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ORIGINAL ARTICLE

Biomechanical evaluation of fixation techniques for posteromedial tibial plateau fractures: A cadaveric model

Mahmut Kalem, MD[1], Çağatay Baltacı, MD[1], Halil İbrahim Açar, MD[2], Yunus Uslan[3], Elif Naz Perdeci[4], Ercan Şahin, MD[5]

[1]Department of Orthopedics and Traumatology, Ankara University Faculty of Medicine, Ankara, Türkiye
[2]Department of Anatomy, Ankara University Faculty of Medicine, Ankara, Türkiye
[3]Department of Mechanical Engineering, TOBB University of Economics and Technology, Ankara, Türkiye
[4]Department of Biomedical Engineering, TOBB University of Economics and Technology, Ankara, Türkiye
[5]Department of Orthopedics and Traumatology, Zonguldak Bülent Ecevit University, Zonguldak Türkiye

ABSTRACT

Objectives: This study aims to compare the biomechanical performances of five fixation techniques, posteroanterior (PA) screw, anteroposterior (AP) screw, posterior locking compression plate (LCP), anatomic posteromedial plate (PMP), and anterolateral plate (ALP), for isolated posteromedial tibial plateau fractures using cadaveric models under static and dynamic axial loading conditions.

Materials and methods: Twenty-five fresh-frozen cadaveric tibias were used to create standardized posteromedial split-type fractures. Specimens were divided equally into five groups based on the fixation method. Biomechanical testing involved cyclic axial loading (10-250 N, 2500 cycles at 2 Hz), followed by load-to-failure testing under static compression. Outcome parameters included stiffness, load at 3 mm displacement, ultimate load, displacement at failure, and photographic displacement.

Results: The PMP group demonstrated the highest biomechanical stability, with the greatest ultimate load (805.60±218.96 N) and minimal displacement. The PA screw fixation also showed acceptable performance, offering a minimally invasive alternative. In contrast, the AP and ALP groups exhibited the lowest values for load tolerance and fragment control. There were significant differences between the groups, particularly favoring posterior-based techniques ($p<0.05$).

Conclusion: Anatomic PMP provides superior biomechanical stability for isolated posteromedial tibial plateau fractures. The PA screw fixation offers a less invasive, yet stable alternative. Anterior-based fixation strategies such as AP screws and ALP should be avoided due to biomechanical insufficiency.

Keywords: Cadaveric model, biomechanical testing, dynamic loading, posteromedial tibial plateau fracture.

Posteromedial tibial plateau fractures are complex intra-articular injuries which directly compromise knee joint stability. They account for approximately 23 to 28% of all tibial plateau fractures and typically present as isolated fragments in bicondylar fractures caused by high-energy trauma.[1,2] The main goal of surgical stabilization is to prevent displacement of the weight-bearing fragment while preserving soft tissue integrity and vascular supply, thereby allowing early mobilization. Inadequate stabilization causes progressive instability, functional impairment, and post-traumatic osteoarthritis.[2] Due to their anatomically deep and constrained location, achieving reduction and stable fixation is technically challenging and requires a specialized surgical approach and implants.[3]

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Correspondence: Mahmut Kalem, MD. Ankara Üniversitesi Tıp Fakültesi, Ortopedi ve Travmatoloji Anabilim Dalı, 06230 Altındağ, Ankara, Türkiye.

E-mail: drkalem81@gmail.com

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Review of the literature reveals low complication rates following surgeries using the standard posteromedial or direct posterior approach as described by Galla and Lobenhoffer.[4-6] On the other hand, it remains necessary to biomechanically evaluate, and standardize minimally invasive techniques that achieve indirect reduction while preserving the surrounding soft tissue. Recent studies have demonstrated the biomechanical advantages of posterior-based fixation for this fragment.[3,7-10] However, the majority of these techniques have been assessed using a limited number of cadaveric or synthetic bone models, with a narrow range of fixation constructs, and under standardized biomechanical conditions. To the best of our knowledge, there is no biomechanical study in the literature comparing anterior fixation, indirect reduction techniques, and posterior-based fixation methods using cadaveric models.

In the present study, we aimed to evaluate and compare the biomechanical performances of five different fixation methods—posteroanterior (PA) screw, anteroposterior (AP) screw, locking compression plate (LCP), anatomic posteromedial proximal plate (PMP), and anterolateral plate (ALP)—in a cadaveric model of isolated posteromedial split-type tibial plateau fracture under both static and dynamic axial loading and to analyze construct stiffness, load-bearing capacity, and fragment displacement.

