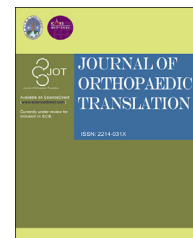




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ORIGINAL ARTICLE

Reconstruction of the lateral tibia plateau fracture with a third triangular support screw: A biomechanical study



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Summary *Background:* Split fractures of the lateral tibia plateau in young patients with good bone quality are commonly treated using two minimally invasive percutaneous lag screws, followed by unloading of the knee joint. Improved stability could be achieved with the use of a third screw inserted either in the jail-technique fashion or with a triangular support screw configuration. The aim of this study was to investigate under cyclic loading the compliance and endurance of the triangular support fixation in comparison with the standard two lag-screw fixation and the jail technique.

Methods: Lateral split fractures of type AO/OTA 41-B1 were created on 21 synthetic tibiae and subsequently fixed with one of the following three techniques for seven specimens: standard fixation by inserting two partially threaded 6.5 mm cannulated lag screws parallel to each other and orthogonal to the fracture plane; triangular support fixation—standard fixation with one additional support screw at the distal end of the fracture at 30° proximal inclination; and jail fixation—standard fixation with one additional orthogonal support screw inserted in the medial nonfractured part of the bone. Mechanical testing was performed under progressively increasing cyclic compression loading. Fragment displacement was registered via triggered radiographic imaging.

Results: Mean construct compliance was 3.847×10^{-3} mm/N [standard deviation (SD) 0.784] for standard fixation, 3.838×10^{-3} mm/N (SD 0.242) for triangular fixation, and 3.563×10^{-3} mm/N (SD 0.242) for jail fixation.

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-3 mm/N (SD 0.383) for jail fixation, with no significant differences between the groups ($p = 0.525$). The mean numbers of cycles to 2 mm fragment dislocation, defined as a failure criterion, were 12,384 (SD 2267) for standard fixation, 17,708 (SD 2193) for triangular fixation, and 14,629 (SD 5194) for jail fixation. Triangular fixation revealed significantly longer endurance than the standard one ($p = 0.047$).

Conclusion: Triangular support fixation enhanced interfragmentary stability at the ultimate stage of dynamic loading. However, the level of improvement seems to be limited and may not legitimate the intervention with an additional third screw.

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Introduction

Fractures of the tibia plateau account for 5–8% of the lower limb fractures [1] and represent about 1% of all fractures [2]. The lateral ones, well-known as type-I according to Schatzker et al [3], or AO/OTA 41-B1 fractures, result from high-energy trauma, mainly caused by sport athletic falls, traffic and motor vehicle accidents, or general trauma [4]. Hence, most of these trauma cases are observed in young patients with an average age of 49 years [2]. The main underlying mechanism leading to such fractures is pure abduction and valgus force combined with axial loading [5].

Schatzker type-I fractures are intra-articular and require absolute fragment stabilization under consideration of the AO principles for surgical treatment. Apart from standard open reduction internal fixation procedures, arthroscopy-assisted percutaneous fixation with reduced soft tissue damage was first described in the 1980s by Caspari et al [6] and Jennings [7]. Based on this, minimally invasive fixation techniques have evolved and become popular in the recent years [8,9]. Subsequently, percutaneous fixation using two lag screws has been established as the standard technique of choice [10]. Postoperative treatment includes passive knee mobilization in the initial phase, followed by active knee movement exercises at a later stage of rehabilitation. No weight bearing is performed for approximately 6–8 weeks after surgery [11] to avoid joint incongruence and fracture displacement. While good outcomes can be expected after treatment of lateral split fractures in good bone quality, screw fixation is contraindicated in case of osteoporosis [10,12]. Possible comorbidities are indicated as damaged soft tissue, infection, loss of reduction, or nonunion [13,14].

In an attempt to increase the stability of fixation while avoiding a considerably more invasive procedure, a technique has been developed with the use of a third screw inserted at the distal end of the fracture, acting as an antiglide screw [15–17]. Another technique, called jail fixation, uses a third screw inserted distally and orthogonal to the two lag screws from anterior to posterior direction in the intact part of the bone close to the fracture site, with the goal to support the screws [1]. Both the abovementioned techniques have been investigated biomechanically; however, they showed only limited to no advantage over the conventional two lag-screw stabilization [1,17–20].

Triangular lateral support fixation is a method combining the standard two lag-screw technique with insertion of an additional screw into the distal apex of the split fracture under a 30° inclination angle in an anteroposterior view, converging between the two proximal screws. In contrast to the use of an antiglide cortical screw, which is inserted horizontally in the metaphysis, this method allows application of a fully threaded cancellous screw and provides better anchorage in the proximal part of the tibia [21].

To the best of authors' knowledge, treatment of lateral tibia split fractures with small fragments has not yet been investigated. Therefore, the aim of the present study was to biomechanically evaluate triangular support fixation and compare it with standard and jail fixations in a setup using artificial tibia with standardized bone quality. Based on the findings of previous investigations [1,17–20], this study examined the hypothesis that none of the fixation techniques using one additionally placed screw in either configuration would considerably outperform the standard technique.

