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ORIGINAL ARTICLE

Biomechanical comparison of three fixation methods under axial loading in proximal humerus fractures with medial metaphyseal defect

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ABSTRACT

Objectives: This study aims to compare the biomechanical performance of three different surgical fixation techniques in the treatment of proximal humerus fractures with medial metaphyseal defects.

Materials and methods: A total of 24 synthetic humerus bone models were used and equally divided into three groups (n = 8 per group). A standardized unstable proximal humerus fracture model with a medial metaphyseal cortical defect extending to the surgical neck was created using a three-dimensional (3D)-printed osteotomy guide. Group 1 received fixation with a lateral anatomical locking plate. Group 2 was treated with a combination of a lateral anatomical plate and a medial buttress plate (dual plating). Group 3 underwent fixation with an intramedullary nail (IMN); in this group, four specimens had distal locking with an endopin (Group 3a), and the other four with static screws (Group 3b). All specimens were subjected to axial loading until failure. Forces at the onset of failure and complete failure were recorded, and fracture patterns were documented.

Results: In Groups 1 and 2, transverse fractures consistently occurred at the level of the most distal screw of the lateral plate. In Group 3, failure was observed either proximally or distally at the nail tip, including butterfly fragment formation and metaphyseal collapse. Group 2 exhibited the highest resistance to axial loading, followed by Group 1 and Group 3, with statistically significant differences between all groups ($p = 0.043$, $p = 0.0003$, $p < 0.00001$). No significant difference was found between subgroups 3a and 3b ($p > 0.05$).

Conclusion: Our study results indicate that double plating provides the greatest axial stability in proximal humerus fractures with medial metaphyseal defects, supporting its use in fracture patterns with medial column deficiency. However, as fixation choice should be guided by patient-specific factors and surgical feasibility, these findings should be interpreted in the context of experimental conditions and loading limitations.

Keywords: Axial loading, biomechanical testing, dual plating, fixation methods, intramedullary nail, lateral anatomic plate, medial calcar defect, Proximal humerus fracture.

Proximal humerus fractures constitute approximately 4 to 10% of all fractures.[1] The incidence has increased over time, accompanied by a corresponding rise in fracture-related complications.[2] Owing to the metaphyseal structure of the proximal humerus, even low-energy trauma can result in fracture. Management is often challenging due to the complex shoulder anatomy, which further complicates reduction and immobilization.[2] Besides fracture-related factors, patient and surgeon variables should also guide treatment choice.[3] While most fractures are managed conservatively, comminuted or displaced cases may require surgical fixation such

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as Kirschner wires, plates, intramedullary nails (IMNs), or shoulder arthroplasty.[2,4,5] The ideal fixation method for proximal humerus fractures, as well as the most appropriate implant type and indications, remain subjects of ongoing debate.[6,7] Although locking plates and IMNs are widely used for surgical fixation of proximal humerus fractures, both techniques present specific limitations in cases involving medial cortical disruption.[2,8,9] Recent biomechanical and clinical studies have shown that loss of medial support leads to varus collapse, screw penetration, and fixation failure, even when lateral plating is performed.[10-12] Consequently, the use of a medial buttress plate has been proposed to restore medial column integrity and enhance construct stability.[13-15] Although dual plating has been shown to improve construct stability in several biomechanical settings, comparative data including IMN, particularly in fracture models with standardized medial metaphyseal defects and axial loading, still remain limited.[16,17] Since medial column deficiency is recognized as a critical determinant of fixation instability in complex proximal humerus fractures, developing an experimental model that includes a standardized medial metaphyseal defect enables precise evaluation of fixation stability under controlled axial loading conditions.

In the present study, we aimed to compare the axial load resistance of three fixation techniques-lateral anatomical plate, dual plating (lateral plus medial buttress plate), and IMN-in the treatment of proximal humerus fractures with two-fragment medial metaphyseal defects.