MATERIALS AND METHODS

This biomechanical study was conducted at Ankara University, Faculty of Medicine, Department of Anatomy. The study protocol was approved by the Ankara University, Faculty of Medicine, Ethics Committee (Date: 14.04.2025, No: 2025000238-1).

Fracture preparation in cadaveric specimens

Twenty-five tibial plateaus were harvested from fresh-frozen cadavers in the Department of Anatomy, Faculty of Medicine, Ankara University. Posteromedial split-type tibial plateau fractures were created by a single orthopedic surgeon using an oscillating saw and an osteotome.

The fracture models were based on the morphology described by Higgins et al.,[1] in which the posteromedial fragment typically involves approximately 24% of the tibial plateau articular surface. The mean articular fragment angle (MAFA) and sagittal angle (SA) of the posteromedial fragment have been reported as 21.4° and 73°, respectively.

For the design of our fracture model, the MAFA and SA were standardized to 25° and 75° (Figure 1). The initial osteotomy was performed with a 1-mm thick saw, from the posteromedial articular surface, extended posteriorly and exited the posterior cortex approximately 4 cm distal to the joint line. This orientation allowed for the creation of a consistent SA of 75°.

Grouping of cadaveric specimens

Each of the 25 specimens was assigned to one of five groups in a homogeneous manner based on age

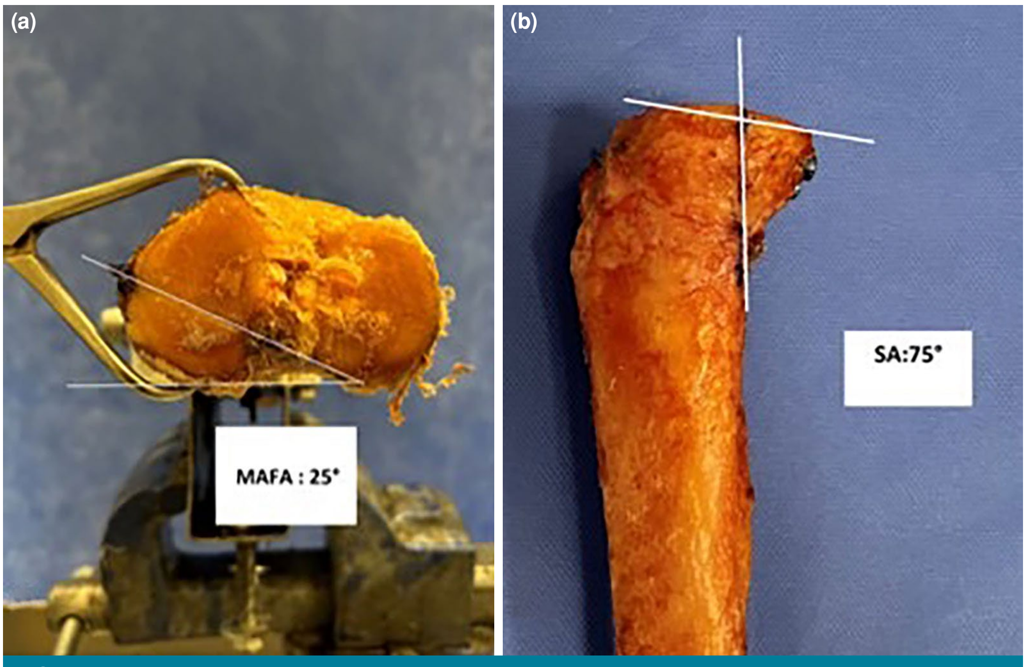

FIGURE 1. The model of posteromedial tibial fracture. **(a)** The mean articular fragment angle (MAFA), **(b)** the sagittal angle.

and sex: A) two PA lag screws, B) two AP lag screws, C) 3.5-mm posterior LCP, D) 3.5-mm anatomic PMP, E) 3.5-mm anatomic ALP (Figure 2).

Fixation methods

After anatomical reduction of the fracture line, temporary fixation was achieved using a Kirschner wire (K-wire) placed through an anterior cruciate ligament (ACL) guide.

All fixation implants used in this study were manufactured by Normmed Medikal (Normmed Medikal San. ve Tic. A.Ş. Ankara, Türkiye). For lag screw fixation, 3.5-mm partially threaded (32-thread), cannulated screws were utilized. For plate fixation, the following titanium implants were employed: 3.5-mm pure titanium, 6-hole LCP; 3.5-mm pure titanium, 5-hole anatomic PMP; and 3.5-mm pure titanium, 4-hole anatomic ALP. All plates were fixed using 3.5-mm titanium cortical and locking screws of appropriate lengths, also provided by Normmed Medikal.

