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Review

Current treatment strategies for hyperextension fractures of the tibial plateau: A systematic review and proposal of a treatment algorithm

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ABSTRACT

Objective: Analyze the current evidence on the treatment and outcomes of hyperextension fractures of the tibial plateau and propose a treatment algorithm.
Methods: An electronic search at PubMed/MEDLINE, Cochrane Library, Embase, and Google Scholar database from December 24th, 2023 to June 26th, 2024 was carried out. The terms for the database search included "Hyperextension AND Tibial plateau fractures" and "Reversed Tibial Slope AND Tibial Plateau Fractures". The research inclusion criteria were scientific articles written in English that addressed hyperextension fractures of the tibial plateau. Studies that have not specifically addressed hyperextension fractures of the tibial plateau or published in a different language than English were excluded. Considering that hyperextension fractures of the tibial plateau are relatively rare and the literature is scarce, studies with all levels of evidence were included. Critical analysis of titles, abstracts, inclusion and exclusion criteria of all potentially eligible articles was performed. A treatment algorithm based on the literature and authors perspective was proposed.
Results: The search identified 34 potentially eligible studies. After application of inclusion and exclusion criteria, 22 articles were carefully analyzed in terms of the most relevant topics related to hyperextension fractures of the tibial plateau. An analysis of the risk of bias of the selected studies was performed according to the Cochrane Risk of Bias in Non-Randomized Studies of Interventions (ROBINS-I).
Conclusion: There is no consensus regarding the gold standard treatment method for this challenging fracture pattern. The hyperextension mechanism is a predictor of worse functional outcome and life quality comparing to other types of tibial plateau fractures.
Study design: Systematic review of the literature (Level of evidence:1)

Introduction

Hyperextension fractures of the tibial plateau represent a challenging subset of knee injuries that primarily affect the sagittal alignment of the tibial condyles, causing inversion of the tibial slope [1]. Hyperextension fractures of the tibial plateau account presumably for less than 20 % of all bicondylar tibial plateau fractures [2]. Usually, hyperextension tibial plateau fractures result from high-energy trauma caused by motor vehicle accidents, falls, or sports-related injuries, wherein the knee undergoes excessive extension, associated or not with varus or valgus deformities. Hyperextension fractures have also been noticed due to low-energy mechanism of injury in elderly patients [1]. Firoozabadi et al. [3] characterized hyperextension tibial plateau fractures as a result of tension forces applied to the posterior cortex of the proximal tibia and compression forces to the anterior cortex, resulting in disruption the continuity of those cortices, and consequently, promoting the inversion of the tibial plateau slope in the sagittal plane. Gonzalez et al. [2] also defined the hyperextension fracture of the tibial plateau as

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the presence of anteromedial or/and anterolateral compression fractures, tension failure of partial or total posterior cortex, or proximal fibular avulsion fractures, and a posterior tibial slope angle of less than 11°

When the knee is hyperextended, the joint may become grossly unstable due to the loss of continuity of the tibial rim, joint incongruency, and associated soft tissue injuries, such as anterior cruciate ligament, posterior cruciate ligament, lateral or medial collateral ligaments (depending on the varus/valgus mechanism, respectively), posterolateral corner structures, capsule and menisci, in addition to the popliteal artery and the peroneal nerve [1–3]. These fractures pose intricate management considerations due to their unique biomechanics and potential for complications. Accurate diagnosis relies on the understanding of the injury mechanism, clinical exam, and interpretation of image studies, including advanced imaging to characterize the fracture pattern, the main plane of the fracture, and associated soft tissues injuries.

This study aims to comprehensively explore the intricacies of hyperextension fractures of the tibial plateau, highlighting the injury mechanism, classification, associated injuries, reduction and fixation strategies, outcomes, and complications. Multiple strategies have been reported, but no standard guidelines exist to approach hyperextension tibial plateau fractures. Our goal is to offer the results of a systematic review about the topic, highlighting the assessment, decision making, and available therapeutic options. In addition, we describe a treatment strategy to support the orthopedic surgeon in the decision-making process when dealing with this injury.