Materials and methods

Specimens and instrumentation

Twenty-one artificial right tibiae (#LD1149; SYNBONE AG, Malans, Switzerland) with low-density cortices and soft cancellous bone were used in this study. A partial articular split fracture AO/OTA 41-B1 was simulated in the proximal lateral tibia by creating a vertical osteotomy at a distance of 10 mm from the lateral tibia plateau using an oscillating saw with a standard 1.0 mm sawblade. An osteotomy line, parallel to the tibia axis in an anteroposterior view, was first marked for this purpose.

The tibiae were assigned to three study groups of seven specimens each for instrumentation with either the standard, triangular support, or jail technique. The fracture was anatomically reduced using Weber forceps.

Standard fixation was performed by insertion of two partially threaded (32 mm thread length) 6.5 mm cannulated lag screws of 65 mm length parallel to each other, orthogonal to the fracture plane and located 7 mm distally to the tibia plateau. The distance between the two screws was standardized to 15 mm.

Triangular support fixation was performed as standard fixation, followed by insertion of an additional fully threaded 6.5 mm cannulated cancellous screw of 65 mm length directly at the distal apex of the fracture under a 30° inclination in an anteroposterior view, acting as an anti-glide screw and converging between the two lag screws (Figures 1A and 1B).

Jail fixation was performed as standard fixation, followed by insertion of a fully threaded 6.5 mm cannulated cancellous screw of 40 mm length from anterior to posterior direction distally and orthogonal to the two lag screws (Figures 1C and 1D). This transverse screw was located 10 mm medial to the fracture line in the nonfractured part of the bone. Care was taken to position it as close as possible to the two lag screws in order to provide immediate support against subsidence.

All screws were inserted together with standard washers. After instrumentation, each tibia was cut distally at a length of 10 cm and embedded in polymethylmethacrylate (Suter Kunststoffe AG, Fraubrunnen, Switzerland) with a vertically oriented axis. Two reference markers of 2.5 mm diameter

were glued at the anterior side of each specimen, medially and laterally to the fracture line at approximately 2 mm distance to the former and to the tibia plateau for radiographic tracking of interfragmentary displacements.

Mechanical testing

Mechanical testing was performed on a servohydraulic material testing system (Bionix 858.20; MTS Systems, Eden Prairie, MN, USA) equipped with a 25 kN/200 Nm load cell. The load cell was calibrated by a certified institute (Swiss Federal Laboratories for Materials Science and Technology, Dübendorf, Switzerland) and operated with inaccuracy of ± 1.11 N and ± 2.2 N for compression forces lower than 250 N and in the range of 250–1000 N, respectively, which was found acceptable for the present study. The setup with a specimen mounted for mechanical testing is shown in Figure 2. Axial compression along the machine axis was applied to the specimen by a horizontally oriented cylindrical indenter of 11 mm diameter and 40 mm length, which

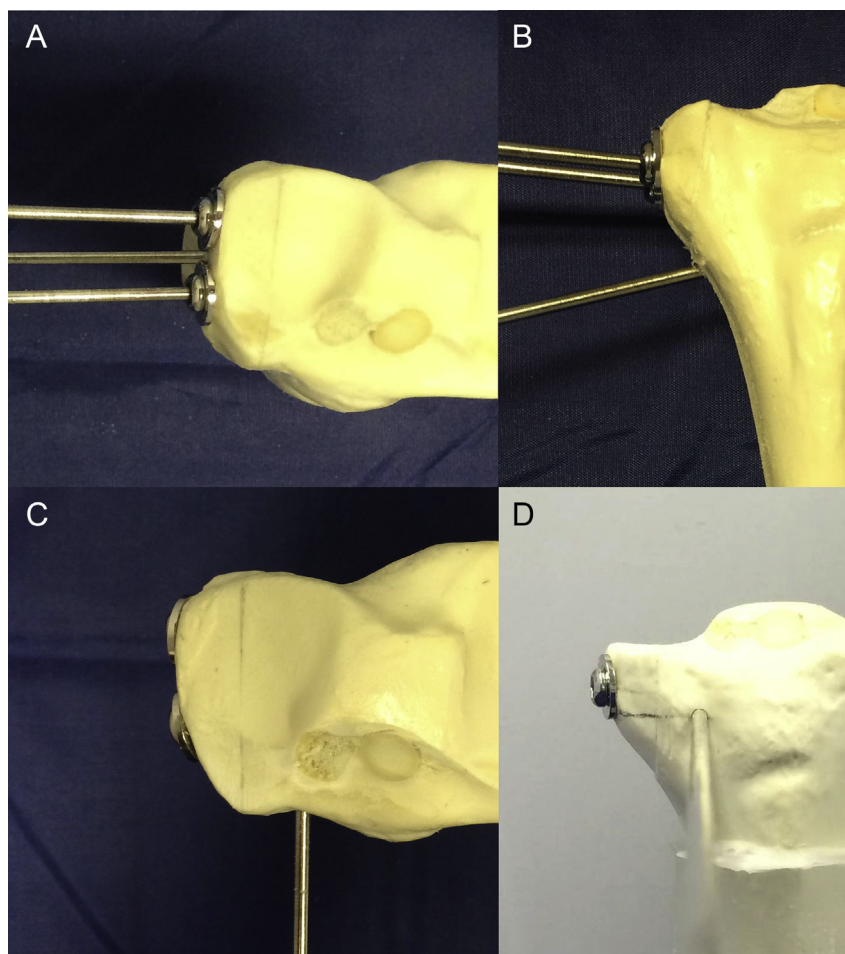


Figure 1 Exemplary photographs showing specimen instrumentation with triangular and jail techniques. (A) The guide wire for the pilot hole of the anti-glide screw was set parallel to the two lag screws in the axial view. (B) Anteroposterior view showing 30° inclination of the guide wire for the pilot hole of the anti-glide screw. (C) The guide wire for the pilot hole of the orthogonal support screw was inserted orthogonal to the two lag screws in the axial view. (D) The guide wire for the pilot hole of the orthogonal support screw was set immediately below the two lag screws at 10 mm distance to the fracture line in anteroposterior view.