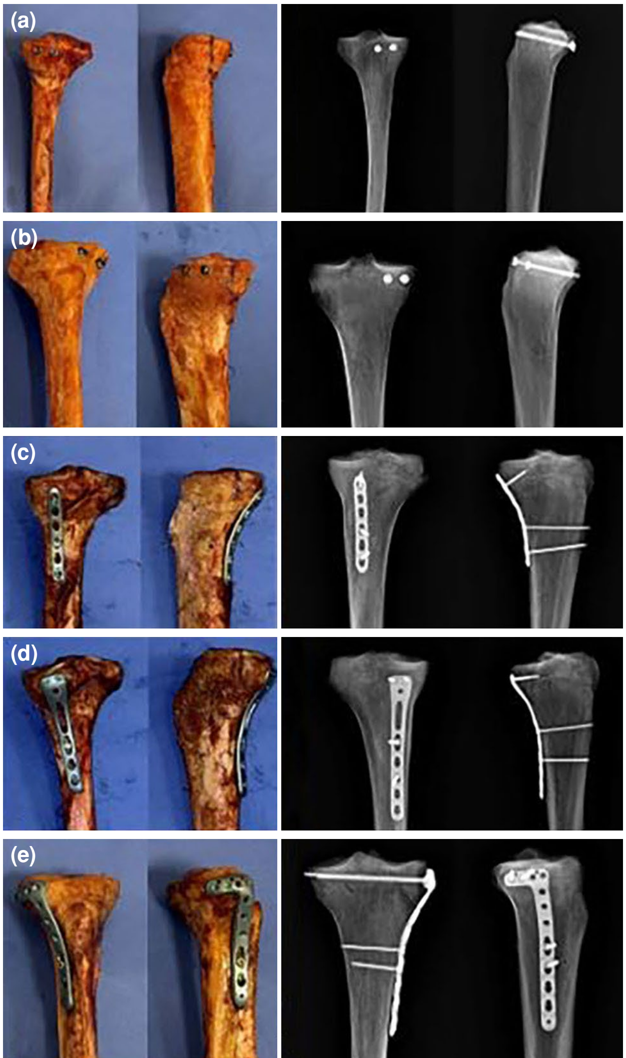

FIGURE 2. Fixation methods in fresh cadaveric bone and X-ray images. **(a)** Posteroanterior two screws, **(b)** anteroposterior two screws, **(c)** posterior locking compression plate, **(d)** posteromedial plate, **(e)** anterolateral plate.

For standardization, all screws were inserted bicortically in this study. However, in clinical practice, partially threaded cancellous screws are often placed unicortically.

Biomechanical testing

All specimens were cut off and potted vertically in 10 cm tubes with rigid polyurethane (PU). The overall lengths of the tibias were the same for all specimens. Specimens were placed into the test device via T-type mold clamps and compressive load applied to the reattached bone fragment with an upper metallic single-point apparatus (Figure 3). A servo-hydraulic test machine (Series No: 2012EY01) designed by Labiotech (Ankara, Türkiye) was used for both static and dynamic loadings. The load increased for the dynamic loading every 500 sinusoidal cycles with five different loading phases. The phases were between 10-50 N, 10-100 N, 15-150 N, 20-200 N, 25-250 N which concluded to 2,500 cycles in total at a rate of 2 Hz. The fifth phase of cyclic loading was adjusted to 250 N based on biomechanical calculations. A total of 70% of the knee joint load is transferred through the tibial plateau and the knee is exposed 130% of the body weight during the swing phase of normal gait.[11,12] As the articular surface area of the fracture fragment is approximately 40% of the medial plateau, the pre-determined upper compressive load of 250 N corresponds the load that the fracture fragment of a 70 kg person experience while walking immediately after surgery. After the cyclic loading, a static load with a rate of 50 mm/min was applied to observe the failure of the specimens. Although all specimens were intended to conclude the cyclic and static loading, 3 mm displacement of the total system was also investigated since it was assigned as an indicator of instability.[13] An illustration of the test method is given in Figure 4. The specimens were marked at parallel points around the fracture line with a marker. Before and after the total cyclic loading, the samples were photographed with a reference to observe the displacement of the marks. The photographs were taken by a high-resolution