Methods

We conducted a Systematic Review of the literature using the Preferred Reporting Items for Systematic Reviews and Meta-Analyses guidelines [4]. Prior to data extraction, the study protocol was registered in PROSPERO (the International Prospective Register of Systematic Reviews), under the number CRD42024497917. An electronic search at PubMed/MEDLINE, Cochrane Library, Embase, and Google Scholar database from December 24th, 2023 to June 26th, 2024 was carried out. The terms for the database search included “Hyperextension AND Tibial Plateau Fractures” and “Reversed Tibial Slope AND Tibial Plateau Fractures”. The PICOS [5] strategy was used to address Participants (patients with hyperextension fractures of the tibial plateau), Intervention (treatment with or without fracture fixation), Comparison (different fixation strategies / non-hyperextension fractures of the tibial plateau), Outcomes (functional and radiographic outcomes, life quality, and complications), and Study Design (all study designs were included due to the rarity of hyperextension fractures of the tibial plateau). The research inclusion criteria were scientific articles written in English language that addressed hyperextension fractures of the tibial plateau. Articles with no reference to the sagittal plane or to mechanism of injuries compromising the alignment of the tibial slope were excluded. Considering the paucity of data about this topic in the literature, we included studies with all levels of evidence. We performed a critical assessment of manuscripts’ titles, abstracts, factoring in the inclusion, and exclusion criteria of all potentially eligible articles. Two investigators independently reviewed the selected full-text articles for confirming inclusion. In case of disparities between the reviewers, a consultation with a senior researcher was undertaken to reach a consensus. A qualitative and critical analysis of risk of bias of the selected studies was performed using the Cochrane Risk of Bias in Non-Randomized Studies of Interventions (ROBINS-I) [6]. The studies were analyzed using seven possible domains to detect the risk of bias (Table 1).

Table 1
Bias domains included in ROBINS-I.

Domain
Pre-intervention
D1 Bias due to confounding
D2 Bias in selection of participants into the study
At intervention
D3 Bias in classification of interventions
Post-intervention
D4 Bias due to deviations from intended interventions
D5 Bias due to missing data
D6 Bias in measurement of outcomes
D7 Bias in selection of the reported result

Results

22 studies were considered eligible for this systematic review, after the analysis conclusion, and the removal of duplicates. The Fig. 1 depicts the review process culminating with the selection of eligible studies, according to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses 2020 [4] (Fig. 1).

No prospective, randomized studies were found in the literature, confirming the scarcity of available high evidence data about this topic. The analysis of the risk of bias of the selected studies is presented in Table 2, according to the Cochrane Risk of Bias in Non-Randomized Studies of Interventions (ROBINS-I) [6] (Table 2).

The literature highlights important information regarding management of hyperextension fractures of the tibial plateau [7–20]. The reviewed studies address the fracture pattern (morphology and classification), injury mechanism, epidemiology, diagnosis, and treatment strategies based on biomechanical and clinical aspects, as well as complications, and life quality [21–36]. We listed categories evaluated in each study, aiming to facilitate data assessment and comparison, as described in Table 3.

Discussion

The management of hyperextension fractures of the tibial plateau remains controversial. Although the topic is undoubtedly relevant, and the complication rates are extremely high, the literature is scarce and lacks prospective studies to more appropriately support a standard treatment strategy [8].

For didactic reasons, a critical analysis of the literature will be thoroughly presented in the form of topics, followed by the presentation of the proposed treatment protocol, supported by cases.

Classification of hyperextension fractures of the tibial plateau

Several classification systems were developed for tibial plateau fractures, but only in the recent years the hyperextension patterns reached the spotlight.

The Kfuri-Schatzker [23] CT-based classification system provides an understanding of the injury mechanism, the three-dimensional location of the main fracture plane, and what component of the fracture makes it unstable. Therefore, this system may help with the decision making about surgical approaches and how to restore and maintain the continuity of the tibial plateau rim. Using the axial view of the CT-scan, and/or the 3D reformations, it is possible to identify the area of discontinuity of the tibial plateau rim, and the pattern of the discontinuity, guiding the surgeon to restore the continuity of the tibial plateau rim, and to maintain it by means of buttressing the newly restored periphery of the tibial plateau, providing stability to the joint.

