How to fix a tibial tubercle osteotomy with distalisation: A finite element analysis

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A B S T R A C T

Background: Antero-medialisation osteotomy combined with a distalisation procedure may require a more stable fixation as the osteotomy fragment loses both proximal and dis-tal support. This finite element analysis aimed to compare the mechanical behaviour of dif-ferent fixation techniques in tibial tubercle antero-medialisation osteotomy combined with distalisation procedure.
Methods: Tibial tubercle osteotomy combined with distalisation was modelled based on computerised tomography data, which were acquired from a patient with patellar instabil-ity requiring this procedure. Six different fixation configurations with two 3.5-mm cortical screws (1), two 4.5-mm cortical screws (2), three 3.5-mm cortical screws (3), three 4.5-mm cortical screws (4), three 3.5-mm screws with 1/3 tubular plate (5), and four 3.5-mm screws with 1/3 tubular plate (6) were created. A total of 1654 N of force was applied to the patellar tendon footprint on the tibial tubercle. Sliding, gap formation, and total defor-mation between the osteotomy components were analyzed.
Results: Maximum sliding (0.660 mm), gap formation (0.661 mm), and displacement (1.267 mm) were seen with two 3.5-mm screw fixation, followed by two 4.5-mm screws, three 3.5-mm screws, and three 4.5-mm screws, respectively, in the screw-only group. Overall, the minimum displacement was observed with the four 3.5-mm screws with 1/3 tubular plate fixation model.
Conclusions: Plate fixation might be recommended for tibial tubercle antero-medialisation osteotomy combined with distalisation procedure because it might allow early active range of motion exercises and weight-bearing.

1. Introduction

Patellofemoral (PF) instability usually occurs in the presence of various underlying anatomical risk factors that cause abnormal patellar kinematics and alignment [1]. The major factors for PF instability include patella alta, medial patellofemoral ligament (MPFL) insufficiency, trochlear dysplasia, and excessive lateralisation of the tibial tubercle [2,3]. The surgical treatment in PF instability is based on restoring the distorted anatomy to obtain a stable patella that glides within the trochlear groove throughout the knee movements [3]. It has been shown that MPFL is the primary restraint to lateral patellar translation, providing 53–67% restraint up to 30° of knee flexion [4]; thus, MPFL reconstruction is almost always indicated in case of its insufficiency [3,4]. Besides, realignment of the extensor mechanism by reducing tibial tubercle lateralisation and adjustment of patellar height is essential to achieve patellar stability [1]. Tibial tubercle antero-medialisation osteotomy, also known as Fulkerson osteotomy [5,6], efficiently manages the increased tibial tubercle–trochlear groove (TT-TG) distance [1,3,4]. Moreover, the patellar height might be adjusted at the time of surgery with the addition of a distalisation procedure. Conversely, the distalisation procedure is a controversial issue. Some authors oppose the need for this procedure because it can increase patellofemoral contact pressure, causing anterior knee discomfort and chondral degeneration, as well as loss of fixation, impaired bone healing, and fractures [7,8]. However, a recent research shows that tibial tubercle osteotomy (TTO) with distalisation is a safe and effective procedure for patients with patella alta and patellar instability [9].

Fulkerson osteotomy is a technically demanding procedure that necessitates careful planning and performance of the osteotomy as well as the fixation [6]. Several complications might happen following Fulkerson osteotomy, such as infection, wound dehiscence, deep vein thrombosis, proximal tibial fracture, failure of the osteotomy fixation, proximal migration of the fragment, and non-union at the osteotomy site [1,3,7]. To avoid implant failure and non-union, maintaining the distal cortical hinge in the osteotomised tibial tubercle is highly recommended [3,7]. However, if distalisation is additionally performed due to patella alta, the procedure both causes loss of distal hinge and proximal contact between the fragment and the tibia, which further impair the stability of the fixation [1,3,7,10].

Although there is no consensus on how to fix a Fulkerson osteotomy, two or three cortical screws are commonly used for the fixation [3,7]. Recently, Stevens et al. [10] advocated plate fixation for Fulkerson osteotomy and reported promising outcomes with a low complication profile. In the relevant literature, few studies investigated various fixation techniques in TTO [10–17]. However, no previous study specifically investigated TTO combined with the distalisation procedure regarding biomechanics. We hypothesised that the plate fixation might provide more rigid fixation compared with the screw fixation. The purpose of the present study was to compare the biomechanical behaviour of various screw and screw-plate fixation configurations through finite element analysis (FEA).

2. Materials and methods

2.1. Study design

This FEA study was conducted under linear static loading conditions and homogenous isotropic linear elastic material model assumptions. Additionally, nonlinear contact behaviour between related components was considered. Tibial tubercle antero-medialisation osteotomy with distalisation was created, and the model was fixed with different screws and plate-screw configurations. A total of six simulation scenarios was set up and analyzed.

2.2. Modeling of the tibial tubercle osteotomy

The knee joint was modeled using computerised tomography (CT) data of a male patient (20 years old, 174 cm in height and 76 kg in weight), who presented to our clinic with recurrent patellar dislocation, to simulate a realistic model. In the radiological evaluation of the patient, there was patella alta (Caton–Deschamps index: 1.3), and the TT-TG distance was 23 mm. Based on both clinical examination and radiological assessments, the tibial tubercle antero-medialisation with distalisation was indicated in this patient.

CT examination was performed using the CT device (Siemens go. Up, Siemens, Munich, Germany) installed in the authors' institution. The scan parameters were as follows:120 KV, 30 mA, slice distance of 1.0 mm, FoV: 218 mm, from supracondylar femur down to the proximal tibia, a total of 232 axial slices. Written informed consent was taken from the patient to use the imaging files anonymously. Materialise Mimics–Medical 3D image-based engineering software (Materialise NV, Belgium), SolidWorks parametric solid modeling software (Dassault Systems SolidWorks Corp, Waltham, USA), and ANSYS Workbench FEA code (ANSYS, Ltd., Canonsburg, PA, USA) were employed in order to model and simulate the FEA scenarios, respectively.

The tibial tubercle antero-medialisation osteotomy with distalisation was created according to the previous descriptions of the technique. The osteotomy length was 72 mm, and the plane of the osteotomy cut was 45° according to the posterior condylar axis of the tibia. Ten millimetres of medialisation and 10 mm of distalisation were performed to normalise the TT-TG distance and correct the patella alta. Distalisation was achieved by removing a 10-mm bone fragment from the distal part. After completing the osteotomy, the model was fixed using either 4.5-mm or 3.5-mm cortical screws or 1/3 tubular plate screws made of Ti–6Al–4 V (Ti G5) alloy (Figure 1). There was no gap between the fragments at the osteotomy plane. A total of six different fixation scenarios was created (Figure 2).