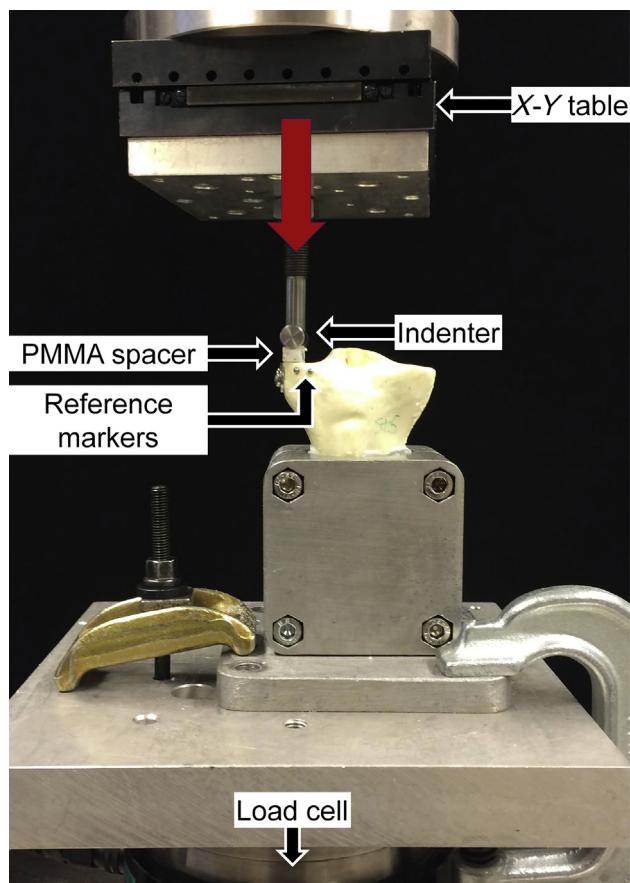


Figure 2 Test setup with a specimen mounted for biomechanical testing. The vertical arrow denotes loading direction. PMMA = polymethylmethacrylate.

was connected to the transducer via an x–y table. The latter allowed compensating for horizontal movements during testing. In order to assure a more homogeneous force distribution of the load at the fracture site, a polymethylmethacrylate spacer was moulded and inlaid between the indenter and the bone surface. A cavity was created on its proximal side to absorb the cylinder, whereas at the distal side the spacer was shaped to fit to the bone surface. The distal part of the specimens was firmly fixed in a custom-made holder to the load cell, which was interconnected to the machine base.

Cyclic loading with a physiological profile of each cycle, adapted from previously reported *in vivo* hip contact forces [22], was applied to each specimen at 5 Hz. Keeping the valley loading constant at 30 N, the peak loading, starting at 150 N, was increased at a rate of 0.02 N/cycle until a test stop criterion of 6 mm machine displacement was fulfilled.

Data acquisition and evaluation

Machine data in terms of axial displacement and axial load were recorded at a rate of 128 Hz. Compliance of the bone-implant construct was derived from the ascending linear slope of the load–displacement curve in the third loading cycle within a range of 60–140 N compression, to account for possible settling effects at the beginning of the cyclic test.

Anteroposterior radiographs were taken at the beginning of the cyclic test and every 500 cycles by the use of a triggered C-arm. For that purpose, cyclic loading was paused for 2 seconds at the peak compression load of the respective cycle. Interfragmentary displacement was evaluated for each radiograph separately by calculation of the change in the distance between the normal projections of the two reference markers on the fracture line in comparison with the initial radiograph with no displacement. Matlab software package (v.R2015; The MathWorks, Natick, MA, USA) was used for this purpose. A failure criterion for construct failure was defined as 2 mm interfragmentary displacement, and was based on clinical findings showing that fractures, that healed under such or bigger incongruency, are associated with early osteoarthritis and poor clinical outcomes [23]. Furthermore, the number of cycles until fulfilment of this criterion, called cycles to failure, was calculated together with the corresponding peak force at failure.

Statistical evaluation of the parameters of interest, including compliance, interfragmentary displacement after 5,000 and 10,000 cycles, as well as cycles to failure and peak force at failure, was performed with the use of SPSS software package (IBM SPSS Statistics V23; IBM, Armonk, NY, USA). Normal distribution within each group was screened with the Shapiro–Wilk test. One-way analysis of variance (ANOVA) with Bonferroni *post hoc* test was applied to identify significant differences between the groups. The level of significance was set to 0.05 for all statistical tests.

Results

Mean construct compliance was 3.847×10^{-3} mm/N [standard deviation (SD) 0.784] for standard fixation, 3.838×10^{-3} mm/N (SD 0.242) for triangular support fixation, and 3.563×10^{-3} mm/N (SD 0.383) for jail fixation, with no significant differences detected between the groups ($p = 0.525$).