Luo et al. [24] proposed the three-column (medial, lateral, and posterior) concept and highlighted the importance of the posterior column fixation, but at this publication the authors did not address in details the hyperextension fracture pattern. Sheehan et al. [25] divided the hyperextension injuries into pure hyperextension, hyperextension with valgus, and hyperextension with varus in the coronal plane, but the authors did not elaborate an analysis of these injuries in the sagittal

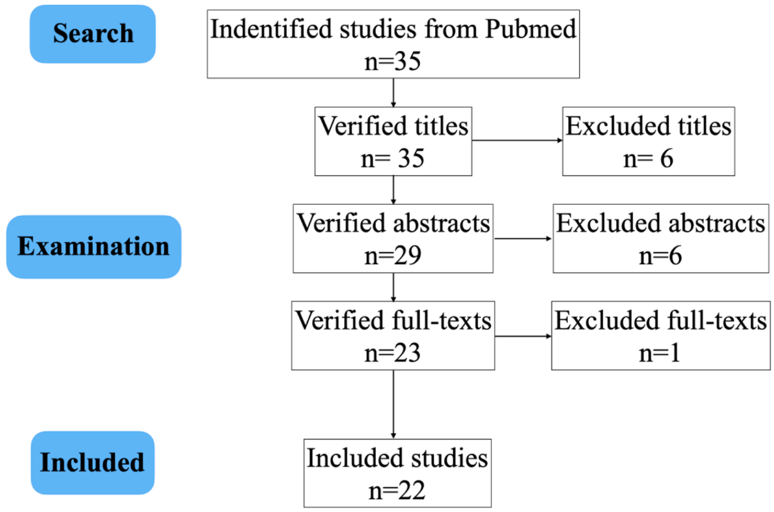

Fig. 1. Literature review flowchart according to the PRISMA method for systematic review of the literature.

plane. Zhang et al. [26] classified the hyperextension fractures of the tibial plateau into small type, large type, and combined type, based on the axial images of the computed tomography.

In the four-column and nine-segment classification system proposed by Yao et al. [27–28], the tibial plateau and fibula were divided into different anatomical segments, labeled from "a" to "i" and identified on the axial plane of the computed tomography. Hyperextension fractures of the tibial plateau were divided into four types based on the coronal plane analysis: pure hyperextension fracture (segment d), hyperextension-varus fracture (segments $a+ d$), hyperextension–valgus fracture (segments $d+ g$), and hyperextension–bicondylar fracture (segments $a+ d+ g$). Based on the injury morphology of the bare area (segment d) and posteroinferior cortex in the sagittal plane, hyperextension patterns were also divided into three injury types: type 1, pure depression of the bare area; type 2, cleavage extending to the posterior cortex with no displacement; and type 3, cleavage extending to the posterior cortex with significant displacement [28] (Fig. 2).

In our practice, we use the Kfuri-Schatzker [23] and the Yao et al. [27,28] classification systems, since both are based on the injury mechanism, and the three-dimensional anatomical location of the fracture, differentiating the posterior tibial rim into posterolateral and posteromedial, facilitating the understanding and decision-making process regarding approach selection, reduction, and fixation strategies.

However, there are still some limitations of existing classification systems, such as the lack of importance given to associated soft tissue damage and the potential residual instability after bony fixation, as observed in some of the studies included in this systematic review [3,7]. Furthermore, residual instability, although not described as a complication in some studies, can be seen as one of the causes for rapid progression to post-traumatic osteoarthritis [2,17]. Therefore, surgeons should be aware that an associated fracture of the proximal fibula or the posteromedial aspect of the tibia may represent injury to the posterolateral corner or posterior cruciate ligament of the knee, respectively. Due to the complications and poor prognosis associated with an unstable knee, an accurate examination of the knee capsuloligamentous complex should be performed after definitive bony stabilization and, if necessary, existing injuries should be repaired as soon as possible. Schatzker and Kfuri [29] focus in the two anatomical areas of each tibial condyle. The area covered by cartilage, which main function is to serve as a weight bearing area, and the areas of bare bone, namely the tibial rim and the tibial spine, which are sites for soft tissues attachments and directly involved in joint stability. Hyperextension injuries compromise the continuity of the anterior cortical rim of the tibial plateau. The condyles of the femur no longer have a contained opposite surface to face, and therefore the weight bearing may result in excessive extension of the femoral condyles over the tibial condyles. Depending on the magnitude of the axial loading, the tibial spines may be avulsed, cruciate ligament attachments may be compromised, and the posterior capsule of the knee may be stretched out. Besides the impaction to the anterior rim of the tibial plateau, associated soft tissues injuries may contribute to the pattern of instability. Therefore, MRI studies may be beneficial in injury patterns that imply damage to the soft tissues prior to a surgical intervention and the implantation of hardware, facilitating the complete understanding of the injury and therapeutic planning.