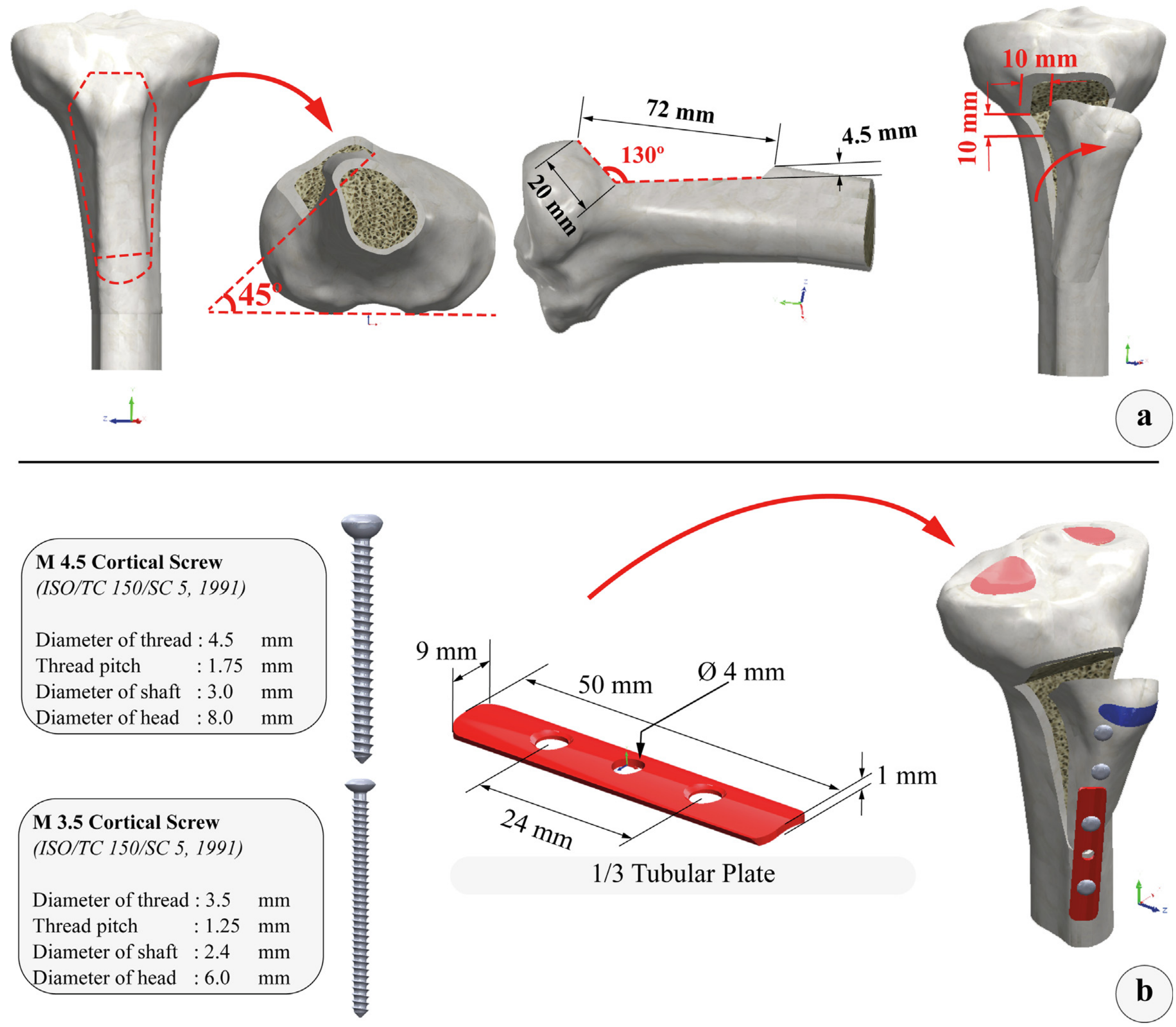


Figure 1. (a) Details of the tibial tubercle osteotomy. (b) Implants used for the fixation of the osteotomy and an example of the resultant solid model.

2.3. Boundary conditions and material properties

To imitate the tension force from the extensor mechanism, the model was loaded with a 1654-N traction force to the patellar tendon footprint at the tibial tubercle [15–17]. According to the biomechanical study conducted on fresh-frozen cadavers, Davis et al. [15] reported that the failure load of tibial tubercle osteotomy fixed with two 4.5-mm cortical screws was 1654 N. Thus, a worst-case scenario was created and tested in this FEA. The area of the patellar tendon footprint and the direction of force were determined from the CT data (Figure 3). The tibia was fixed at the bottom, and two supports were applied on the tibial condyles, medial and lateral, respectively. The contact definitions between 3D model components were included as frictional contact (nonlinear contact) between screw–bone surfaces and the fragment surfaces. Furthermore, bonded contact definitions were defined between cortical and trabecular bone. The implants were preloaded with 50 N as previously described [18]. The coefficients of friction are presented in Table 1 [18–21]. The material properties defined in the FEA were collected from previous literature. The material properties for cortical bone, trabecular bone, cortical screws, and 1/3 tubular plate were separately assigned under consideration of isotropic homogenous linear elastic material model assumptions (Table 2) [22–28].

2.4. The mesh structure of the models and its verification

The quality of the mesh structure of a model significantly affects the accuracy of an FEA simulation. Therefore, verification of the mesh structure is an important issue. One of the primary quality measures for a mesh structure in an FEA is the skewness metric. Skewness determines how close to ideal a face or cell is in a finite element model. The shape and asymmetry of a