MATERIALS AND METHODS

Study design and study samples

In this study, 24 synthetic humerus models were used (Synbone, No: 5010, Switzerland). As this was an *in vitro* biomechanical study using synthetic materials with no human or animal subjects, a waiver of ethical approval was obtained in accordance with institutional policies for non-human experimental studies. The study was conducted in accordance with relevant institutional and laboratory research guidelines for *in vitro* biomechanical testing.

The sample size (n = 24; 8 per group) was chosen in accordance with prior proximal humerus biomechanical studies where 6 to 10 specimens per group are commonly employed, recognizing that a formal *a priori* power analysis is not feasible in destructive *in vitro* testing.[14,18,19] All the humerus models used are 326-mm long, 22-mm shaft diameter, 47-mm humerus head diameter models that simulate cortical and cancellous bone. All bone models were three dimensional (3D)-scanned using the EXScan Pro_v3.6.0.5 software with an Einscan Shining Pro HD scanner (China) to capture precise external geometry. These data were, then, used to digitally define osteotomy lines and ensure reproducible defect creation across specimens. Custom osteotomy guides were designed using ZBrush 2022 and Ultimaker Cura 4.12.1, and printed on a Raise3D Pro2 (Raise3D, CA, USA) using the Raise Premium ABS filament to resist heat- and vibration-induced deformation during cutting. This methodology ensured consistent osteotomy geometry and minimized operator-related variation. In all specimens, a standardized unstable proximal humerus fracture pattern with a medial metaphyseal cortical defect was created by removing a 1-cm wedge at a 30° oblique angle using a precision bone saw (Stryker Corp., MI, USA). The configuration was designed to model metaphyseal instability associated with medial calcar deficiency. A 30° orientation was selected to replicate the obliquity commonly reported at the metaphyseal-diaphyseal junction in unstable fractures.[20] In addition, a 1-cm wedge defect was created to simulate medial column loss and bone voids frequently described in clinical studies of calcar-deficient fractures (Figure 1).[21]

Surgical technique

All bone models were operated by a senior orthopedic surgeon. A total of 24 bone models were divided into three groups with eight samples in each group. A lateral anatomical proximal humeral plate (Group 1) (Height: 124 mm, TST SAN, Istanbul, Türkiye) was applied to the first group (Figure 2). A medial buttress plate (Group 2) (2.4 mm Y plate, TST SAN, Istanbul, Türkiye) was applied to the second group together with the lateral anatomical proximal humerus plate (Figure 3). A humerus nail (Group 3) (diameter: 7 mm, length: 180 mm, TST SAN, Istanbul, Türkiye) was applied to the third group. While all specimens with humerus nail application were fixed with three screws proximal to the fracture line, four of the distal samples were locked with endopin (Group 3a), and four samples were locked with a distal static screw (Group 3b) (Figure 4).

Biomechanical testing

Axial loading test was planned for all bone models. For mounting the bone models to the testing machine, custom interfaces were designed

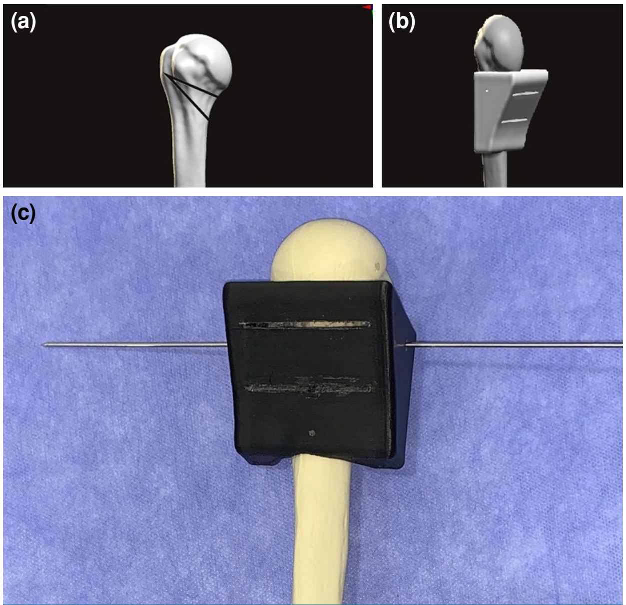

FIGURE 1. (a) 3D scanning of the synthetic humerus model and simulation of the medial metaphyseal fracture line using digital modeling software. **(b)** Digital design of the osteotomy guide based on the scanned humerus model using slicing and modeling software. **(c)** Application of the 3D-printed osteotomy guide on the synthetic humerus model to perform standardized osteotomies at the pre-defined location and angle.