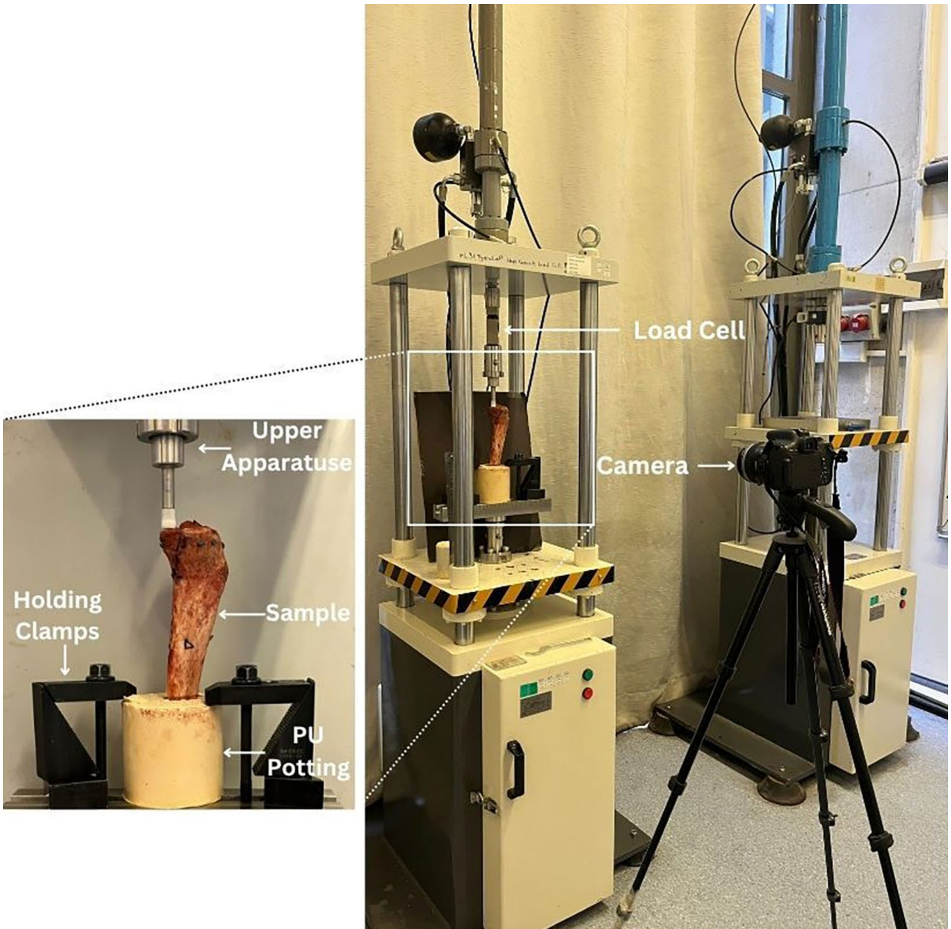

FIGURE 3. Test configuration.