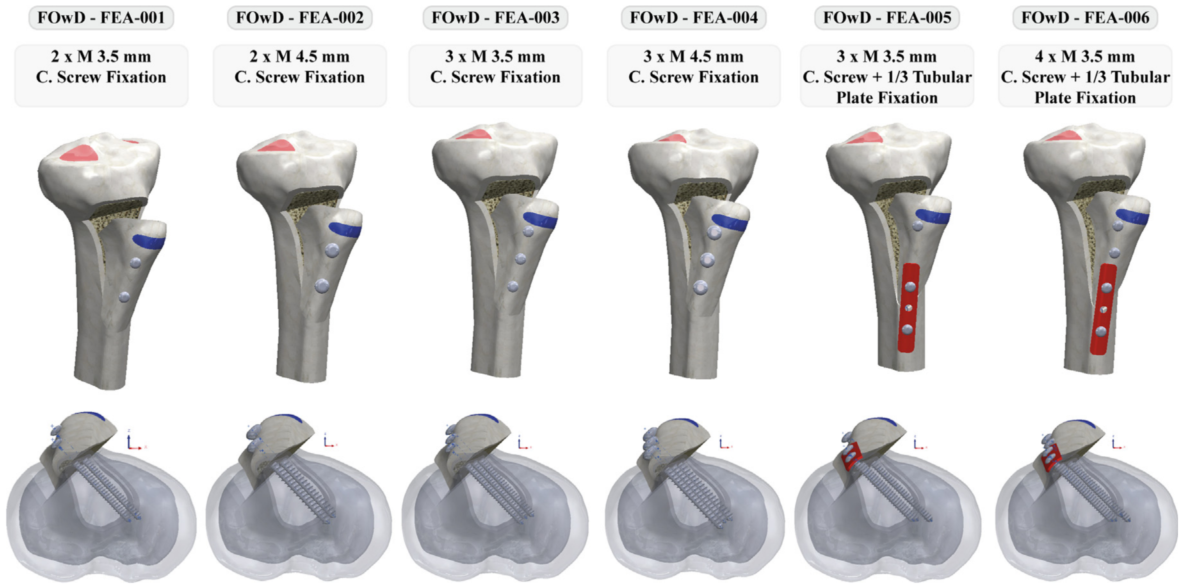


Figure 2. Solid models showing the configuration of the fixation and the implants. Note that the screws were inserted perpendicular to the osteotomy plane.

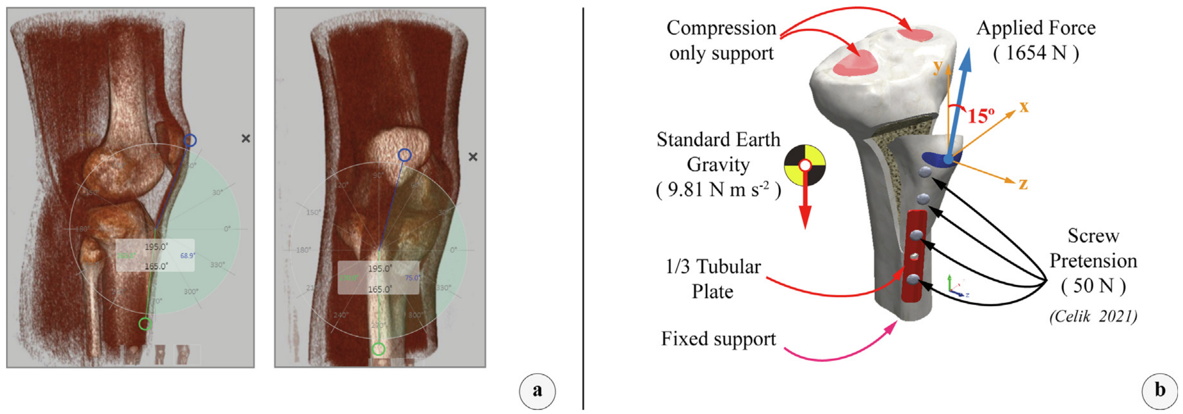


Figure 3. (a) Volume rendered 3D computerised tomography image from the lateral and anterior view. The patellar tendon footprint and the patellar tendon force vector were calculated. (b) Boundary condition of the models during loading.

Table 1
Coefficients of friction and fixation screw preload assigned in the finite element analysis set up.

Coefficient of friction between	Bony parts and fixation screw/plate	0.37
	Bony parts	0.46
Fixation Screw Preload (N)	50	

Table 2
Material properties assigned in the finite element analysis set up in accordance with the homogenous isotropic linear elastic material model.

Parameters	Unit	Model components		
		Cortical bone	Trabecular bone	Fixation screws and 1/3 tubular plate (Ti-6Al-4V)
Modulus of elasticity	(MPa)	19,100	1000.61	115,000
Poisson's ratio	(–)	0.30	0.30	0.33
Density	(kg m^{-3})	1980	830	4500

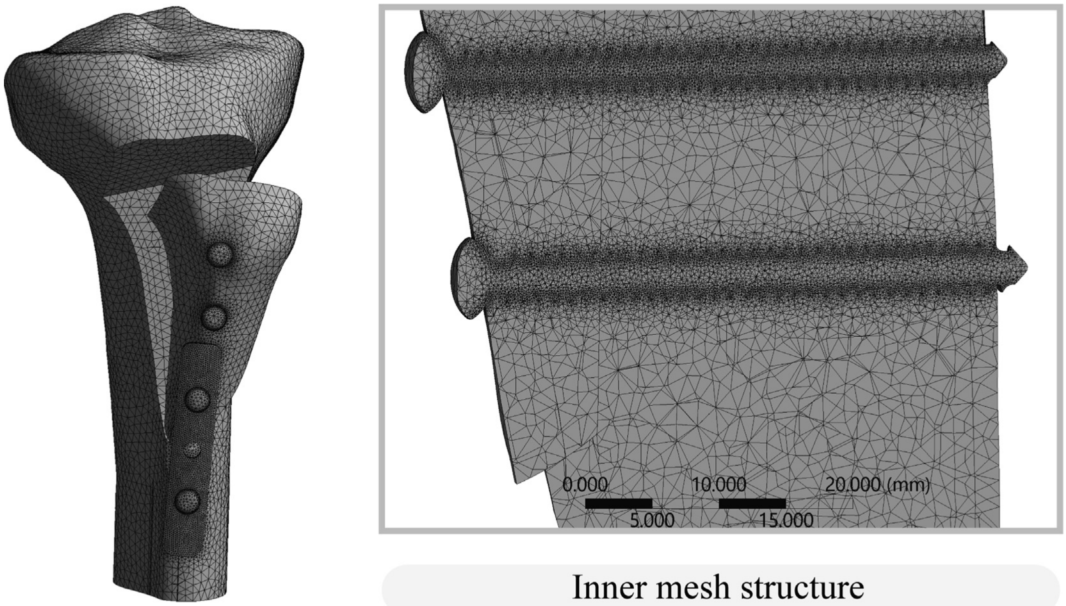


Figure 4. Finite element model mesh structure and the numerical details.

distribution can be measured by its skewness, providing mesh structure verification [29]. According to the definition of skewness in the analysis code, a value of zero (0) indicates an equilateral cell (best), and a value of one (1) indicates an entirely degenerate cell (worst) [30]. Therefore, skewness metric (mesh quality) control was performed to verify the mesh structure in this study. The skewness values showed good mesh quality with a mean of 0.285 ± 0.01 for all tested scenarios.

A curvature-based meshing strategy was utilised to create the final mesh structure of the solid models. An average of 1.28 million elements and 1.93 million nodes in total were obtained for all finite element models (detailed information is available in the Supplementary Material). A visual example of the meshing of the models is given in Figure 4. Finally, each simulation scenario was run separately with identical boundary conditions after completing the pre-processor steps, and then visual and numerical outputs were recorded. The solving platform was a Dell Precision M4800 Series (Intel Core™ i7 4910MQ CPU @ 2.90 GHz), NVIDIA Quadro K2100M-2 GB, and Physical Memory: 32 GB) mobile workstation.