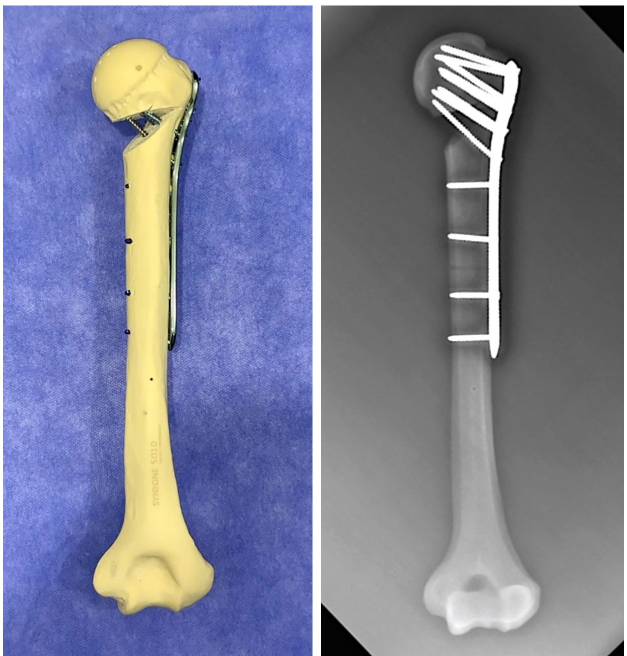

FIGURE 2. Lateral anatomical plate applied bone model.

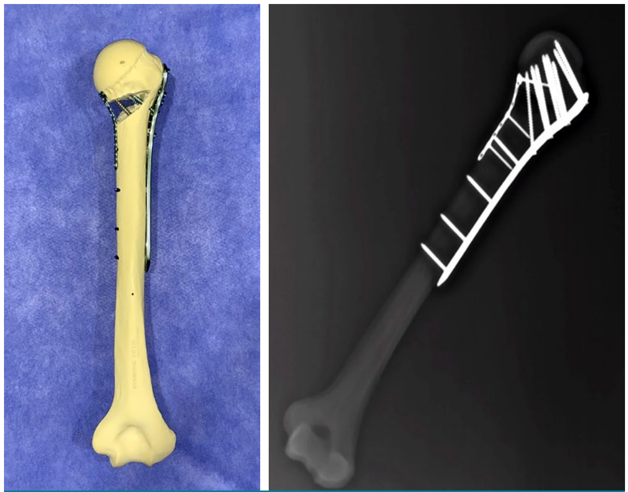

FIGURE 3. Lateral anatomic plate and medial buttress plate (dual plating) applied bone model.