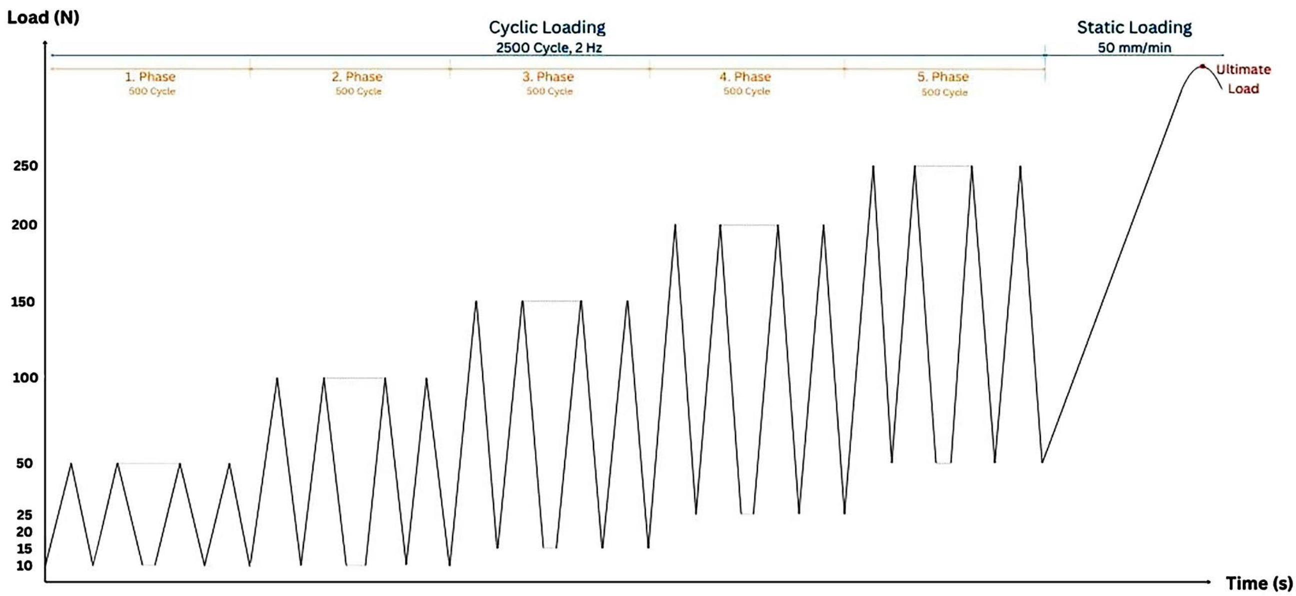

FIGURE 4. An illustration of the test method.

camera (EOS 750D, Canon, Tokyo, Japan) located 1 m away from the samples.

Tested samples were evaluated in respect of ultimate load (N), load at 3 mm (N), stiffness (N/mm), total displacement (mm), and cyclic displacement (mm) values which were calculated or measured from the recorded data. Ultimate load is the maximum load in which the sample endured during all phases of the testing. Load at 3 mm is an important indicator, since stiffness is a measure of the resistance of the sample to applied loads and was calculated from the slope of elastic regions of load-displacement plot. The displacement value is the general displacement of the specimen until the failure point. The cyclic displacement is the displacement difference before and after the cyclic loading when maximum load values of the sinusoidal wave are selected as a designated point for such measure. Besides, the displacement experienced by the fracture line as a result of the movement occurred during the loading was considered to be significant and was examined in addition to the overall displacement of the entire system. The longitudinal distance between the corresponding marks were measured via AutoCAD 2020 (version 24.1, Autodesk, San Rafael, CA, USA) at the beginning and the end of the cyclic loading phase from the taken photographs which is defined as photographic displacement (mm) for this study.

Statistical analysis

Study power and sample size calculation were performed using the G*Power version 3.1.9.7 software (Heinrich-Heine-Universität Düsseldorf, Düsseldorf, Germany).[14] Based on the similar studies, the mean and standard deviations and pre-determined parameters of the test were taken into account. The statistical power was set at 0.95 (95%) and the statistical significance was accepted as 0.05 (5%). The effect size calculated as 2.73 from the similar studies.[3] The sample size was found as five per group.

Statistical analysis was performed using the IBM SPSS version 27.0 software (IBM Corp., Armonk, NY, USA). Normality of continuous variables was assessed using the Shapiro-Wilk test. Continuous variables were presented in mean ± standard deviation (SD) or median (min-max), while categorical variables were presented in number and frequency. One-way analysis of variance (ANOVA) test was used to compare the data sets. A p value of <0.05 was considered statistically significant.

RESULTS

A total of 25 tibial plateau specimens were successfully tested. The mean age of the specimens in the groups ranged from 63.5 to 67 years. The sex distribution was three males to two females in each group. The demographic characteristics of the cadaveric specimens used in the study are shown in Table I. There was no statistically significant difference between the groups in terms of sex (p=0.76) and mean age (p=1.00).

Biomechanical data

All tests were conducted and recorded successfully. The phases that the 3-mm criterion was reached, the failure modes and the failure phases were also observed and tabulated in Table II for all samples. Three main failure modes were observed. The fragment misalignment signified for the samples in which fracture fragment displaced downward axially. Specimens described as having rotational misalignment indicates not only axial displacement of the fragment downward but also an additional rotational movement. The term "subsidence of bone" was used to describe failures in which the loading device penetrates into the bone by damaging the cadaver.

The ALP group was the only group that the photographic investigation could not be carried out due to the samples inability to complete the cyclic phase.

TABLE I
Demographics of the cadaveric specimens

	Two PA lag screws	Two AP lag screws	3.5 mm LCP	Anatomic posteromedial proximal tibia plate	Anatomic anteromedial proximal tibia plate	*p*
Mean age	64	66	64	63.5	67	0.76
Sex						1.00
Male	3	3	3	3	3	
Female	2	2	2	2	2	

PA: Posteroanterior; AP: Anteroposterior; LCP: Locking compression plate.