Current management of hyperextension fractures of the tibial plateau

Hyperextension fractures of the tibial plateau still represent a real challenge for the orthopedic trauma surgeon due to several intrinsic characteristics: 1- Knee instability related to meniscus tear and ligament injuries can be associated. Therefore, seemingly innocent peripheral fractures can hide serious instability. In cases of knee instability after fracture fixation, it is important to consider repair of peripheral ligament injuries and/or fixation of avulsion fractures; 2- Hyperextension fractures can determine loss of the tibial plateau perimeter and/ or shear pattern. It is essential to identify if the fracture pattern is mainly an impaction, where the split wedge is longer horizontally, or predominantly a shearing, where the split wedge is longer longitudinally [23, 29]; 3- The fracture reduction is demanding. Anterior maneuvers can lead to posterior displacement. If the posterior tension hinge is displaced, it is of paramount importance to restore it before reduction of the anterior impaction [3]; 4- After reduction of the anterior impaction with restoration of the tibial slope, a significant anterior wedge gap develops. If a stable construct cannot be achieved with plate fixation, one must consider a structural support provided by either a bone graft or a metal cage applied to the defect [3]; 5- The bone stock for fixation of the subchondral area can be poor, hindering traditional fixation techniques applied for tibial plateau fixation, even using precontoured locking plates.

The literature is still controversial regarding approaches. Although the midline anterior approach can be a rational alternative considering that the anterior impaction is the major displacement and the possibility of a future arthroplasty, excessive soft tissue devitalization may be necessary to address the whole injury, especially in bicondylar hyperextension fractures [14]. In addition, if the posterior hinge is displaced and cannot be restored with anterior maneuvers, the posteromedial approach is indicated [1,3]. Identifying the injury mechanism, fracture location, and the displacement of the posterior hinge is the key for the

Table 2
Evaluation of cochrane risk of bias in non-randomized studies of interventions (ROBINS-I) visualized in traffic light plots for each individual domain, using the Robvis tool of visualization.

Study	D1	D2	D3	D4	D5	D6	D7	**Overall**
Li et al. [7]	?	?	?	?	X	X	X	X
Bu et al. [8]	-	+	+	+	+	-	+	+
Xu et al. [9]	-	+	+	+	+	-	+	+
Gonzalez et al. [2]	-	+	+	+	+	+	+	+
Wakefield et al. [10]	?	?	?	?	X	X	X	X
Firoozabadi et al. [3]	-	-	+	+	-	-	-	-
Jung et al. [1]	?	?	?	?	?	?	?	X
Zhao et al. [11]	-	-	-	-	-	-	-	-
O'Neill et al. [12]	-	-	-	-	-	+	+	+
Huang et al. [13]	-	+	+	+	+	-	-	-
Zeng et al. [14]	-	-	-	-	-	-	-	-
Liangjun et al. [15]	-	+	+	+	-	-	-	-
Sun et al. [16]	-	+	+	+	+	+	+	+
Liu et al. [17]	-	+	-	+	+	+	+	+
Chouhan et al. [18]	X	-	-	-	-	X	-	-
Lin et al. [19]	X	X	X	X	X	X	X	X
Chanasit et al. [20]	?	?	?	?	X	X	X	X
Campbell et al. [36]	-	-	-	-	-	-	+	-

Judgement

X High risk of bias
- Some concerns
+ Low risk of bias
? No information

correct approach selection. Anterolateral, anteromedial, posteromedial, or medial extensile are helpful approaches to address hyperextension fractures of the tibial plateau [1,3,14,29–34]. Regarding fixation, the literature supports horizontal rim plates and or longitudinal oriented buttressing plates (precontoured locking and/or minifragment plates) associated of not with bone graft or spinal cage augmentation [1,3,30–34]. Plating the tibial rim is of critical importance to maintain the newly restored continuity of the tibial plateau rim, buttressing and containing the perimeter of the tibial condyle.