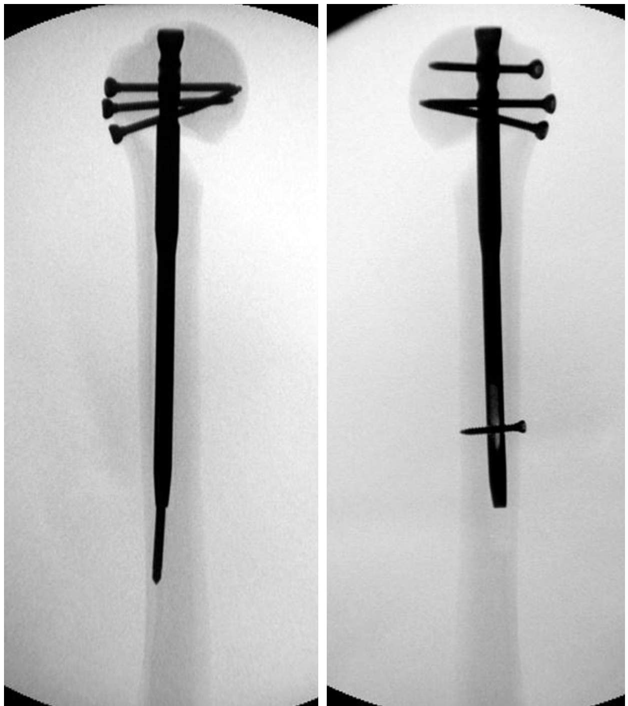

FIGURE 4. Direct radiography of the IMN applied bone model with distal locking by endopin and static screw.
IMN, intramedullary nail.

based on the 3D-scanned geometries and printed on an Ultimaker 2+ (Utrecht, The Netherlands) using Filamentum NGEN material. Print preparation and slicing were performed using IdeaMaker 4.2.3 and Ultimaker Cura 4.12.1 to ensure accurate alignment of the humeral mechanical axis during axial loading (Figure 5). Axial loading tests were carried out in the biomechanical study laboratory (Shimadzu Autograph AGS, Kyoto, Japan) under the supervision of a senior metallurgical and materials engineer.

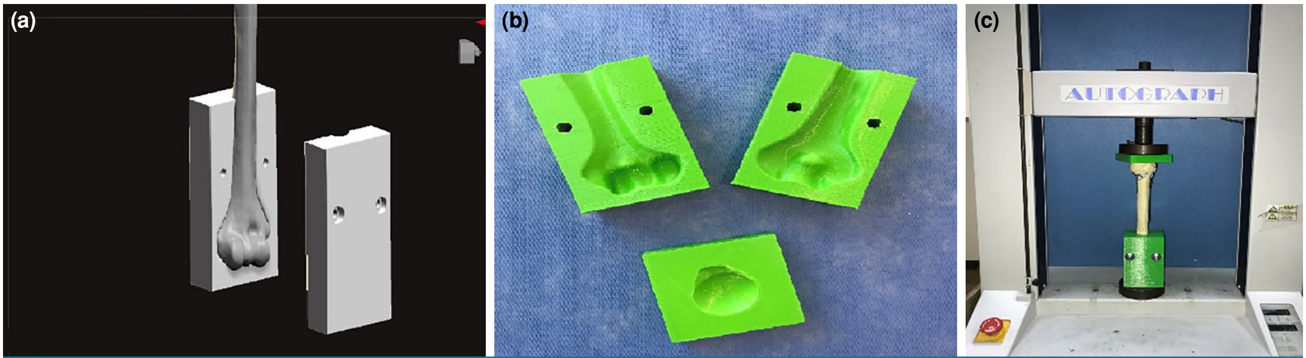

FIGURE 5. (a) Digital design of the interfaces intended to adapt the synthetic humerus models to the axial loading test device. **(b)** 3D-printed interfaces corresponding to the anatomical geometry of the humerus for accurate alignment and fixation during biomechanical testing. **(c)** Experimental setup showing the humerus model mounted on the axial loading test machine using the custom-designed interface components.

Axial force was applied to the specimens at a speed of 10 mm/min, parallel to the mechanical axis of the humerus (Figure 5). The values at the moment of failure begin and the force values (in Newtons, N) at the moment of final failure were recorded using the machine software. During testing, the system simultaneously monitored load and displacement; the first failure was defined as the initial drop in the load–displacement curve indicating loss of construct integrity, whereas the final failure corresponded to complete structural collapse and cessation of load-bearing capacity (Figure 6). However, only the force values at the onset and final failure were analyzed to compare fixation stability among groups. A representative load-displacement curve illustrating the typical elastic and failure behavior of the specimens has been provided. Testing was performed until catastrophic failure of either the bone model or the fixation construct, defined as the abrupt loss of load-bearing capacity.