The mean interfragmentary displacements after 5,000 and 10,000 cycles (with corresponding peak load of 250 N and 350 N) were 0.4 mm (SD 0.4) and 1.3 mm (SD 0.6) for the standard, 0.3 mm (SD 0.2) and 0.6 mm (SD 0.5) for the triangular support, and 0.6 mm (SD 0.7) and 1.0 mm (SD 0.8) for jail fixation, respectively, with no significant differences between the groups ($p \geq 0.097$; Figure 3).

The mean number of cycles to failure and the corresponding mean peak force at failure were, respectively, 12,384 (SD 2267) and 397.7 N (SD 45.3) for the standard, 17,708 (SD 2193) and 504.2 N (SD 43.9) for the triangular support, as well as 14,629 (SD 5194) and 442.6 N (SD 103.9) for jail fixation (Figure 4). Both the parameters, cycles to failure and peak force at failure, were significantly higher for triangular support fixation compared with standard fixation ($p = 0.047$). No other significant differences were detected between the groups with regard to these two parameters ($p \geq 0.418$).

Failure mode

All tested specimens failed according to the criterion of 2 mm interfragmentary displacement. No screw breakage

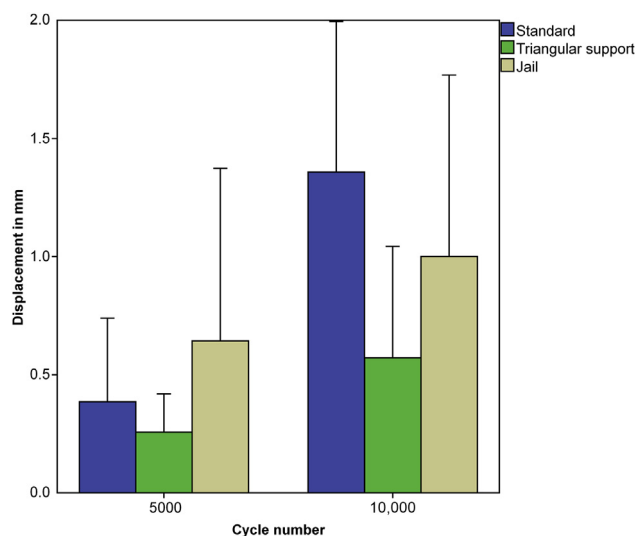


Figure 3 Diagram representing relative fragment displacement after 5,000 (250 N corresponding peak load) and 10,000 (350 N corresponding peak load) cycles in the three study groups in terms of mean and standard deviation values.

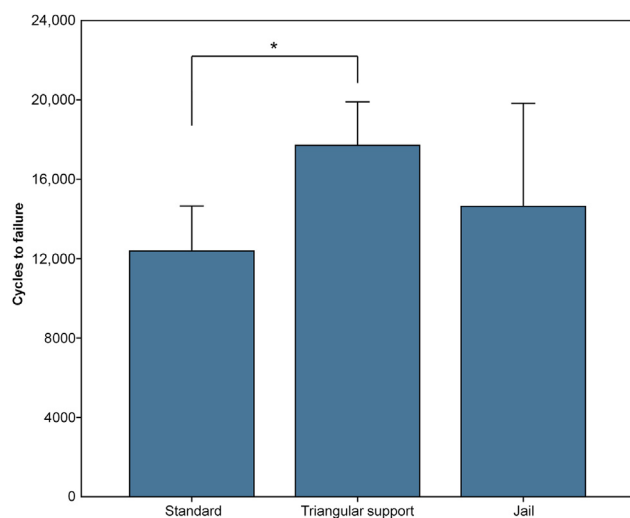


Figure 4 Diagram representing cycles to failure in the three study groups in terms of mean and standard deviation values. * Significant difference.

or loosening was observed in any of the groups. No screw perforations through the medial cortex were observed in any of the specimens, nor did the screws show any kind of movement at their distal end, as shown in [Figures 5 and 6](#).

Discussion

This study compared three different fixation techniques for proximal lateral tibia plateau fractures.

With regard to construct compliance and interfracture displacement after 5,000 and 10,000 cycles, no significant differences were found between the techniques. However, triangular support fixation outperformed the standard one in terms of a significantly higher number of

cycles to failure and corresponding peak force at failure. The mean force at failure in the former was approximately 27% higher than that in the latter.

Significantly higher stability of fixation was observed only at the ultimate stage of cyclic loading, with no significant differences in primary stability. This fact makes the potential advantage of triangular fixation questionable. Moreover, the amount of improved endurance could rather be considered as limited and clinically may not legitimate the intervention with a third screw. Unless absolute stability and maintenance of joint congruency are achieved, healing of such intra-articular fractures at the lateral tibia plateau will be inhibited by shear movement initiation [24]. Therefore, new fixation techniques need to target increased stability in the immediate postoperative phase in order to gain a benefit for fracture healing.

Quantification of the abovementioned shear movements as indicators of the healing potential was of utmost interest in the present study. Whereas machine data were used to assess construct compliance at the initial stage of cyclic testing, their use for shear movement analysis is not optimal for the reason that, despite the approximately parallel loading direction to the osteotomy line, these data include artefacts from the overall bending of the bone-implant construct. For that purpose, pure interfracture movements were calculated from radiographic images with the use of reference markers. They reflect both elastic deformation and fatigue-like displacement at the fracture site during dynamic loading.