2.5. Assessment of sliding and separation

The maximum separation and sliding distance magnitudes between the osteotomy fragments were calculated from the FEA results (Figure 5). Additionally, the equivalent (von Mises) stress and total deformation distributions on the fragments were extracted from the simulation results.

3. Results

In the screw-only groups (FEA-001–FEA-004), the highest values of gap formation (0.660 mm), maximum sliding (0.661 mm), and displacement (1.267 mm) were seen with two 3.5-mm screws, followed by two 4.5-mm screws (gap formation: 0.608 mm, maximum sliding: 0.522 mm, and displacement: 0.995 mm), three 3.5-mm screws (gap formation: 0.578 mm, maximum sliding: 0.353 mm, and displacement: 0.750 mm), and three 4.5-mm screws (gap formation: 0.590 mm, maximum sliding: 0.312 mm, and displacement: 0.680 mm), respectively. The three 3.5-mm screws with 1/3 tubular plate fixation model demonstrated better results (gap formation: 0.590 mm and maximum sliding: 0.312 mm) except displacement (0.696 mm) than the screw-only group. Overall, the most favourable results were seen with the four 3.5-mm screws with 1/3 tubular plate fixation model (gap formation: 0.410 mm, maximum sliding: 0.176 mm, and displacement: 0.618 mm) (Figure 6).

Under defined boundary conditions, any permanent deformation or damage was not detected on any of the analysed components; cortical bone, trabecular bone, and the screws. Maximum equivalent (Von Mises) stress values on each component were far less than their yield stress points reported in previous studies [22,26,31,32]. Visual simulation outputs of each scenario are presented in Figure 7.

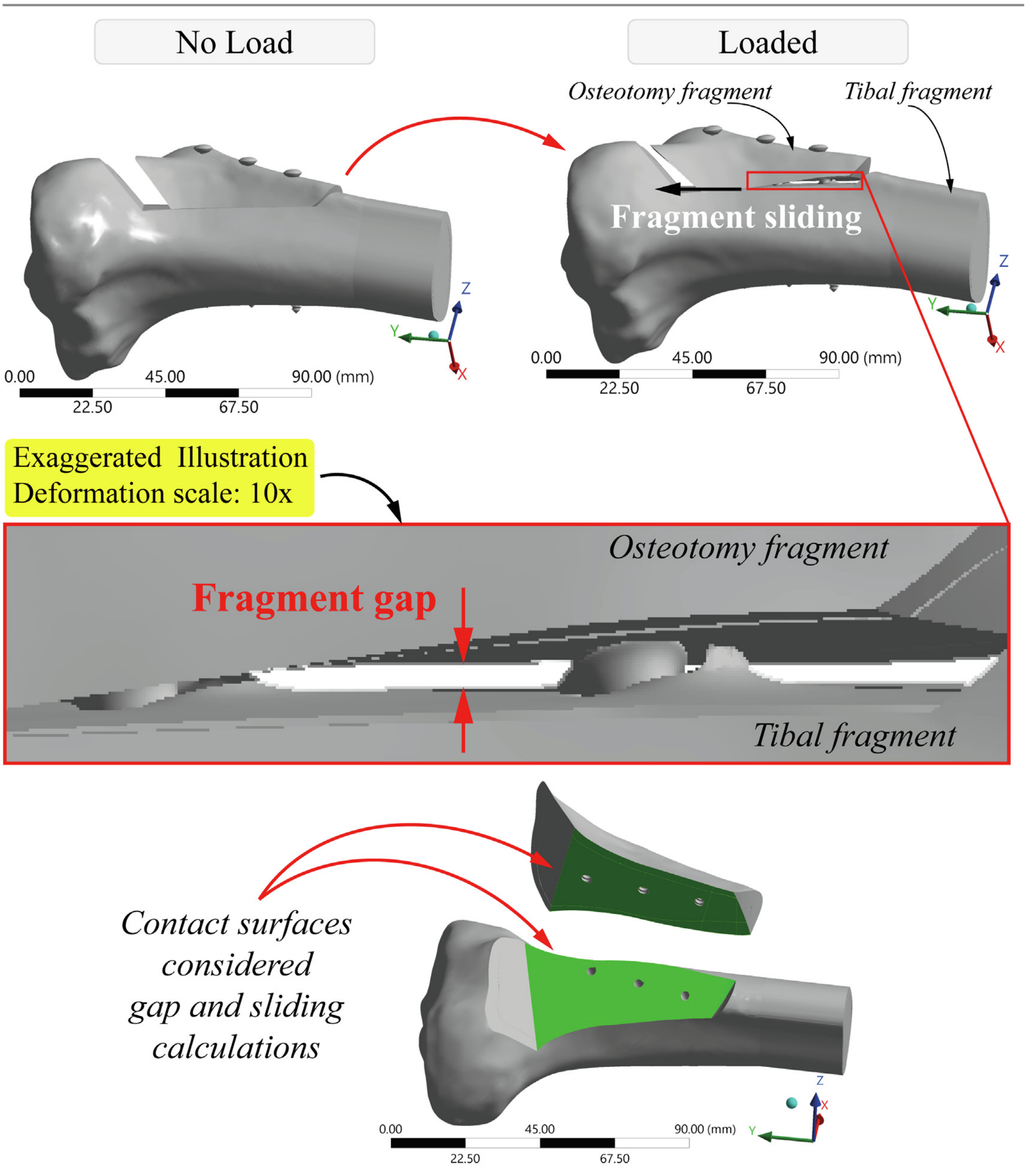
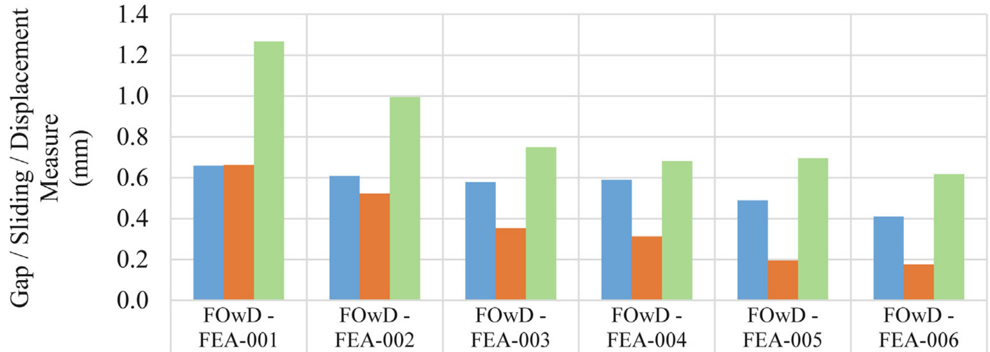


Figure 5. The sliding and the gap between the osteotomy fragment and the tibia were calculated after loading.