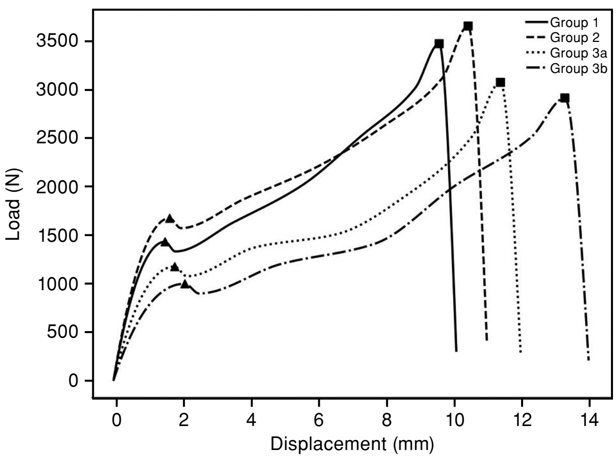

FIGURE 6. Representative load-displacement curves obtained during axial loading for each fixation group. One specimen representative of each group is shown. Triangle markers (▲) indicate the onset of failure, defined as the first measurable drop in load during continuous loading, and square markers (■) indicate the final failure, corresponding to complete loss of load-bearing capacity and termination of the test.

Stiffness (N/mm) was calculated from the linear elastic region of the load-displacement curve as the slope (Δload/Δdisplacement) before the onset of failure.

Statistical analysis

Statistical analysis was performed using the SPSS version 25.0 software (IBM Corp., Armonk, NY, USA). The normality of the distribution was determined by the Kolmogorov-Smirnov test. Descriptive data were presented in mean ± standard deviation (SD), median (min-max) or number and frequency, where applicable. The comparison of the difference between the independent groups with normal distribution was determined by the independent sample t-test. A p value of <0.05 was considered statistically significant

RESULTS

The location and shape of the fracture line resulting from axial loading in all groups were analyzed observationally. Accordingly, in all specimens in Group 1, the fracture line formed after loading was at the level of the distal of the lateral proximal humerus anatomical plate and at the level of the most distal locking screw. The resulting fracture was in the form of a transverse fracture in all

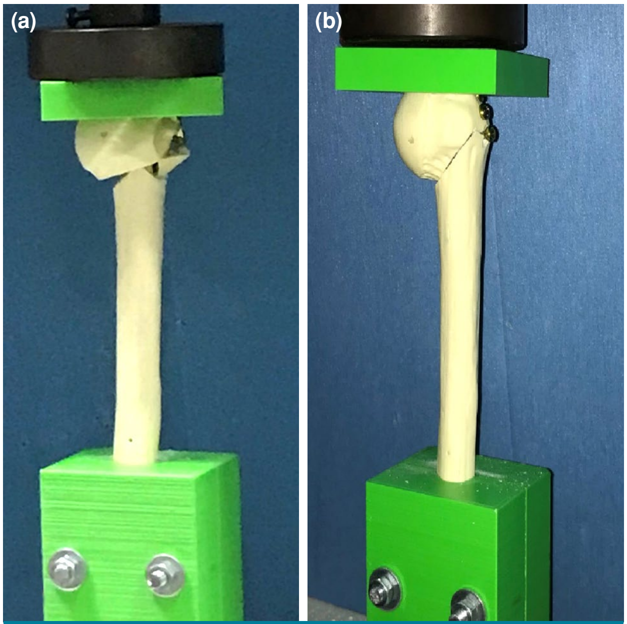

FIGURE 7. (a) Butterfly fragment formation observed at the level of the proximal locking screws during axial loading in an intramedullary nail applied specimen. **(b)** Collapse at the medial metaphyseal defect region during the loading test in another IMN-applied specimen.

samples in Group 1. Similar to Group 1, the fractures that occurred after loading were at the distal level of the lateral anatomical plate and at the level of the most distal locking screw in all the specimens in Group 2, where dual plating was applied. In Group 3, where IMN was applied, the fracture line formed after loading in one of the samples was at the level of the proximal locking screws and formed a butterfly fragment. In another sample, disruption of the system was observed in the form of collapse of the defected region in the medial metaphysis created on the bone model before the application of IMN. An oblique fracture line was formed from the distal level of the nail during the loading test in one sample of Group 3a, whose distal fixation was performed with endopin (Figure 7). In all other specimens with IMN, the fracture line was at the distal level of the nail and in transverse shape.