TABLE II
Sample failure details

Groups	Failure mode	Phase at 3 mm	Failure phase
Posteroanterior			
1	Displacement	Cyclic	Static loading
2	Rotation	Phase 2	Phase 4
3	Rotation	Phase 5	Static loading
4	Rotation	Static loading	Static loading
5	Rotation	Static loading	Static loading
Anteroposterior			
1	Rotation	Static loading	Static loading
2	Rotation	Phase 3	Static loading
3	Rotation	Phase 5	Static loading
4	Rotation	Phase 3	Phase 5
5	Subsidence	Phase 4	Static loading
Locking compression plate			
1	Subsidence	Static loading	Static loading
2	Subsidence	Static loading	Static loading
3	Subsidence	Static loading	Static loading
4	Subsidence	Static loading	Static loading
5	Rotation	Static loading	Static loading
Posteromedial plate			
1	Subsidence	Static loading	Static loading
2	Subsidence	Static loading	Static loading
3	Subsidence	Static loading	Static loading
4	Subsidence	Phase 5	Static loading
5	Subsidence	Static loading	Static loading
Anterolateral plate			
1	Rotation	Phase 2	Phase 5
2	Rotation	Phase 5	Phase 5
3	Rotation	Phase 3	Phase 5
4	Rotation	Phase 3	Phase 5
5	Rotation	Phase 5	Static loading

TABLE III
Test results as mean and standard deviation per groups

Groups	Load at 3 mm (N)	Ultimate load (N)	Displacement at ultimate load (mm)	Stiffness (N/mm)	Photographic displacement (mm)
	Mean±SD	Mean±SD	Mean±SD	Mean±SD	Mean±SD
PA	413.00±297.61	726.40±398.66	16.22±7.86	419.01±202.71	2.84±1.37
AP	228.00±99.60	462.00±176.82	12.07±2.11	213.02±109.85	4.42±4.83
LCP	433.40±150.06	754.60±283.37	10.69±3.71	478.55±265.69	0.33±0.22
PMP	585.20±243.00	805.60±218.96	9.76±6.18	387.66±71.25	0.28±0.09
ALP	180.00±67.08	251.80±4.02	21.31±11.84	149.94±92.03	-

SD: Standard deviation; PA: Posteroanterior; AP: Anteroposterior; LCP: Locking compression plate; PMP: Posteromedial plate; ALP: Anterolateral plate.

All results are summarized in Table III. The mean load at 3 mm displacement was 413.00±297.61 N for the PA group, 228.00±99.60 N for the AP group, 433.40±150.06 N for the LCP group, 585.20±243.00 N for the PMP group, and 180.00±67.08 N for the ALP group. The mean ultimate load values recorded were 726.40±398.66 N for PA, 462.00±176.82 N for AP,

TABLE IV
Statistical comparison results

Compared groups	Load at 3 mm (N)	Maximum load (N)	Displacement at maximum load (mm)	Stiffness (N/mm)	Photographic displacement (mm)
PA-AP	0.144	0.113	0.371	0.063	0.354
PA-LCP	0.868	0.862	0.238	0.576	0.130
PA-PMP	0.172	0.625	0.170	0.768	0.123
PA-ALP	0.070	0.008*	0.277	0.018*	-
AP-LCP	0.106	0.082	0.765	0.020*	0.020*
AP-PMP	0.008*	0.044*	0.617	0.111	0.019*
AP-ALP	0.697	0.203	0.056	0.554	-
LCP-PMP	0.226	0.735	0.840	0.369	0.970
LCP-ALP	0.050*	0.005*	0.030*	0.005*	-
PMP-ALP	0.003*	0.002*	0.019*	0.035*	-

PA: Posteroanterior; AP: Anteroposterior; LCP: Locking compression plate; PMP: Posteromedial plate; ALP: Anterolateral plate; * Indicates statistical significance.

754.60±283.37 N for LCP, 805.60±218.96 N for PMP, and 251.80±4.02 N for ALP. The displacement at ultimate load showed values of 16.22±7.86 mm for PA, 12.07±2.11 mm for AP, 10.69±3.71 mm for LCP, 9.76±6.18 mm for PMP, and 21.31±11.84 mm for ALP. Stiffness results were 419.01±202.71 N/mm (PA), 213.02±109.85 N/mm (AP), 478.55±265.69 N/mm (LCP), 387.66±71.25 N/mm (PMP), and 149.94±92.03 N/mm (ALP). Finally, photographic displacement results were 2.84±1.37 mm in PA, 4.42±4.83 mm in AP, 0.33±0.22 mm in LCP, 0.28±0.09 mm in PMP, and data for ALP was not available.

