. Illustration of analysis model after meshing with Solid 187 element. [Color figure can be viewed in the online issue, which is available at www.aott.org.tr]

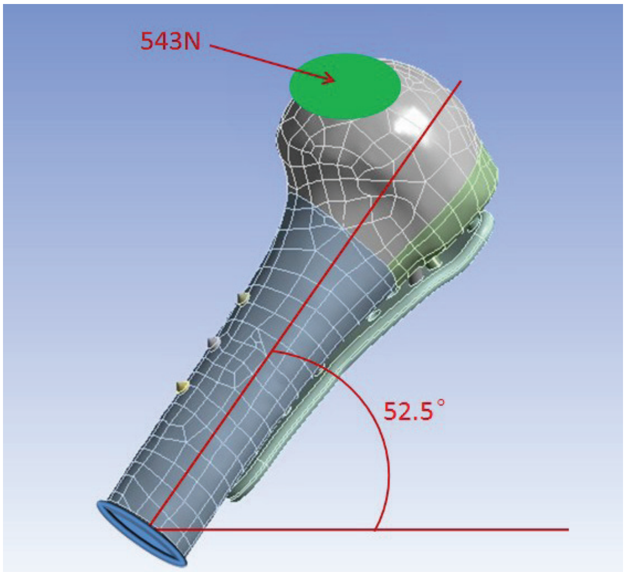

Fig. 3. Fracture fixation and loading. [Color figure can be viewed in the online issue, which is available at www.aott.org.tr]

Maximum shear stresses along screw-bone interfaces particularly indicate possible screw pullout. In addition, von Mises stresses on the plate were also considered in order to provide peak stress distribution.

In summary, we studied two types of medial fracture fragment fixation modes (with and without medial cortex-to-cortex contact) and two types of calar screw fixation modes (with or without the insertion of calcar screws running tangentially to the medial curvature of the humeral surgical neck) at the loading condition of 90° arm abduction after three part fractures with a medial gap following locking plate osteosynthesis.

Results

Maximum shear stress of screw-bone interface– Shear stress of the screw-bone interface in the four models is shown in Fig. 4. The basic model (without medial cortical support and without medial screw support) shows a maximum shear stress of 1.69 MPa (Fig. 4a). In the presence of medial screw support, maximum shear stress

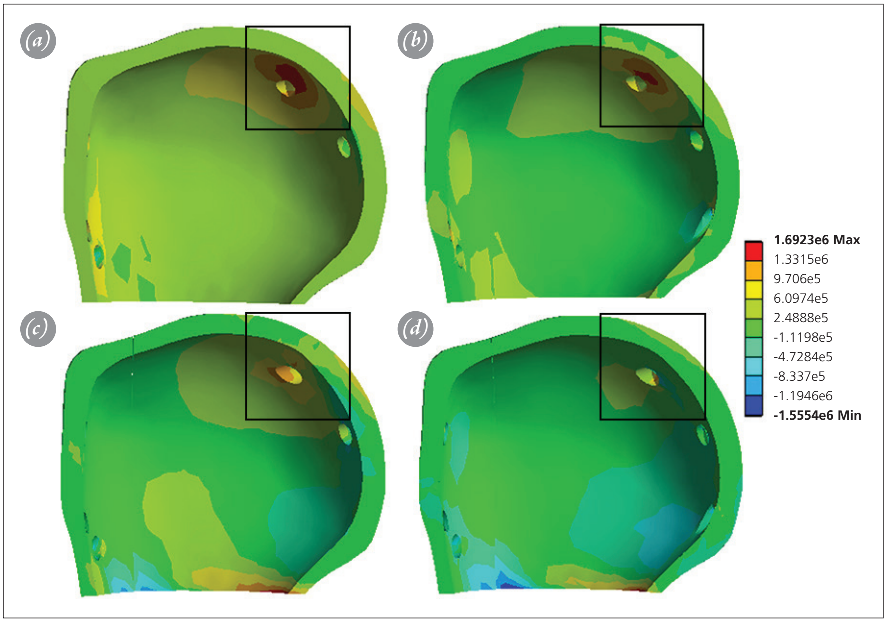

Fig. 4. Maximum shear stress of screw-bone interface: **(a)** Model A; 1.69 MPa, **(b)** Model B; 1.41 MPa, **(c)** Model C; 1.29 MPa, and **(d)** Model D; 0.75 MPa. [Color figure can be viewed in the online issue, which is available at www.aott.org.tr]