4. Discussion

The present study compared six different fixation models for Fulkerson osteotomy with distalisation using the finite element method. The first group comprised four different screw fixations that represented conventional fixation techniques, and the second group comprised two different plate-screw fixations that represented a relatively new fixation technique. Both the sliding and gap between fragments were higher in the screw-only fixation configurations. Three 4.5-mm screws inserted perpendicular to the osteotomy plane resulted in the highest stiffness among the screw-only fixation models. Plate fixation decreased shearing forces between the fragments and reduced the gap formation due to its buttress effect. Plating with four 3.5-mm screws provided the most robust construct among the tested models. Distalisation of Fulkerson osteotomy results in loss of proximal support and the distal continuity of the fragment, and is thus prone to complications related to fixation failure. Based on the results of this study, the use of tubular plate fixation might be suggested for Fulkerson osteot-



	FOwD - FEA-001	FOwD - FEA-002	FOwD - FEA-003	FOwD - FEA-004	FOwD - FEA-005	FOwD - FEA-006
Gap (mm)	0.660	0.608	0.578	0.590	0.489	0.410
Sliding (mm)	0.661	0.522	0.353	0.312	0.194	0.176
Resultant Displacement (Total Deformation) (mm)	1.267	0.995	0.750	0.680	0.696	0.618

Figure 6. The summary of sliding, gap formation, and total displacement.

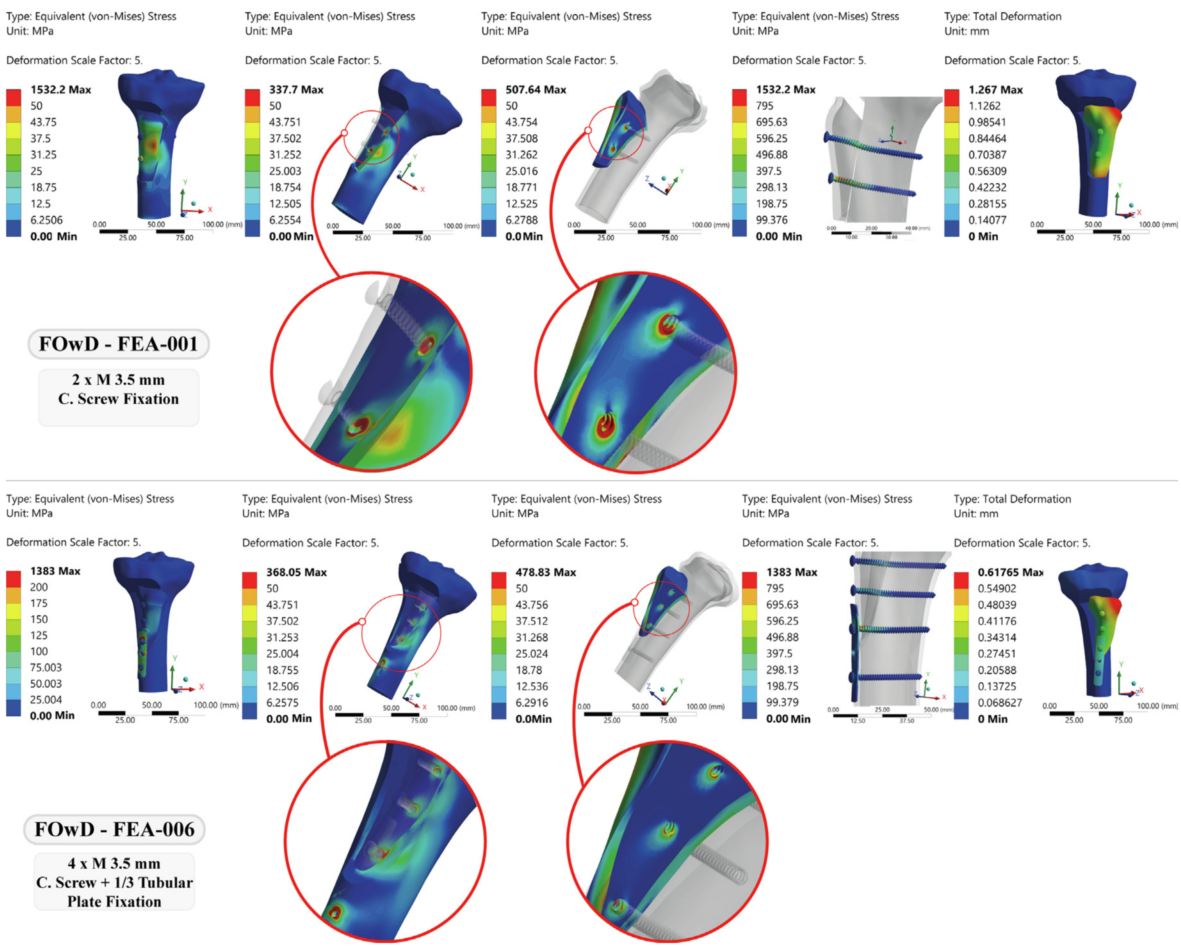


Figure 7. Visual simulation outputs showing the first (two 3.5-mm screws) and the last model (1/3 tubular plate with four 3.5-mm screws). See the Supplementary Material for all the data.

Table 3
List of previous studies on the biomechanical behaviour of the various fixation methods of tibial tubercle osteotomy.