The ANOVA test results are given in Table IV. For Load at 3 mm, significant differences were observed between AP *vs.* PMP (p=0.008), LCP *vs.* ALP (p=0.050), and PMP *vs.* ALP (p=0.003). In maximum load, significant differences occurred between PA *vs.* ALP (p=0.008), AP *vs.* PMP (p=0.044), LCP *vs.* ALP (p=0.005), and PMP *vs.* ALP (p=0.002). Regarding displacement at maximum load, statistically significant comparisons included LCP *vs.* ALP (p=0.030) and PMP *vs.* ALP (p=0.019). In stiffness, significant differences were found for PA *vs.* ALP (p=0.018), AP *vs.* LCP (p=0.020), LCP *vs.* ALP (p=0.005), and PMP *vs.* ALP (p=0.035). Finally, photographic displacement showed significant differences between AP *vs.* LCP (p=0.020) and AP *vs.* PMP (p=0.019).

DISCUSSION

Posteromedial tibial plateau fractures are serious intra-articular injuries which directly compromise load transmission and threaten the stability of the posterior column of the knee joint.[15,16] These fractures commonly occur following high-energy trauma and, if not adequately stabilized, may lead to functional impairment and post-traumatic osteoarthritis.[7,16,17] The literature highlights that posteromedial fractures are associated with a wide range of displacement rates, significantly affecting biomechanical stability.[18-21] Stable fixation with respect to soft tissue is vital to maximize patient outcomes in these fractures.[22] The results of this study showed that PMP for posteromedial tibial fractures had superior biomechanical stability compared to other methods.

Previous studies utilizing both synthetic and cadaveric bone models have consistently demonstrated that posteriorly placed implants provide superior load-bearing capacity and biomechanical stability in the fixation of posteromedial tibial plateau fractures.[3,9,10] The findings of our study are in agreement with this body of literature. Zeng et al.[3] reported that posterior T-shaped plate demonstrated the highest biomechanical stability; however, their experiments were limited to synthetic bone models, which may not fully replicate the mechanical properties and variability of human bone. In contrast, our study employed fresh-frozen cadaveric specimens to provide a more physiologically relevant and clinically translatable assessment. Similarly, Twinprai et al.[9] utilized cadaveric models and compared three different posterior fixation techniques, ultimately identifying the posterior buttress plate as the most stable option. While their study was limited to posterior techniques, our study expands upon this by comparing five distinct fixation methods, including anterior, anterolateral and posterior constructs. This broader comparison allows for a more comprehensive evaluation of fixation strategies. Collectively, these findings reinforce the biomechanical advantage of posterior-based fixation methods in the treatment of isolated posteromedial tibial plateau fractures.

In the comparison of posterior plating techniques, we evaluated the biomechanical performance of the LCP and anatomically contoured PMP groups. While the LCP demonstrated higher stiffness values, the PMP group showed superiority in terms of overall biomechanical stability, including ultimate load and fragment displacement parameters. The enhanced performance of the PMP construct is likely attributable to its ability to accommodate two screws directed into the posteromedial fragment, in contrast to the LCP group, which permitted only a single screw. This difference in screw configuration may play a crucial role in achieving rotational stability, which is particularly critical in managing shearing fracture patterns commonly seen in posteromedial tibial plateau injuries. Although the LCP offers a thicker, more rigid plate construct, our findings suggest that the fixation strategy's ability to engage and stabilize the fracture fragment effectively, particularly through multiple points of fixation, has a greater impact on mechanical stability than plate rigidity alone.

Despite the demonstrated biomechanical superiority of anatomical PMP in the fixation of posteromedial tibial plateau fractures, it is essential to consider the soft tissue condition and overall clinical status of the patient when selecting a fixation method.[23] In elderly patients or those with comorbidities which impair soft tissue healing, less invasive techniques may be preferable. Posteroanterior screw fixation offers a minimally invasive alternative, with reduced soft tissue dissection and lower risk of vascular compromise compared to posterior plating techniques. Our study found that although the LCP group exhibited slightly higher stiffness and stabilization values, the differences between LCP and PA screw fixation were relatively small across key parameters, including stiffness, ultimate load, and load at 3 mm displacement. From a surgical standpoint, PA screw application may be advantageous in cases where the posterior approach is contraindicated or poses elevated risk. Similar biomechanical comparisons have been reported in the literature regarding the fixation of posterior malleolar fractures, evaluating the use of screws versus locking plates. Locking plates were usually considered to provide superior stability. However, in fracture patterns where lag screws alone can achieve sufficient stability screw, only fixation has been shown to offer comparable outcomes and is often preferred due to reduced implant bulk and surgical invasiveness. In this context, our current study parallels these findings, exploring similar considerations in the fixation of posteromedial tibia plateau fractures regarding the role of plate augmentation versus screw-only constructs.[24,25] While PMP remains the most stable construct biomechanically, its requirement for extensive posterior dissection may not be suitable for all patients. Therefore, when fracture morphology, patient comorbidities, and soft tissue considerations preclude a posterior approach, PA screw fixation represents a viable and less invasive alternative which still provides satisfactory mechanical stability.