Construct compliance at the beginning of cyclic testing was the only machine data-based parameter of interest in the current study. Its evaluation revealed similar overall primary construct stability achieved with all three fixation techniques.

Although there were no significant differences between the triangular and jail fixation methods, some indications, for example, the trend towards less fragment subsidence under cyclic loading of the former, are in favour of triangular fixation as a valuable alternative. In addition, radiographic images with this fixation showed that all screws remained in a stable position during the whole test. The major mechanism for failure in both groups with standard and jail fixation was subsidence of the lateral fragment. Therefore, this fragment should be buttressed rather than supported. Furthermore, metal abrasion during drilling of some pilot holes for jail screws was indicated. The procedure for jail fixation could be optimized by means of an aiming device for the entry point of the orthogonal screw.

In view of a relatively high rate of wound complications associated with treatment of tibia plateau fractures, keeping the surgical technique as less invasive as possible is of tremendous importance. Each of the investigated fixation techniques can be performed in a minimally invasive fashion, being advantageous over the use of other fixation techniques, such as plating.

Some attempts in the past have been undertaken to increase the fixation stability of tibia plateau fractures with the use of an additional third screw in different configurations [1,17,20]. In spite of all efforts, none of these alternative techniques could be established over time. The approach of using an antiglide screw in a triangular configuration adopts the idea of a third screw insertion.

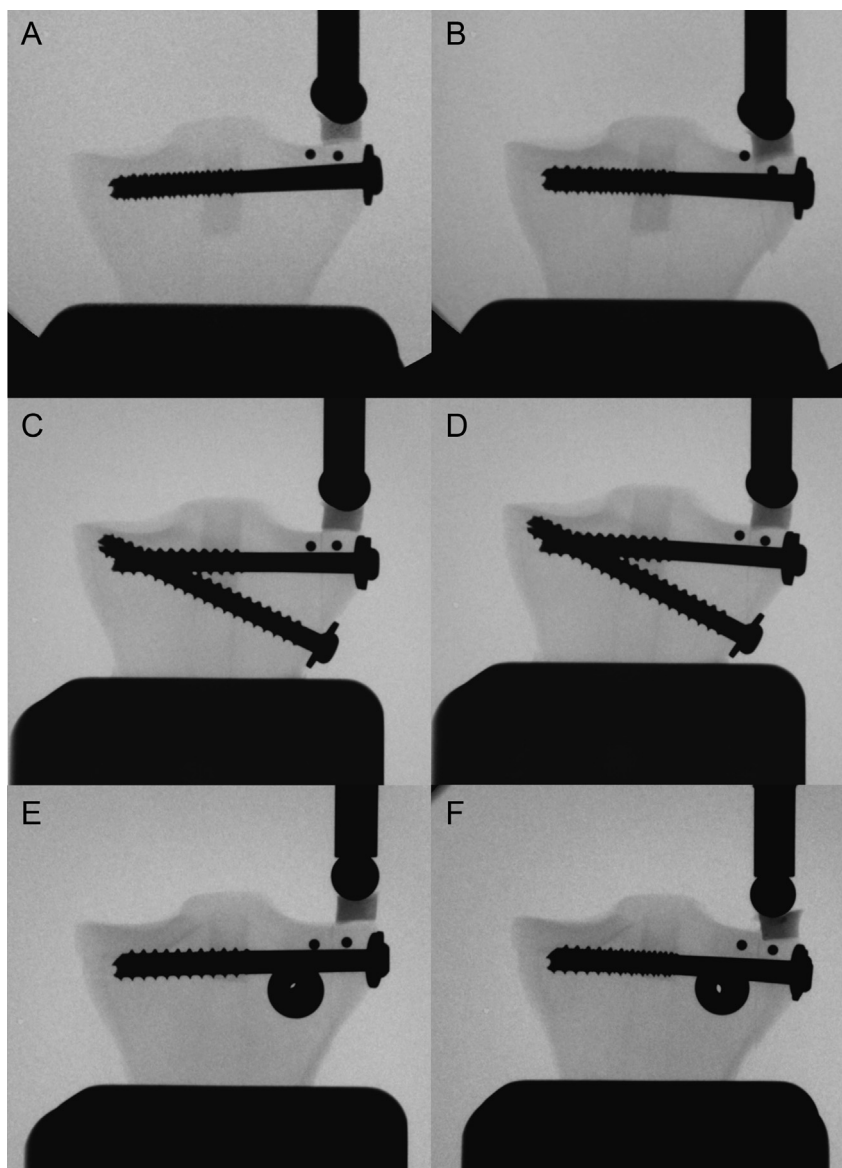


Figure 5 Exemplary anteroposterior radiographs of each specimen instrumented with the (A and B) standard, (C and D) triangular support, and (E and F) jail techniques; (A, C, and E) before and (B, D, and F) after mechanical testing.

However, a direct comparison with the previous studies is not feasible due to diversity of used testing conditions and parameters.