The loads at the time (in N) when the system started to fail and at the time the bone model broke were recorded in all samples. When the forces encountered by the samples at the time of the first failure were compared between the groups, a statistically significant difference was observed between Group 1 *vs.* Group 2 $p = 0.02$; Group 1 *vs.* Group 3 $p = 0.002$; Group 2 *vs.* Group 3 $p < 0.00001$ (Table I). No statistically significant difference was observed between Group 3 subgroups at the time of the first failure ($p = 0.14$) (Table I).

In the comparison of all groups at the moment of final failure, the failure load in Group 2 was found

TABLE I
Statistical analysis of forces between specimen groups at the start of failure

	Sample size (n)	Mean±SD	Min-Max (N)	*p*
Group 1	8	1420±200.64	1142-1630	0.02*¶
Group 2	8	1662.5±153.45	1479-1879	0.002*†
Group 3	8	1076.62±165.18	910-1445	< 0.00001*¥
Group 3a	4	1165±192.07	1023-1445	0.14‡
Group 3b	4	988.25±77.08	910-1084	

SD, standard deviation; * p < 0.05; ¶ Group 1 *vs.* Group 2; † Group 1 *vs.* Group 3; ¥ Group 2 *vs.* Group 3; ‡ Group 3a *vs.* Group 3b.

TABLE II
Statistical analysis of forces between specimen groups at the moment of fracture

	Sample size (n)	Mean±SD	Min-Max (N)	*p*
Group 1	8	3456.44±191.14	3160.5-3730	0.043*¶
Group 2	8	3638.44±129.79	3501.5-3812	0.0003*†
Group 3	8	2978.56±214.73	2750-3412.5	< 0.00001*¥
Group 3a	4	3058.75±278.12	2763-3412.5	0.32‡
Group 3b	4	2898.38±114.4	2750-3020.5	

SD, standard deviation; * p < 0.05; ¶ Group 1 *vs.* Group 2; † Group 1 *vs.* Group 3; ¥ Group 2 *vs.* Group 3; ‡ Group 3a *vs.* Group 3b.

TABLE III
Statistical analysis of stiffness values between specimen groups

	Sample size (n)	Mean±SD	Min-Max (N/mm)	*p*
Group 1	8	331.11±16.28	298.86-350.46	< 0.01*¶
Group 2	8	342.94±19.1	317.07-368.07	0.1†
Group 3	8	237.62±46.75	130.77-284.9	< 0.01*¥
Group 3a	4	255.2±23.05	236.09-284.9	0.16‡
Group 3b	4	220.03±61.18	130.77-263.11	

SD, standard deviation; * p < 0.05; ¶ Group 1 *vs.* Group 2; † Group 1 *vs.* Group 3; ¥ Group 2 *vs.* Group 3; ‡ Group 3a *vs.* Group 3b.

to be significantly higher than in Group 1, and both Groups 1 and 2 demonstrated significantly greater failure loads compared to Group 3, indicating statistically significant differences ($p < 0.05$) (Table II). However, no significant difference was observed between the subgroups of Group 3 (Groups 3a and 3b) ($p = 0.32$).

According to inter-group comparisons, the stiffness in Group 3 was significantly lower than in Group 1 and Group 2 (Table III). However, the intra-group analysis revealed no significant difference between Group 3a and Group 3b subgroups (p = 0.16) (Table III).