Author	Year	Type of study	Model	Fixation methods	Results
Cosgarea et al. [36]	1999	Cadaver (13 pairs)	Fulkerson osteotomy Flat osteotomy	Two 3.5-mm screws (screw material unspecified)	Mean load to failure was significantly higher in the flat osteotomy specimens (1639 N vs. 1166 N, $P < 0.05$).
Warner et al. [13]	2013	Cadaver (five pairs)	Fulkerson osteotomy	Two 4.5-mm screws vs. Three 3.5-mm screws	Maximum failure load for osteotomies secured with two 4.5-mm screws was 1459 ± 540 N, and for three 3.5-mm screws, it was 1360 ± 707 N ($P = 0.723$).
Nurmi et al. [14]	2017	Cadaver (22 pairs)	Flat osteotomy	4.5-mm PLLA screws vs. 4.5-mm stainless-steel screws	The mean yield load was 566 ± 234 N in the bioabsorbable screw group and 984 ± 630 N in the metal screw group ($P = 0.002$).
Chang et al. [16]	2019	FEA	Flat osteotomy	Two titanium 4.5-mm screws with six configurations: parallel horizontal screws placed at a 20-mm interval, parallel horizontal screws placed at a 30-mm interval, parallel upward screws, parallel downward screws, trapezoid screws, and divergent screws	The configuration of two parallel downward screws yielded the highest stability with the lowest fragment displacement and gap opening. The configuration of two upward screws resulted in the highest fragment displacement and gap deformation between the fragment and tibia. The stress of the osteotomised bone fragment was highest with the configuration of two upward screws.
Chang et al. [17]	2019	FEA	Flat osteotomy with three fragment shapes: step cut, bevel cut, and straight cut	Two titanium 4.5 mm screws with three configurations: parallel horizontal screws with an interval of 20 mm, trapezoidal screws with an angle of 45, and parallel downward screws with an interval of 15 mm	The step cut resulted in higher stability than the bevel and straight cut, but the stress was higher as well. Among the screw configurations, two parallel downward screws resulted in the highest stability, given the same fragment shape. In the horizontal configuration, the step cut tibia developed the largest contact force to achieve stability of the bone fragment under loading.
Current study	2021	FEA	Fulkerson osteotomy + distalisation	Two 3.5-mm cortical screws Two 4.5-mm cortical screws Three 3.5-mm cortical screws Three 4.5-mm cortical screws Three 3.5-mm screws with 1/3 tubular plate Four 3.5-mm screws with 1/3 tubular plate	Maximum sliding (0.660 mm), gap formation (0.661 mm) and displacement (1.267 mm) were seen with two 3.5-mm screw fixation, followed by two 4.5-mm screws, three 3.5-mm screws, and three 4.5-mm screws, respectively, in the screw group. The minimum displacement was observed with plate and two 3.5-mm screw fixation models.

PLLA: poly-L-lactide; FEA: finite element analysis.

omy with distalisation. If screw fixation is preferred, three 4.5-mm cortical screws inserted perpendicular to the osteotomy plane might be a better choice.

Another significant issue in this study was that the screws were inserted perpendicular to the osteotomy plane but not to the posterior cortex. Because Fulkerson osteotomy is an oblique osteotomy, tips of the screws were directed towards the posteromedial cortex of the tibia. This configuration protects the neurovascular structures from iatrogenic injury during drilling and bicortical fixation. Two previous studies by Hernigou et al. [33] and Shetty et al. [34] described the safe zone for TTO fixation to avoid neurovascular injury. They reported that the posteromedial cortex is safe for bicortical fixation. Therefore, perpendicular fixation might be a better option both for stability and the reduced risk of neurovascular injury.

Several previous studies have been conducted to compare the fixation techniques of TTO [10–12,35]. However, the majority of those researches have focused on the osteotomies used to extend the surgical exposure in revision knee arthroplasty [12,35]. None of them has evaluated the effect of medialisation and distalisation. Only a few studies specifically assessed the biomechanical behaviour of oblique and flat TTO used for patellar instability (Table 3). Cosgarea et al. [36] reported a cadaveric study in which they compared the fixation strength of two 3.5-mm bicortical screws in oblique versus flat TTOs. Interestingly, they found that flat osteotomy was stronger despite a larger contact area in the oblique osteotomy. Warner et al. [13] compared two 4.5-mm and three 3.5-mm cortical screws in Fulkerson osteotomy in a cadaver model. They reported that 4.5-mm fixation resulted in higher stability than three 3.5-mm screws, similar to the results of the present study. Nurmi et al. [14] compared the bioabsorbable 4.5-mm screws made of poly-L-lactide (PLLA) with conventional stainless-steel screws on a flat osteotomy cadaver model. Because the mechanical properties of PLLA were weaker than stainless steel, the metallic screws demonstrated almost two-fold higher stiffness. But, bioabsorbable screws were still capable of withstanding patellar traction force during active knee extension.

The most common cause of secondary surgical intervention following TTO is the requirement for removal of the hardware because the soft tissue overlying tibial tubercle is thin, which is a frequent contact area during kneeling. Prominent screw heads might be symptomatic and necessitate implant removal [7]. In a recent systematic review, Saltzman et al. [37] reported a 19% overall incidence of implant removal in 1055 TTO procedures. In another systematic review, almost half of the cases (49%) required hardware removal after Fulkerson osteotomy [3]. Moreover, some authors reported routine implant removal in all patients (100%) regardless of symptoms [38,39]. Thus, using bioabsorbable screws to fix the tibial tubercle may prevent secondary procedures and thus avoid any additional expenses. Furthermore, Ünal et al. [40] have reported the clinical efficiency of 4.8 mm magnesium bioabsorbable screws in the fixation of Fulkerson osteotomy in 10 patients.

Besides these cadaver studies, two FEA studies evaluated the fixation of TTO [16,17]. Both studies focused on the TTO used in knee arthroplasty extended exposure. The first study compared the fixation of flat osteotomy with two 4.5-mm titanium screws implanted in parallel horizontal, parallel downward, parallel upward, trapezoid, and divergent configurations [16]. The authors reported that two parallel downward screw configurations had demonstrated the highest stability as well as the least magnitude of fragment displacement and gap opening. The second study compared the three configurations of TTO (step-cut, bevel-cut, and straight-cut), in addition to various two 4.5-mm screw configurations [17]. Step-cut was found to be the most stable TTO.

The present study is distinct from the previous studies in several aspects. First of all, CT images of a patient with excessive lateralisation of the tibial tubercle and patella alta have been utilised for the modelling. Thus, the model is much more realistic compared with the previous studies. The second distinctive feature is the assessment of the effect of distalisation. Due to loss of proximal support and distal continuity with the distalisation procedure, the fixation of this sort of osteotomy should be performed more meticulously. The third distinctive feature is the inclusion and biomechanical assessment of the plate-screw configurations.

Patella alta has been demonstrated as a strong predisposing risk factor for recurrent PF instability, and approximately one-quarter of patients have patella alta in combination with other risk factors [41]. In the current treatment algorithms of PF instability, the distalisation procedure is recommended in the presence of patella alta despite controversies that exist [42]. The distalisation procedure brings some problems, particularly regarding the union of the osteotomy. In a series of 153 patients (122 standard Fulkerson osteotomies versus 31 Fulkerson osteotomy and distalisation procedure), Johnson et al. [7] reported a significant rate of a delayed union in the distalisation group. Payne et al. [3] reviewed 19 studies including 787 tibial tubercle osteotomies. They also reported a high risk of complications (10.7%) related to the distalisation procedures that involve complete detachment of the tubercle. All these previous studies suggest that more stable fixation is required for these patients. An optimal fixation technique should allow early rehabilitation and weight-bearing, resulting in complete bony union and reducing complications regarding hardware. In the relevant literature, a single clinical study, conducted by Stevens et al. [10], has described plate fixation to address all these problems and reported 30 consecutive patients treated with TTO and distalisation procedure. Union was observed in all patients, and only one screw breakage was observed. Similarly, the present study indicates greater stability of plate-screw fixation models than the stability of screw fixation models. Distal placement of the plate-screw constructs appears to provide a buttress effect on the fragment, thus diminishing the magnitudes of proximal sliding and gap formation. The findings of this study shed light on these clinical results and provide a biomechanical explanation.