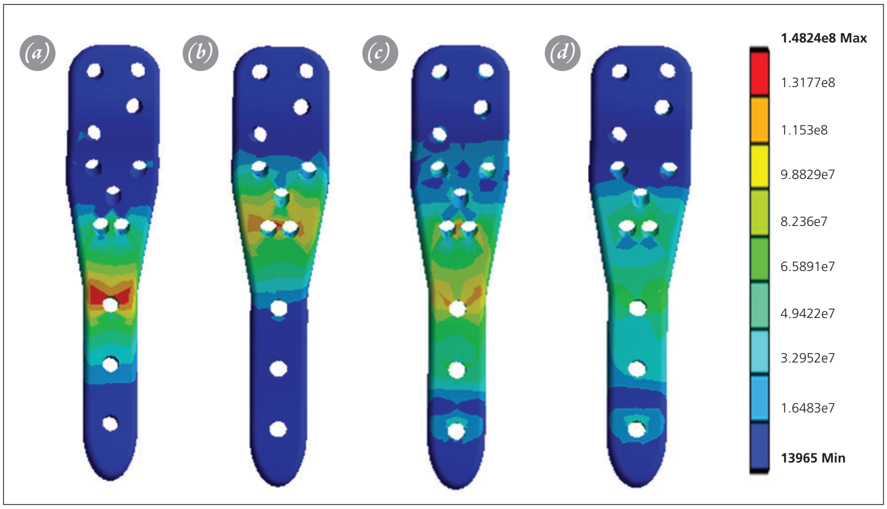

Fig. 5. Maximum von Mises stresses of the locking plate. **(a)** Model A; 148.24 MPa, **(b)** Model B; 132.01 MPa, **(c)** Model C; 116.83 MPa, and **(d)** Model D; 68.58 MPa. [Color figure can be viewed in the online issue, which is available at www.aott.org.tr]

around the screw holes in the medial fracture fragment decreased by 17% from 1.69 to 1.41 MPa (Fig. 4b). In the presence of medial cortical support, maximum shear stress around the screw hole in the articular fragment decreased by 23% from 1.69 to 1.29 MPa (Fig. 4c). When both supports were present, maximum shear stress around the screw hole in the medial fracture fragment significantly decreased, by 56% from 1.69 to 0.75 MPa (Fig. 4d).

Maximum von Mises stress on the locking plate: Von Mises stresses on the locking plates are shown in Fig. 5. A maximum von Mises stress of 148.24 MPa is seen in the basic model A, where the distribution of this stress is around the first distal screw hole (Fig. 5a). In the presence of medial screw support, the maximum von Mises stress decreased by 11% from 148.24 to 132.01 MPa, and appeared between the two calcar screws holes (Fig. 5b). In the presence of medial cortical support, the maximum von Mises stress decreased by 22% from 148.24 to 116.83 MPa, and occurred around the first distal screw hole and between the two calcar screws holes (Fig. 5c). When both supports were present, the maximum von Mises stress around the first distal screw hole and between the two calcar screws holes significantly decreased, by 54% from 148.24 to 68.58 MPa (Fig. 5d).

Discussion

This study provides, for the first time, a computational measurement of the effect of medial cortical support and medial screw support on the mechanical behavior of locking plate osteosynthesis for proximal humeral fractures with a medial gap, focusing on the maximum shear stress of screw-bone interface and the maximum von Mises stress on the locking plate at 90° arm abduction. Additional calcar screws to obtain medial screw support (model B) resulted in a 17% reduction in the maximum shear stress at the screw-bone interface, and a 11% reduction in the maximum von Mises stress on the locking plate. Medial cortical contact, achieving medial cortical support (model C), resulted in a 23% reduction in the maximum shear stress at the screw-bone interface and a 22% reduction in the maximum von Mises stress on the locking plate. The combination of these two medial supports (model D) resulted in a 56% reduction in the maximum shear stress at the screw-bone interface, and a 54% reduction in the maximum von Mises stress on the locking plate. Any reduction in stress on these stress concentration areas will reduce the likelihood of fixation failure.