DISCUSSION

In the present study, we compared the biomechanical performance of three different surgical fixation techniques in the treatment of proximal humerus fractures with medial metaphyseal defects. The primary finding of this study was that dual plate fixation provided the highest stability under axial loading in proximal humerus fractures with medial metaphyseal defects. These findings suggest that dual plate fixation may provide enhanced stability under axial loading in proximal humerus fractures with medial metaphyseal defects and can be considered a biomechanically advantageous option in fractures with medial column insufficiency.

The treatment of unstable proximal humerus fractures presents multiple challenges to surgeons. In fracture types with medial metaphyseal cortex insufficiency, varus collapse, screw cut-out, and fixation loss may occur.[8,9] Although locking plates are effective in these cases, they are not always sufficient. Reduction loss has been reported in one third of cases where the medial support screw was not used.[8] Mechanical support of the medial column is, therefore, crucial until union is achieved. Medial support plating may be required when the medial cortex is absent, the neck–shaft angle is < 120°, or a medial metaphyseal defect or head-splitting fracture exists.[10,11] The continuity of the medial hinge also plays a role in humeral head perfusion; however, ischemia does not always result in collapse. In 80% of patients evaluated with laser Doppler flowmetry, no collapse occurred despite an "ischemic head".[12] Thus, fixation should still be attempted, particularly in younger patients, even when ischemia is suspected.

Previous biomechanical studies have examined the strength of different surgical techniques under cyclic loading, bending, and torsional forces.[13,14] Finite element analyses have shown that double plating can provide biomechanical advantages over single-plate fixation; however, such models typically simplify soft-tissue forces and boundary conditions, which should be considered when interpreting results across experimental settings.[2,15,16] These simulations apply controlled loading to approximate clinical conditions, yet they cannot fully capture the complexity of time-dependent muscle activation patterns.[16] Accordingly, axial loading was selected in the present study as a controlled and reproducible loading condition to allow isolated comparison of fixation constructs, rather than as a comprehensive simulation of physiological shoulder mechanics. In the present study of proximal humerus fractures with medial metaphyseal defects, specimens treated with a lateral anatomical plate plus a medial support plate exhibited the highest resistance to axial load. Medial plating contributed substantially to construct stability and restoration of the medial column. However, this technique requires additional soft-tissue dissection, which may place critical neurovascular structures at risk.[22,23] Furthermore, medial plating may compromise the already reduced vascular supply to the proximal humerus due to the fracture itself.[24] Although only axial loading was evaluated in this study, future work incorporating cyclic, torsional, and bending forces that better approximate dynamic muscle activity is warranted to provide a more comprehensive assessment of construct behavior. While these approaches provide valuable information about construct performance, accurately reproducing dynamic muscle co-contractions and soft-tissue constraints remains challenging, and necessary model simplifications limit direct translation to physiologic conditions. Lateral anatomical plates, shaped according to the proximal humerus and providing multi-angle locking options, are widely accepted as the primary fixation choice for proximal humerus fractures.[25] Recent studies have highlighted that additional medial column fixation and double plating may offer certain biomechanical advantages, and this concept is gaining wider acceptance.[26] The main indication for medial support plate augmentation is a severe medial defect where the lateral plate alone cannot ensure sufficient support.[15,24] The reported incidence of unstable proximal humerus fractures requiring a medial plate ranges between 11% and 25%.[27,28] In the present study, specimens with medial support plates demonstrated greater resistance to axial loading than those with lateral plates or IMN, confirming the stabilizing role of medial plating in such fracture patterns.