The present study has some strengths and limitations. First, the limitations specific to the FEA should be kept in mind. Various predefined assumptions, including boundary conditions, material properties, and modelling, were applied. But, a pathological tibia was used to obtain a realistic model. Cortical bone and trabecular bone were modelled separately, and bonded contact definitions were defined. Multiple scenarios were studied. Although the model was not verified with a cadaveric study, the current research is valuable in understanding the biomechanical behaviour of TTOs.

5. Conclusions

The outputs of this FEA favour the fixation with the plate and screw combinations in TTO. Plate and screw fixation prevents superior migration of the fragment and gap formation by its buttress and anchor effect. Early rehabilitation, including active range of motion exercises and weight-bearing, might be allowed with plate-screw fixation combinations. However, the plate-screw fixation increases the costs, moreover the risk of skin irritation and subsequent implant removal. Thus, the pros and cons should be carefully weighed.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.knee.2022.06.002.

References

[1] Knapik DM, Kunze KN, Azua E, Vadhera A, Yanke AB, Chahla J. Radiographic and clinical outcomes after tibial tubercle osteotomy for the treatment of patella alta: A systematic review and meta-analysis. Am J Sports Med 2021;26. doi: https://doi.org/10.1177/03635465211012371.

[2] Dejour H, Walch G, Nove-Josserand L, Guier C. Factors of patellar instability: an Anatomic radiographic study. Knee Surg Sports Traumatol Arthrosc 1994;2(1):19–26. doi: https://doi.org/10.1007/BF01552649.

[3] Payne J, Rimmke N, Schmitt LC, Flanigan DC, Magnussen RA. The incidence of complications of tibial tubercle osteotomy: A systematic review. Arthroscopy 2015;31(9):1819–25. doi: https://doi.org/10.1016/j.arthro.2015.03.028.

[4] Noyes FR, Barber-Westin SD. Operative options for extensor mechanism malalignment and patellar dislocation. In: Noyes FR, editor. Noyes' Knee Disorders: Surgery, Rehabilitation, Clinical Outcomes, 2nd ed., Philadelphia: Elsevier; 2017, p. 970-1013. https://doi.org/10.1016/B978-0-323-32903-3.00035-4.

[5] Fulkerson JP, Becker GJ, Meaney JA, Miranda M, Folcik MA. Anteromedial tibial tubercle transfer without bone graft. Am J Sports Med 1990;18(5):490–6. doi: https://doi.org/10.1177/036354659001800508. discussion 496-7.

[6] Maffulli N. Editorial commentary: Standing the test of time and sport: Fulkerson tibial tubercle osteotomy of the knee. Arthroscopy 2018;34(4):1030–1. doi: https://doi.org/10.1016/j.arthro.2017.12.023.

[7] Johnson AA, Cosgarea AJ, Wolfe EL. Complications of tibial tuberosity osteotomy. Sports Med Arthrosc Rev 2017;25(2):85–91. doi: https://doi.org/10.1097/JSA.0000000000000151. Erratum in: Sports Med Arthrosc Rev. 2018;26(2):86. Wolfe, Elizabeth L [added].

[8] Yang JS, Fulkerson JP, Obopilwe E, Voss A, Divenere J, Mazzocca AD, et al. Patellofemoral contact pressures after patellar distalization: A biomechanical study. Arthroscopy 2017;33(11):2038–44. doi: https://doi.org/10.1016/j.arthro.2017.06.043.

[9] Leite CBG, Santos TP, Giglio PN, Pécora JR, Camanho GL, Gobbi RG. Tibial tubercle osteotomy with distalization is a safe and effective procedure for patients with patella alta and patellar instability. Orthop J Sports Med 2021. doi: https://doi.org/10.1177/2325967120975101.

[10] Stevens JM, Barton SB, Alexander M, Eldridge JD, Clark D. Plate and screw fixation of arthroscopically assisted tibial tuberosity osteotomy: Technique and results. Eur J Orthop Surg Traumatol 2020;30(1):139–45. doi: https://doi.org/10.1007/s00590-019-02536-x.

[11] Frame M, Hauck O, Newman M, Cirtautas A, Wijdicks C. Suture tape augmentation of screw fixation reduces fragment migration in tibial tubercle osteotomy: A biomechanical study. Orthop J Sports Med 2021;9(10). doi: https://doi.org/10.1177/23259671211038495.

[12] Caldwell PE, Bohlen BA, Owen JR, Brown MH, Harris B, Wayne JS, et al. Dynamic confirmation of fixation techniques of the tibial tubercle osteotomy. Clin Orthop Relat Res 2004;424:173–9. doi: https://doi.org/10.1097/01.blo.0000130205.57095.a2.

[13] Warner BT, Kamath GV, Spang JT, Weinhold PS, Creighton RA. Comparison of fixation methods after anteromedialization osteotomy of the tibial tubercle for patellar instability. Arthroscopy 2013;29(10):1628–34. doi: https://doi.org/10.1016/j.arthro.2013.06.020.

[14] Nurmi JT, Itälä A, Sihvonen R, Sillanpää P, Kannus P, Sievänen H, et al. Bioabsorbable versus metal screw in the fixation of tibial tubercle transfer: A cadaveric biomechanical study. Orthop J Sports Med 2017;5(7). doi: https://doi.org/10.1177/2325967117714433.

[15] Davis K, Caldwell P, Wayne J, Jiranek WA. Mechanical comparison of fixation techniques for the tibial tubercle osteotomy. Clin Orthop Relat Res 2000;380:241–9. doi: https://doi.org/10.1097/00003086-200011000-00033.

[16] Chang CW, Chen YN, Li CT, Chung CR, Tseng CC, Chang CH, et al. Biomechanical investigation of tibial tubercle osteotomy fixed with various screw configurations. Injury 2019;50(2):263–71. doi: https://doi.org/10.1016/j.injury.2018.12.004.

[17] Chang CW, Chen YN, Li CT, Chung CR, Chang CH, Peng YT. Finite element study of the effects of fragment shape and screw configuration on the mechanical behaviour of tibial tubercle osteotomy. J Orthop Surg (Hong Kong) 2019;27(3). doi: https://doi.org/10.1177/2309499019861145.