Parker et al [17] compared the addition of a horizontal antiglide or a lag screw with standard two lag-screw fixation in a cadaveric model. The simulated fracture model in their investigation consisted of considerably larger fragments with 20° inclined fracture lines in comparison with the present study with a vertical fracture line. A larger fragment size, compared with that in the current investigation, was also used by Koval et al [20], who compared lag screw fixation with additional horizontal antiglide screw versus six-hole L-shaped buttress plating on embalmed osteopenic cadaveric tibiae with vertically oriented fracture lines, allowing testing of the implants in a worst-case scenario with no bone support between the fragments. In a clinical trial, Molenaars et al [25] performed computed-tomography-based mapping of tibia plateau fractures to

conclude that lateral splits mostly result in small fragments. From this point of view, the currently simulated fracture model is justified.

Another contrast to previous studies is represented by the used loading protocol. Parker et al [17] applied quasi-static ramped loading in displacement control without detecting any differences between the groups. Koval et al [20] used cyclic loading with a peak value of 250 N constantly held over 10,000 cycles, which is considerably lower than *in vivo* loading during normal gait as reported in literature [26]. In contrast to these, the present study used cyclic loading with progressively increasing peak compression. Cyclic loading is advantageous over quasistatic loading as it can reflect better physiological conditions during the rehabilitation period. In addition, the test protocol with progressively increasing loading offers the possibility to achieve failure of all specimens within a predefined number of cycles, which was reported to be beneficial in previous

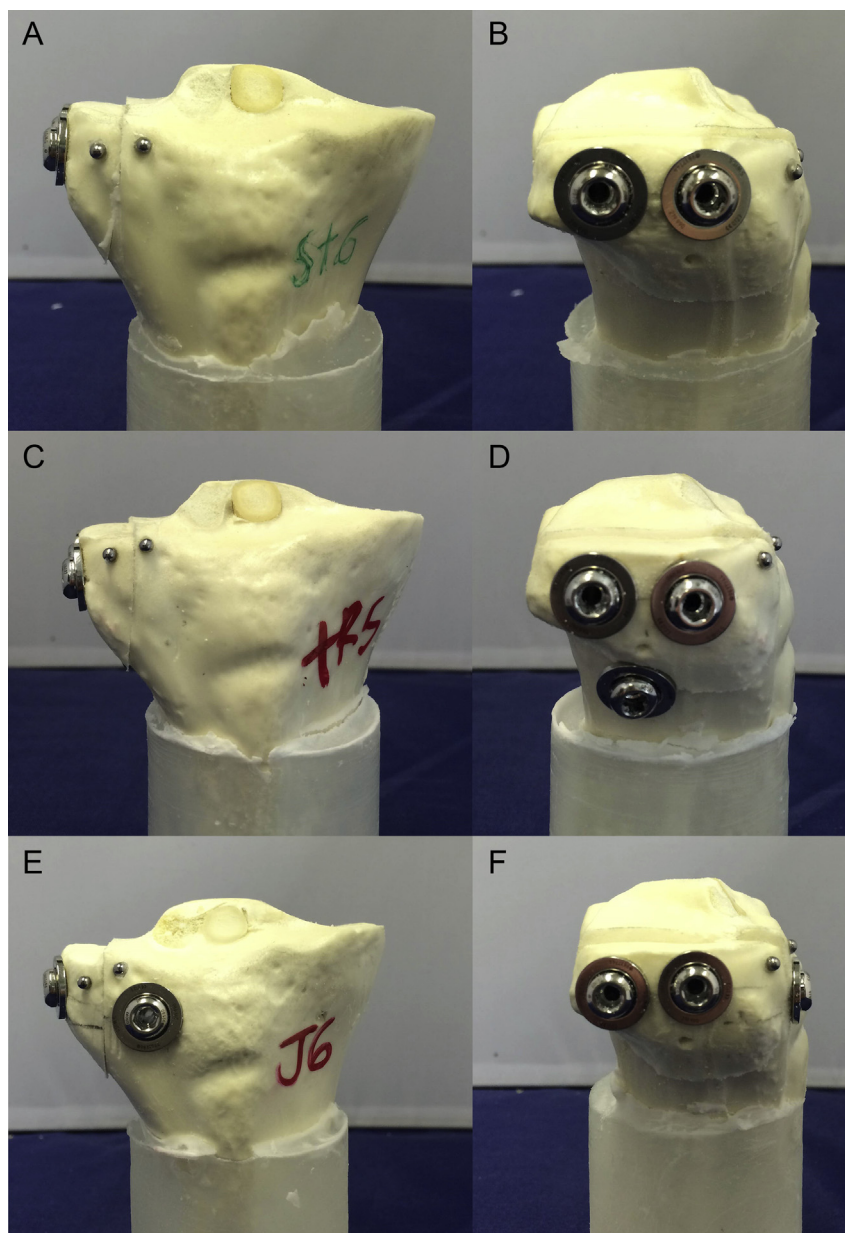


Figure 6 Exemplary photographs of each specimen instrumented with the (A and B) standard, (C and D) triangular support, and (E and F) jail techniques after mechanical testing in (A, C, and E) anteroposterior and (B, D, and F) mediolateral views.

studies [27,28]. Hence, the loading pattern represents a methodological strength of our work.