The authors proposed protocol

Our proposed protocol involves the interpretation of the injury mechanism and classification according to Kfuri-Schatzker [23] and Yao et al. [27,28]. If the hyperextension fracture is unicondylar and presents loss of the tibial plateau perimeter, by means of an impaction, we use the anteromedial (hyperextension-varus) or the anterolateral approach (hyperextension-valgus), reduce the fracture by opening an anterior wedge under the osteochondral impacted area, and apply a rim plate (Fig. 3). If shearing forces are associated, and a split component is identified, buttressing plates (precontoured or minifragment plates) are also indicated [1,3]. If the depressed area extends centrally, anterior midline approach is the choice, with the same fixation strategy.

If we are facing a bicondylar hyperextension tibial plateau fracture, we consider starting the procedure addressing the condyle with the simpler fracture pattern. We use anteromedial and anterolateral approaches. If necessary, a femoral distractor can be applied to assist the reduction of the valgus or varus displacement. The reduction maneuver begins with the application of an osteotome at the level of the fracture to elevate the impacted area. A lamina spreader reduction tool progressively restores the tibial slope under lateral projection of the fluoroscopy. It is important to calculate the tibial slope of the contralateral side in order to minimize the risk of under or overcorrection. Radiographs of the contralateral knee are important and may be used as a template to the affected side. If the posterior cortical hinge is reduced, there is no need to fix it. However, if the posterior hinge displaces after the anterior

Table 3
Summary of the number of hyperextension cases per publication, study designs, applied approaches, reduction and fixation strategies, outcomes, and complications.

Authors	Study design and number of hyperextension cases (N)	Approach	Reduction strategy	Fixation method	Outcomes	Complications
Li et al. [7]	Case report N = 1	Anteromedial	Not reported	T-plate + bone graft	Not reported	Some degree of knee instability
Bu et al. [8]	Retrospective case series *N* = 17	Medial + lateral	Not reported	Medial T and Lateral L locking plates. Anterior 1/3 tubular plate for isolated marginal fragments	Average bone healing time was 14.1 weeks. HSS score was (89.3 ± 3.5)	1 amputation due to extensive muscle necrosis. Three superficial infections. Deep vein thrombosis occurred in 10 patients
Xu et al. [9]	Retrospective case series *N* = 12	Modified anterior midline incision or dual incisions (posteromedial + anterolateral) – when tension failure of the posterior cortex hinge point was present. A spinal cage was used to fill the anterior defect before plating the tibial plateau	Elevation of the anterior plateau to restore normal sagittal alignment by spreader.	Lateral L shaped locking plate and medial T shaped or posteromedial locking plate	Average time of bone healing was 13.58 ± 2.57 weeks. Rasmussen radiological criteria and HSS scores were 83.33 % and 91.67 %, respectively.	1 case of superficial wound infection and dehiscence, 1 case of delayed union combined with limited range of motion of the knee joint and 2 cases of deep vein thrombosis
Gonzalez et al. [2]	Retrospective Cohort *N* = 15	Dual and single approaches, according to the surgeon discretion. Calcium phosphate substitute was used in all cases it was deemed necessary	Not reported	More anterior plating cases than lateral and posteromedial	No differences in terms of range of motion comparing to the non-hyperextension fracture group. No statistical differences in terms of coronal and sagittal alignments in the postoperative radiographs. Trend towards greater pain in the final follow-up, but with absence of statistical significance comparing to the non-hyperextension group	Early post-traumatic osteoarthritis at the follow-up of 17 months was 33 %. In the non-hyperextension group, the incidence was 10 %
Wakefield et al. [10]	Case report (neglected hyperextension fracture) N = 1	Single anterior midline approach	Using osteotomes under image intensifier control, the medial plane of the non-union was first identified, the depressed segment mobilised, and the varus and hyperextension malalignment corrected. The reduction was assisted by the application of a femoral distractor	A Tutobone (xenograft) wedge block was implanted to fill and support the created gap. Anterolateral and anteromedial locking precontoured plates were applied. Any remaining gaps were filled with Hydroset bone substitute	At final follow-up, patient EuroQual in° was 892. On examination, the patient presente°ull knee extension with 100 ° of flexion	A slight loss of range of motion (100 ° of flexion)
Firoozabadi et al. [3]	Retrospective Cohort Study. *N* = 23	Anterolateral and posteromedial	The authors reported that the key to reduction and maintenance of reduction was to address the tension failure of the posterior cortex hinge point and then to address the compression failure of the anterior metaphysis through the elevation of the anterior plateau, to restore normal sagittal alignment. Then, reduction of the articular surface of the tibial plateau articular surface and restoration of sagittal plane alignment by disimpaction and elevation of the	When reduction was achieved, care was taken to use relatively flexible fixation with flexible implants (eg, one-third tubular plates or 3.5 mm screws from anterior–distal to proximal posterior). Spinal cage and bone graft were used when necessary. Anterolateral precontoured locking plate was also used.	All but one fracture healed without additional procedures. The only one patient with a nonunion, who also presented medial joint arthrosis was treated with total knee replacement at 18 months after injury.	Three patients presented preoperative popliteal artery disruptions that required vascular repair (no amputation required). Four patients presented partial or total peroneal nerve palsy. Two patients developed radiographic medial joint arthrosis. One patient developed a deep venous thrombosis. One patient required removal of symptomatic internal fixation. All 3 patients with compartment syndrome had 4 compartment fasciotomies. Radiographically, implant failure was observed in the one