[18] Celik T. Biomechanical evaluation of the screw preload values used in the plate placement for bone fractures. Proc Inst Mech Eng H 2021;235(2):141–7. doi: https://doi.org/10.1177/0954411920964628.

[19] Gao X, Fraulob M, Haïat G. Biomechanical behaviours of the bone-implant interface: a review. J R Soc Interface 2019;16(156):20190259. doi: https://doi.org/10.1098/rsif.2019.0259.

[20] Hayes WC, Perren SM. Plate-bone friction in the compression fixation of fractures. Clin Orthop Relat Res 1972;89:236–40.

[21] Eberle S, Gerber C, von Oldenburg G, Högel F, Augat P. A biomechanical evaluation of orthopaedic implants for hip fractures by finite element analysis and in-vitro tests. Proc Inst Mech Eng H 2010;224(10):1141–52. doi: https://doi.org/10.1243/09544119JEIM799.

[22] Dong XN, Acuna RL, Luo Q, Wang X. Orientation dependence of progressive post-yield behaviour of human cortical bone in compression. J Biomech 2012;45(16):2829–34. doi: https://doi.org/10.1016/j.jbiomech.2012.08.034.

[23] Wang X, Nyman JS, Dong X, Leng H, Reyes M. Fundamental biomechanics in bone tissue engineering. Synthesis Lectures Tissue Eng 2010;2(1):1–225. doi: https://doi.org/10.2200/s00246ed1v01y200912tis004.
[24] Kim SH, Chang SH, Jung HJ. The finite element analysis of a fractured tibia applied by composite bone plates considering contact conditions and time-varying properties of curing tissues. Compos Struct 2010;92:2109–18. doi: https://doi.org/10.1016/j.compstruct.2009.09.051.
[25] Klekiel T, Będziński R. Finite element analysis of large deformation of articular cartilage in upper ankle joint of occupant in military vehicles during explosion. Arch Metall Mater 2015;60:2115–21. doi: https://doi.org/10.1515/amm-2015-0356.
[26] Oldani C, Dominguez A. "Titanium as a biomaterial for implants," in Recent Advances in Arthroplasty (InTech) 2012. http://www.intechopen.com/books/recent-advances-inarthroplasty/titanium-as-a-biomaterial-for-implants [accessed 30 November 2021].
[27] Alonso-Rasgado T, Jimenez-Cruz D, Karski M. 3-D computer modelling of malunited posterior malleolar fractures: Effect of fragment size and offset on ankle stability, contact pressure and pattern. J Foot Ankle Res 2017;10:13. doi: https://doi.org/10.1186/s13047-017-0194-5.
[28] Novitskaya E, Zin C, Chang N, Cory E, Chen P, D'Lima D, et al. Creep of trabecular bone from the human proximal tibia. Mater Sci Eng C Mater Biol Appl 2014;40:219–27. doi: https://doi.org/10.1016/j.msec.2014.03.057.
[29] Brys G, Hubert M, Struyf A. A robust measure of skewness. J Comput Graph Stat 2004;13(4):996–1017. doi: https://doi.org/10.1198/106186004X12632.
[30] ANSYS Product Doc. ANSYS Meshing User's Guide: Skewness (Release 2019 R2). ANSYS Inc, USA. https://ansyshelp.ansys.com/account/secured?returnurl=/Views/Secured/corp/v191/wb2_help/wb2_help.html [accessed 25 September 2020].
[31] Jensen NC, Hvid I, Krøner K. Strength pattern of cancellous bone at the ankle joint. Eng Med 1988;17(2):71–6. doi: https://doi.org/10.1243/emed_jour_1988_017_020_02.
[32] Sierpowska J, Hakulinen MA, Töyräs J, Day JS, Weinans H, Jurvelin JS, et al. Prediction of mechanical properties of human trabecular bone by electrical measurements. Physiol Meas 2005;26(2):S119–31. doi: https://doi.org/10.1088/0967-3334/26/2/012.
[33] Hernigou J, Chahidi E, Kashi M, et al. Risk of vascular injury when screw drilling for tibial tuberosity transfer. Int Orthop 2018;42(5):1165–74. doi: https://doi.org/10.1007/s00264-017-3554-7.
[34] Shetty AA, Tindall AJ, Nickolaou N, James KD, Ignotus P. A safe zone for the passage of screws through the posterior tibial cortex in tibial tubercle transfer. Knee 2005;12(2):99–101. doi: https://doi.org/10.1016/j.knee.2004.03.010.
[35] Chalidis B, Kitridis D, Givissis P. Tibial tubercle osteotomy in revision total knee arthroplasty: A systematic review. World J Orthop 2020;11(6):294–303. doi: https://doi.org/10.5312/wjo.v11.i6.294.
[36] Cosgarea AJ, Schatzke MD, Seth AK, Litsky AS. Biomechanical analysis of flat and oblique tibial tubercle osteotomy for recurrent patellar instability. Am J Sports Med 1999;27(4):507–12. doi: https://doi.org/10.1177/03635465990270041601.
[37] Saltzman BM, Rao A, Erickson BJ, Cvetanovich GL, Levy D, Bach Jr BR, et al. A systematic review of 21 tibial tubercle osteotomy studies and more than 1000 knees: Indications, clinical outcomes, complications, and reoperations. Am J Orthop (Belle Mead NJ) 2017;46(6):E396–407.
[38] Tecklenburg K, Feller JA, Whitehead TS, Webster KE, Elzarka A. Outcome of surgery for recurrent patellar dislocation based on the distance of the tibial tuberosity to the trochlear groove. J Bone Joint Surg Br 2010;92(10):1376–80. doi: https://doi.org/10.1302/0301-620X.92B10.24439.
[39] Shelbourne KD, Porter DA, Rozzi W. Use of a modified Elmslie-Trillat procedure to improve abnormal patellar congruence angle. Am J Sports Med 1994;122:318–23. doi: https://doi.org/10.1177/036354659402200304.
[40] Ünal M, Demirayak E, Ertan MB, Kilicaslan OF, Kose O. Bioabsorbable magnesium screw fixation for tibial tubercle osteotomy; a preliminary study [accessed 27 November 2021]. Acta Biomed [Internet] 2021;92(6). https://mattioli1885journals.com/index.php/actabiomedica/article/view/11716.
[41] Magnussen RA, De Simone V, Lustig S, Neyret P, Flanigan DC. Treatment of patella alta in patients with episodic patellar dislocation: a systematic review. Knee Surg Sports Traumatol Arthrosc 2014;22(10):2545–50. doi: https://doi.org/10.1007/s00167-013-2445-8.
[42] Dejour DH, Mesnard G, Giovannetti de Sanctis E. Updated treatment guidelines for patellar instability: "un menu à la carte". J Exp Orthop 2021. doi: https://doi.org/10.1186/s40634-021-00430-2.