Clinically, fixation failure has been linked to the absence of medial support in locking-plate fixation of proximal humeral fractures.[18,19,29] Continuous varus stress of the rotator cuff may result in varus displacement of the humeral head and collapse of the articular surface during early rehabilitation, when the fracture fails to achieve medial cortical contact. The high incidence of screw perforation may be secondary to the rigidity of the implant in combination with medial inadequate support.[21,25] In the current study, the lack of medial support (model A) resulted in extremely high cortical bone stress surrounding the screw hole. The lack of medial support also resulted in extremely high locking plate stress around the first distal screw hole, indicating a high potential for locking plate breakage. This is a reported clinical failure mode for these devices.[30]

Stable medial support can decrease the likelihood of implant-related fixation failure and achieve excellent clinical outcomes in proximal humeral fractures. On the one hand, some surgeons tend to avoid placement of calcar screws, especially when done percutaneously in minimal invasive plating, due to the increased the risk of lesions to the axillary nerve and delayed union.[31] Although calcar screws may increase the risk of screw pullout due to stiffening of the osteosynthetic construct,[32] recent clinical data suggested that an increased risk for screw pullout could not be observed.[24] A cadaveric biomechanical study found that the grasping force of a screw inserted under the subchondral bone of the medial and inferior region was comparably stronger than that of a screw placed either in the middle of the humeral head or in the lateral and superior region.[33] We found that medial screw support resulted in a 11% reduction in the maximum shear stress at the screw-bone interface, but that the shear stress concentration surrounding screw tips still appeared to indicate a potential for screw pullout under cyclic daily activities load. On the other hand, a biomechanical study using a synthetic two-part fracture model evaluated the stability of medial cortical support only, and found that a medial cortical contact construct can achieve better biomechanical stability in shear and axial stiffness than a construct with the loss of medial support removing medial cortex.[23] This is similar to the findings of our study, but we found that the stress concentration areas of the cortical bone surrounding the screw, and of the locking plate around the first distal screw hole also appeared.

In order to offer optimal stability in locking plate fixation of proximal humeral fractures with a medial gap, it is suggested that, in combination with good medial cortical contact in varus, the placement of calcar screws in the inferomedial region of the proximal humerus fragment be considered to decrease the apparent risk of fixation failure. In the present study, medial support by the placement of medial calcar screws combined with medial cortex-to-cortex contact resulted in a big reduction in the maximum stress at the screw-bone interface and on the locking plate, and distributed the stress concentration areas well. Our study is supported by other clinical studies based on anatomical reduction of fracture fragments showing that additional placement of medial support screws in 3- and 4-part fractures can help to maintain mechanical stability and improve functional outcomes.[34,35]

The present study has many limitations. First, the use of a simplified load to replicate the forces at 90° arm abduction on the proximal humerus with no muscle simulation included has been reported.[27,28] However, a previous finite element analysis of a shoulder joint reported peak stresses occurred at 90° arm abduction,[36] so we have only evaluated the stability of two medial supports at the loading condition of 90° arm abduction. Secondly, we have focused on the stability of proximal humeral fracture fixation at only 0° of varus malreduction, ignoring that at other degrees of varus malreduction, However, models of different degrees of varus malreduction with medial cortical contact have produced only small stiffness differences in two part fractures.[23] Moreover, the effect of bone mineral density (BMD) on the biomedical characteristics of proximal humeral fracture osteosynthesis was not considered in the present study. Fourthly, this FEA model assumed bone to have linear, isotropic and elastic mechanical properties, thus significantly simplifying the analysis. In reality, non-linearity, anisotropy and viscoelasticity may affect the bulk mechanical behaviour of the humerus. Finally, the effect of the number and position of screws on the stability of locking plate fixation of proximal humeral fractures with a medial gap was not taken into account. These limitations will be simulated in future studies.

In the present FEA of the effect of medial cortical support and medial screw support on the locking plate fixation of the proximal humeral fractures with a medial gap, our study indicated that medial support by calcar screw placement alone, or good medial cortical contact alone, can reduce stress gradients on the bone-screw interface and the locking plate. However, stress concentration still appears at the implant-bone interface. More importantly, when there is a medial fracture gap, the placement of calcar screws in combination with good medial cortical contact in varus resulted in a big reduction in the stress gradients, decreased significantly the likelihood of fixation failure, and provided optimal stability for the fixation.

Conflics of Interest: No conflicts declared.

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