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Table 3 (*continued*)

Authors	Study design and number of hyperextension cases (N)	Approach	Reduction strategy	Fixation method	Outcomes	Complications
			anterior metaphysis was performed using an osteotome or a Cobb elevator, or a laminar spreader			nonunion case with broken screws. In the coronal plane, one patient presented progression to 7 ° of varus at time of union compared with 2 ° immediately after surgery. Loss of reduction on the sagittal plane was noted only in the nonunion case
Jung et al. [1]	Update in reduction technique for hyperextension tibial plateau fractures $N = 0$ (Not applicable)	The authors advocate for medial and lateral approaches rather than a midline incision to avoid un-necessary elevation of the soft tissue envelope. The medial incision can be placed in a standard posteromedial location if access to the posterior surface of the tibia is required for clamp placement or can be moved to a more equatorial position in order to allow for reduction and implant placement along the anteromedial surface of the tibia	Femoral distractor in association with laminar spreader. If the cortical hinge is broken, it must be reduced and maintained. Reduction is performed through the posteromedial approach with a clamp or instrument such as a dental pick and secured with Kirschner wires. If the hinge is incomplete or there is subchondral depression, elevation can proceed from the anterolateral or medial window, often through the metaphyseal defect	Anterolateral and anteromedial precontoured locking plates. Minifragment medial plates can also be applied. Structural bone graft is used in the anterior bone defect	Not applicable due to the study design	Not applicable due to the study design
Zhao et al. [11]	Retrospective case series $N = 11$	Fractures with no or minimal displacement of the posterior tibial cortex (usually ≤2 mm) were operated using the modified anterior midline incision, while fractures with a large displacement (usually > 2 mm) were operated by anterolateral and posteromedial double incisions	Reduction was performed pulling the proximal metaphysis of the tibia forward and pulling the distal end of the tibia distally. Tiankeng-like collapsed fragment would be reduced by ligamentotaxis.	T-shaped medial locking plate and l-shaped lateral locking plate	There were no significant differences on the radiographs between immediately postoperatively and at final follow-up ($P < 0.05$). At final follow-up, the average range of motion of the affected knees was 3.4–130° According to the Rasmussen functional score, the average functional score was 26.8 (24–29), with five patients ranked excellent, and the remaining six ranked as good. The mean time to radiographic fracture union was 12.5 weeks (range 10–26 weeks)	Three patients were accompanied by popliteal artery rupture or embolism. One patient presented late infection, requiring debridement and implants removal. developed deep vein thrombosis, requiring a temporary filter
O'Neill et al. [12]	Retrospective comparative study $N = 17$	Not reported	Not reported	Not reported	Compared to non-hyperextension fracture patterns, hyperextension fractures presented significantly more ligamentous knee (29 % vs 6 %, $p = 0.007$) and vascular (12 % vs 1 %, $p = 0.035$) injuries. PROMIS-PF scores were similar between groups (hyperextension and non-hyperextension patterns), however, PROMIS-Preference (0.37 vs 0.51, $p = 0.017$) was significantly lower in hyperextension patterns. KOOS pain, activities of daily living, and quality-of-life scores were statistically lower in	Not reported