Among all the fixation methods evaluated, the AP screw and ALP groups demonstrated the weakest biomechanical performance. Prior studies have highlighted the limitations of AP screw fixation, particularly its reduced capacity to control rotation and maintain compression across the fracture site, compared to PA screw configurations.[3,26] Consistent with this, our findings showed that the PA screw group exhibited significantly higher stiffness and load-bearing capacity than the AP group, underscoring the biomechanical advantage of posterior-to-anterior screw trajectory in engaging the load-bearing posteromedial fragment. Furthermore, the ALP group yielded the lowest values across all mechanical parameters. This outcome aligns with the findings of Twinprai et al.,[9] who demonstrated that ALP fixation was biomechanically suboptimal for isolated posteromedial fractures due to its anatomical contour and limited screw angulation, which failed to achieve sufficient fixation of the posteromedial fragment. Taken together, these results reaffirm that anterior-based fixation strategies, particularly AP screws and ALP constructs, are inadequate for stabilizing posteromedial tibial plateau fractures and should be avoided in favor of posteriorly oriented techniques, when anatomically and clinically feasible.

To the best of our knowledge, this is the first study to comprehensively evaluate five distinct fixation techniques for isolated posteromedial tibial plateau fractures using fresh-frozen cadaveric models subjected to both static and dynamic loading conditions. The experimental design was meticulously structured to closely replicate clinical scenarios, enhancing the translational relevance of the findings. Notably, the inclusion of dynamic cyclic loading simulated the inadvertent weight-bearing forces encountered during early postoperative ambulation, providing critical insights into the real-world mechanical endurance and fatigue behavior of each construct. This comprehensive approach not only strengthens the validity of our results, but also positions our study as a significant contribution to the biomechanical understanding of posteromedial fracture fixation.

Nonetheless, there are some limitations to this study. First, the use of cadaveric models does not replicate the biological healing processes or the complex responses of living tissues. However, cadaveric specimens remain the most appropriate and ethically acceptable option for achieving controlled and reproducible biomechanical testing. Second, the sample size was relatively small, which limited the statistical power of certain comparisons. Nonetheless, a priori power analysis conducted using G*Power software confirmed that five specimens per group were sufficient to achieve adequate statistical power for the primary outcome measures. Third, the biomechanical testing protocol included only axial loading; torsional and lateral forces, which may also influence fracture stability during physiological loading, were not assessed. Axial loading was selected due to its clinical relevance, as it represents the predominant force during early weight-bearing in the postoperative period. Finally, it is of utmost importance to acknowledge that, although bicortical screw insertion was employed for consistency in this study, partially threaded cancellous screws in clinical practice are often placed unicortically, given their thread design, which may limit the direct applicability of our biomechanical findings to real-world surgical scenarios. Future studies should consider incorporating larger sample sizes and more complex, multidirectional loading scenarios to better simulate *in vivo* conditions and improve the generalizability of the findings.

In conclusion, our study results demonstrated that anatomical PMP provides superior biomechanical stability in the fixation of isolated posteromedial tibial plateau fractures compared to other fixation methods. The PMP minimized fragment displacement under both static and dynamic loading conditions. Additionally, posterior-anterior screw fixation emerged as a minimally invasive yet sufficiently stable alternative in appropriately selected cases in which soft tissue should be adequately respected. In contrast, AP screw and ALP fixations were found to be biomechanically inadequate. These findings highlight the critical role of implant selection and surgical planning in optimizing functional outcomes and minimizing complications in the management of posteromedial tibial plateau fractures.

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

Author Contributions: Were responsible for organizing and coordinating the study: M.K., E.Ş.; Specimen dissections were performed: Ç.B., H.İ.A.; Biomechanical testing was conducted: Y.U.; Who managed all laboratory procedures: E.N.P.; Data analysis and literature comparison were carried out: Ç.B., M.K., E.Ş.; The manuscript was written: M.K., Ç.B., E.Ş.

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