Intramedullary nail fixation offers several advantages, including minimal soft-tissue disruption, reduced blood loss, and shorter operative time.[29] However, it also has inherent disadvantages such as the risk of rotator cuff irritation during entry portal creation and potential radial nerve injury during distal locking.[30,31] Although modern IMN designs have improved with optimized entry portals and enhanced locking mechanisms, these implants still allow a limited number of proximal screws, which restricts fixation in the humeral head region, and may limit the ability to achieve sufficient calcar support.[30,31] In the present study, IMN specimens demonstrated lower axial load resistance compared with plate-based constructs, and failure was frequently observed either around the proximal locking region or at the distal nail level in the presence of a medial metaphyseal defect. While the ultimate fracture lines were often located distally, the current experimental setup does not allow definitive determination of the exact initiation site or stress propagation pathway. Therefore, the reduced number and angular spread of proximal screws should be interpreted as a literature-supported biomechanical limitation rather than a direct causal finding of the present experiment.[30,31]

Stiffness is defined as the resistance of a material to deformation under applied force and is related to the structural organization rather than the material composition itself.[32] Although only peak failure loads were presented, the recorded load-displacement data exhibited consistent elastic and failure behavior across groups, confirming the reliability of the comparative findings. Future biomechanical studies should include detailed curve analyses to better define the elastic limit, yield point, and overall deformation characteristics of different fixation constructs. Michel et al.[32] demonstrated that, in open reduction and internal fixation, adding a second plate increased torsional stiffness without major deformation under compression. They also reported that single locking plates demonstrated higher stiffness compared with dual non-locking plate configurations under axial and extra-axial bending loads. Although the plate configurations differ from those in the present study, their findings highlight that the specific design and locking mechanism of plates substantially influence construct stiffness.[32] Increasing stiffness not only strengthens the construct, but also promotes faster fracture healing, reducing the risk of delayed or nonunion.[33] Although stiffness values were higher with dual plating in this study, the choice between single and double plating should ultimately depend on the fracture pattern and patient-specific factors. Although synthetic bone models do not fully replicate the elastic properties or load-bearing behavior of human bone, the use of identical homogeneous specimens across all groups ensured consistent baseline mechanical characteristics. Thus, the relative differences in failure load and stiffness among the fixation methods remain reliable for comparative interpretation.

Nonetheless, several limitations of this study should be acknowledged. The main limitation of this study is that only axial loading was evaluated, without simulating other physiological forces acting on the proximal humerus. Therefore, the performance of fixation methods under more complex loading conditions could not be fully assessed. However, axial loading was selected as a controlled and reproducible testing condition to allow isolated comparison of construct stability in the presence of a medial metaphyseal defect, rather than to replicate the full spectrum of *in vivo* shoulder biomechanics. Although synthetic bone models allow excellent reproducibility and eliminate biological variability, their absolute load-bearing capacity differs from that of cadaveric or living bone. Nevertheless, the use of identical homogeneous specimens across all groups minimized variability and ensured valid comparison among fixation methods. Moreover, although the testing setup was capable of recording displacement, only the force data at the onset and final failure were analyzed for consistency and clarity. Future studies incorporating full load-displacement characterization could provide a deeper understanding of the mechanical response of each construct. Finally, the lateral plate used in this study was slightly longer than those typically applied in clinical practice. While this ensured secure distal fixation beyond the metaphyseal defect, the increased working length may have influenced construct stiffness and should be considered when interpreting the findings. Despite these limitations, the present study may provide valuable biomechanical evidence on the comparative axial stability of different fixation techniques for proximal humerus fractures with medial metaphyseal defects, contributing to the understanding of optimal fixation strategies in such challenging fracture patterns.

In conclusion, our study results indicate that double plating provides the greatest axial stability in proximal humerus fractures with medial metaphyseal defects, supporting its use in fracture patterns with medial column deficiency. However, as fixation choice should be guided by patient-specific factors and surgical feasibility, further experimental and clinical studies are needed to validate these findings under dynamic loading conditions.

Data Sharing Statement: The data that support the findings of this study are available from the corresponding author upon reasonable request.

Author Contributions: M.A.: Idea/concept, design, writing the article, other (performed surgical procedures); E.K.: Data collection and processing, analysis, writing the article; A.Ç.: Other (performed surgical procedures), data collection, references; Y.I.: Design, literature review; C.K.: Critical review, control/supervision; I.T.: Materials, idea/concept, control/supervision.

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