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Table 3 (*continued*)

Authors	Study design and number of hyperextension cases (N)	Approach	Reduction strategy	Fixation method	Outcomes	Complications
					hyperextension fractures, but only KOOS quality-of-life was clinically relevant (41.7 vs 59.3, $p = 0.004$)	
Huang et al. [13]	Retrospective case series $N = 25$	The supine position was used for patients who required an anteromedial approach, posterior medial approach or a conventional internal and external combined approach. The prone position was taken first after the posterior side inverted 'L' incision was performed. After the internal column and the posterior column were fixed, the position was changed to a supine position. The anteromedial and/or anterolateral incision was used to reset and fix the anteromedial fracture block and the lateral column. For patients with complex, three-column fractures, the floating position may be used to observe the intra-operative reduction.	The collapsed articular surface was restored using tools of the periosteum, the top bar was placed through the fractured window and an allograft, autograph or artificial bone graft was implanted at the defect. When the articular surface was satisfactorily restored, K-wires were temporarily placed to fix the subchondral bone.	Lateral and medial (anteromedial or posteromedial) locking plates. Rim plates (3.5 mm reconstruction plates) when necessary	The mean Rasmussen score immediately after the surgical procedure was 15.6 points (range, 12-18 points). Fracture healing was achieved in all 25 patients. Twenty patients achieved anatomical reduction (out a total of 25 cases). The average time of healing and full weight-bearing was 12.1 weeks (range, 8-14 weeks) and 15.8 weeks (range, 13-20 weeks), respectively. The HSS scores of all the patients at 12 months post-operatively averaged 87.6 (range, 68-96), yielding an excellent to good rate of 91.5 %. The average range of motion of the affected knee ranged from 2.3° to 125.1° 12 months after the operation	Three patients presented articular surface collapse by <2 mm. Partial skin necrosis occurred post-operatively in 1 case, which uneventfully healed after wound management. Two cases presented pre-operative common peroneal nerve injury reported with a dorsal sense of numbness, which healed after 3 months of neurotrophic drug administration
Zeng et al. [14]	Retrospective case series $N = 18$	Modified midline anterior approach (slightly lateral to the anterior midline of the knee, began at the superior border of the patella and proceeded to the lateral tibial tubercle). Tibial tubercle osteotomy was performed for better exposure and easier reduction in cases of old bicondylar tibial plateau fractures or severely displaced bicondylar fractures	First, the authors performed tractive reduction opposite the force of the initial injury by pulling the tibial metaphysis forward and pulling the tibial shaft distally during knee flexion, which provided partial reduction. Second, for collapsed fractures, the authors fenestrated the cortical bone using an osteotome, then we used a periosteal elevator to raise the collapsed articular surface	Precontoured 3.5 mm T- and l-shapt locking plates. 3.5 mm bicortical screws were used to fix the anterior tubercle osteotomy.	None postoperative loss of reduction was observed. The mean time to bony union was 13.7 weeks (range, 10–24 weeks), and postoperative radiography indicated no signs of malreduction according to the evaluation criteria described above. The mean VAS score was 0.7 (Range, 0–2) at the final follow-up. The average Rasmussen score was 27.2 (range, 23–29) at the final follow-up. Excellent results were achieved in 14 (77.8 %) patients and good in 4 (22.2 %) patients. ROM in flexion was 123.2° ± 8.9° (range, 110° –140 °), and ROM in extension was 2.9° ± 2.1° at the final follow-up, suggesting satisfactory post- operative function	Two patients developed subcutaneous hematomas in the early postoperative period and were treated with complete drainage and pressure dressings. No complications, such as infection, skin necrosis, or internal fixation breakage or loosening occurred perioperatively
Liangjun et al. [15]	Case series $N = 25$	Medial and/or anterolateral approaches	Not reported	L- and/or T-shaped locking plates with bone graft	Anatomic reduction was achieved in 20 cases, good reduction in 5 cases (between 2 and 5 mm of articular surface col-lapse). All fracture achieved bone healing at the last follow-up, and the fracture healing time was 3–6 months (average 3.3 months). Postoperative Rasmussen score was 18–29 (mean 24.9), and postoperative knee joint	One popliteal artery injury. One compartmental syndrome. Two common peroneal nerve palsies