The current study best compares with the one performed by Weimann et al [1], who introduced the jail fixation technique and biomechanically compared it with standard lag screw fixation in a porcine model. They created osteotomies at 13 mm distance from the lateral end of the tibia plateau and tested the specimens in a five-step staircase fashion by increasing the load from 200 N to 1,000 N every 1,000 cycles. Although no significances were indicated between the fixation techniques in terms of mechanical stability, jail fixation was found to be more successful in preventing screw cutting through cancellous bone, and therefore the authors concluded that it could be a feasible alternative to the standard technique. Hence,

using jail fixation seemed to be appropriate for comparison purposes in our biomechanical investigation. However, in the present study, this technique did not reveal any advantages over the standard fixation with respect to stability and cut-through prevention.

This finding could be related to the most striking limitation of our study. An inappropriate artificial bone model was used, rendering the test conditions less physiological. The model itself was primarily developed for surgical training and education purposes, but not for biomechanical investigations. Screw cut-through, a commonly observed clinical failure mode, was not detected in any of the specimens. Instead, subchondral bone compression was the main failure mode observed in the group with an antiglide screw, which could have been different if human cadaveric

fresh-frozen tibiae with intact cartilage and subchondral bone had been used. In addition, the artificial bones proved to be too soft in terms of stiffness. In two unrelated previous studies, intact artificial femora with same material composition as the currently used tibiae were tested nondestructively versus human cadaveric femora, revealing significantly lower axial bending stiffness (approximately 14 N/mm vs. 3000 N/mm) and torsional stiffness (approximately 0.4 Nm/degree vs. 10 Nm/degree) in comparison with human bones [Todorov D, Zderic I, Gueorguiev B, Richards RG, Lenz M. Biomechanical evaluation of alternative fixation techniques for distal femur fracture fixation. Davos, Switzerland: AO Research Institute Davos; 2016 (unpublished manuscript); Schmitz N, Gehweiler D, Zderic I, Todorov D, Richards RG, Gueorguiev B, et al. Biomechanical investigation of the RIA reaming diameter on failure load of human cadaveric femora. Davos, Switzerland: AO Research Institute Davos; 2016 (unpublished manuscript)]. Therefore, in a further step, the triangular support technique should be investigated in a cadaveric environment or by the use of more appropriate bone models explicitly developed for biomechanical testing purposes.

A further limitation of this study was the restricted clinical relevance based on the study groups selected for comparison. Treatment of tibia plateau split fractures by buttress plating is common clinical practice, allowing immediate postoperative knee mobilization with a gradual increase of the weight bearing. Therefore, plate fixation as a fourth group would have added clinical value to this study. In order to address the surgical technique as less invasively as possible, only screw fixation methods were considered for comparison purposes. In addition, the jail technique is not primarily indicated for simple split fractures in tibiae with good bone quality, but rather for those involving comminution and articular depression as a result of low-energy trauma in elderly patients.

Another twofold limitation in our work was the used fracture model. First, although the osteotomy was set in a standard fashion to minimize possible deviations from the vertical orientation, the fracture line was defined in a manual marking process. Second, the split fracture was located more laterally in comparison with previous studies to allow inclined insertion of the antiglide screw orthogonal to the cortex. A comparison with a horizontally inserted antiglide screw, which showed no improvements in previous studies, would be of special interest in the future.

Furthermore, the screws were inserted manually and without any aiming devices, deeming the instrumentation process less standardized. In particular, insertion of the jail screw was not controlled, which influenced the results negatively.

Moreover, cyclic loading was performed at a rate of 5 Hz, which is higher than that during normal human gait.

Finally, the resolution of radiographic images was limited, thus making other measurement systems, such as optical motion tracking, more preferable.

The strengths of the present study were as follows. First, a standardized bone model was used, allowing better comparability between the three fixation techniques. Second, the used loading protocol represents a methodological strength comprising advantages as previously discussed.

Third, pure interfragmentary movements were calculated based on radiological data instead of using machine data only. Fourth, the arbitrary failure criterion of 2 mm interfragmentary displacement seems to be reasonable, since it has been shown that such incongruence represents a higher risk for development of post-traumatic osteoarthritis.

Conclusion

An alternative technique for fixation of lateral tibia plateau fractures with a triangular support screw configuration was biomechanically investigated, revealing significantly higher competence than the standard two lag-screw fixation at the ultimate stage of dynamic loading to failure. However, the improvement in endurance with this technique was rather low and may not justify the use of its third screw. Moreover, although triangular support fixation had similar performance to the jail technique, the former seems to be advantageous over the latter in terms of failure mechanism and related risks during implantation.

Conflicts of interest

The authors are not compensated, and no other institutional subsidies, corporate affiliations, or funding sources support this work unless clearly documented and disclosed.

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References

- [1] Weimann A, Heinkele T, Herbort M, Schliemann B, Petersen W, Raschke MJ. Minimally invasive reconstruction of lateral tibial plateau fractures using the jail technique: a biomechanical study. *BMC Musculoskelet Disord* 2013;14:120.
- [2] Court-Brown CM, Caesar B. Epidemiology of adult fractures: a review. *Injury* 2006;37:691–7.
- [3] Schatzker J, McBroom R, Bruce D. The tibial plateau fracture. The Toronto experience 1968–1975. *Clin Orthop Relat Res* 1979;138:94–104.
- [4] Albuquerque RP, Hara R, Prado J, Schiavo L, Giordano V, do Amaral NP. Epidemiological study on tibial plateau fractures at a level I trauma center. *Acta Ortop Bras* 2013;21:109–15.
- [5] Kennedy JC, Bailey WH. Experimental tibial-plateau fractures. Studies of the mechanism and a classification. *J Bone Joint Surg Am* 1968;50:1522–34.
- [6] Caspari RB, Hutton PM, Whipple TL, Meyers JF. The role of arthroscopy in the management of tibial plateau fractures. *Arthroscopy* 1985;1:76–82.
- [7] Jennings JE. Arthroscopic management of tibial plateau fractures. *Arthroscopy* 1985;1:160–8.
- [8] Ali AM, Saleh M, Bolongaro S, Yang L. The strength of different fixation techniques for bicondylar tibial plateau fractures—a biomechanical study. *Clin Biomech* 2003;18:864–70.
- [9] Gosling T, Schandelmaier P, Muller M, Hankemeier S, Wagner M, Krettek C. Single lateral locked screw plating of bicondylar tibial plateau fractures. *Clin Orthop Relat Res* 2005;439:207–14.

- [10] Müller M, Allgöwer M, Schneider R, Willenegger H. Manual of internal fixation. Techniques recommended by the AO-ASIF-group. 3rd ed. Berlin, Heidelberg: Springer-Verlag; 1991.
- [11] Segal D, Mallik AR, Wetzler MJ, Franchi AV, Whitelaw GP. Early weight bearing of lateral tibial plateau fractures. *Clin Orthop Relat Res* 1993;294:232–7.
- [12] Biyani A, Reddy NS, Chaudhury J, Simison AJ, Klenerman L. The results of surgical management of displaced tibial plateau fractures in the elderly. *Injury* 1995;26:291–7.
- [13] Hansen M, Mehler D, Voltmer W, Rommens PM. [The extra-articular proximal tibial fractures]. *Unfallchirurg* 2002;105: 858–72.
- [14] Honkonen SE. Degenerative arthritis after tibial plateau fractures. *J Orthop Trauma* 1995;9:273–7.
- [15] Toolan BC, Koval KJ, Kummer FJ, Sanders R, Zuckerman JD. Vertical shear fractures of the medial malleolus: a biomechanical study of five internal fixation techniques. *Foot Ankle Int* 1994;15:483–9.
- [16] Szyszkowitz R. Patella and tibia. In: Allgöwer M, editor. Manual of internal fixation. Springer: Berlin Heidelberg; 1992. p. 553–94.
- [17] Parker PJ, Tepper KB, Brumback RJ, Novak VP, Belkoff SM. Biomechanical comparison of fixation of type-I fractures of the lateral tibial plateau. Is the antilglide screw effective? *J Bone Joint Surg Br* 1999;81:478–80.
- [18] Cift H, Cetik O, Kalaycioglu B, Dirikoglu MH, Ozkan K, Eksioglu F. Biomechanical comparison of plate-screw and screw fixation in medial tibial plateau fractures (Schatzker 4). A model study. *Orthop Traumatol Surg Res* 2010;96:263–7.
- [19] Dohrt S, Lehnert T, Frey S, Fehske K, Jansen H, Blunk T, et al. Effective combination of bone substitute and screws in the jail technique: a biomechanical study of tibial depression fractures. *Int Orthop* 2012;36:2121–5.
- [20] Koval KJ, Polatsch D, Kummer FJ, Cheng D, Zuckerman JD. Split fractures of the lateral tibial plateau: evaluation of three fixation methods. *J Orthop Trauma* 1996;10:304–8.
- [21] Cooper HJ, Kummer FJ, Egol KA, Koval KJ. The effect of screw type on the fixation of depressed fragments in tibial plateau fractures. *Bull Hosp Jt Dis* 2001;60:72–5.
- [22] Bergmann G, Deuretzbacher G, Heller M, Graichen F, Rohlmann A, Strauss J, et al. Hip contact forces and gait patterns from routine activities. *J Biomech* 2001;34:859–71.
- [23] Giannoudis PV, Tzioupis C, Papathanassopoulos A, Obakponovwe O, Roberts C. Articular step-off and risk of post-traumatic osteoarthritis. Evidence today. *Injury* 2010;41: 986–95.
- [24] Yamagishi M, Yoshimura Y. The biomechanics of fracture healing. *J Bone Joint Surg Am* 1955;37-A:1035–68.
- [25] Molenaars RJ, Mellema JJ, Doornberg JN, Kloen P. Tibial plateau fracture characteristics: computed tomography mapping of lateral, medial, and bicondylar fractures. *J Bone Joint Surg Am* 2015;97:1512–20.
- [26] McDonald E, Chu T, Tufaga M, Marmor M, Singh R, Yetkinler D, et al. Tibial plateau fracture repairs augmented with calcium phosphate cement have higher *in situ* fatigue strength than those with autograft. *J Orthop Trauma* 2011;25:90–5.
- [27] Gueorguiev B, Ockert B, Schwieger K, Wahnert D, Lawson-Smith M, Windolf M, et al. Angular stability potentially permits fewer locking screws compared with conventional locking in intramedullary nailed distal tibia fractures: a biomechanical study. *J Orthop Trauma* 2011;25:340–6.
- [28] Windolf M, Muths R, Braunstein V, Gueorguiev B, Hanni M, Schwieger K. Quantification of cancellous bone-compaction due to DHS blade insertion and influence upon cut-out resistance. *Clin Biomech* 2009;24:53–8.