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Table 3 (*continued*)

Authors	Study design and number of hyperextension cases (N)	Approach	Reduction strategy	Fixation method	Outcomes	Complications
					mobility was 90–130° (mean 118°)	
Sun et al. [16]	Retrospective case series $N = 13$	Anterolateral and/or anteromedial approaches. Posteromedial approach in cases of bicondylar fractures with posterior tension pattern	Fracture reduction involved inserting an osteotome or spreader into the impaction area of the anterior metaphysis and elevating it. Structural artificial bone augmentation was also applied.	L- and/or T-shaped locking plates. To reinforce the "bare area" located behind and in close proximity to the patella tendon, a 2.7 mm minifragment plate was pre-contoured to adapt to the curve of the anterior plateau.	All patients achieved satisfactory reduction, which was radiographically maintained throughout the follow- up period. At the last follow-up, a satisfying clinical outcome was observed with a mean HSS knee score of 96.2 ± 2.0 (range: 90–98).	One common peroneal nerve palsy (requiring microsurgery)
Liu et al. [17]	Retrospective case series $N = 26$	Anteromedial aod/or anterolateral approaches. For tricolumn hyperextension pattenrs, Posteriomedial and anterolateral approaches.	Not reported	L- and/or T-shaped locking plates. Tomofix plate in association with anterolateral locking plate for hyperextension tricolumn patterns. Horizontal plate for containment of the anterior perimeter, when necessary. Bone grafting to fill large bone defects	Both the Lachman and pivot shift test findings were normal in 24 patients and nearly normal in 2 patients. The posterior drawer test was normal in 25 patients and nearly normal in 1 patient. The varus stress test was normal in 24 patients and nearly normal in 2 patients, while the valgus stress test at 30of flexion was normal in 23 patients, nearly normal in 2 patients, and abnormal in 1 patient. The patient's knee joint extended 0o and flexed 100 ± 8.2o at 6 weeks postoperatively. Twelve months after surgery, the range of motion (ROM) was 100o –137o, with an average of 125o ±11.7o. The HSS knee score at the last follow up was 79–98 points, with an average of 87.54 ± 8.36 points; the results were excellent in 21 cases and good in 5 cases. Therefore, 100 % of results were excellent or good	Two patients presented superficial wound infections. One patient presented symptomatic osteoarthritis. Two patients presented poor recovery of common peroneal nerve palsy
Chouhan et al. [18]	Retrospective case series $N = 4$	Posterior approach (described by Chouhan et al. [22])	The articular fragment was fixed with locking screws inserted, through the horizontal limb of a fixed angle T-plate, parallel to the articular surface. The long arm of the plate was brought down to the posterior tibial diaphysis with the posterior fracture apex as a fulcrum and subsequently fixed with cortical screws. This maneuver disimpacted the anterior cortex and restored the normal posterior sagittal slope of the fragment. Any associated anterior rim fragment also fell into place with the correction of the articular slope	L- and or T-shaped locking plates	All four patients presented radiological union at an average of 12 weeks (10–15 weeks) postoperatively. The restored posterior tibial slope was maintained at the final follow up. The mean knee flexion was 133°	Articular malreduction (> 2 mm step-off) was observed in one patient. All patients attained excellent KSS (mean score = 93) at one year of follow- up. All patients were able to sit cross-legged, squat, and carry out their daily activities without any pain or symptoms of instability in their knees.
Lin et al. [19]	Retrospective case series $N = 12$	Not reported	Not reported	Posteromedial locking plates, small-fragment T plates, T- and l-	The Average KOOS was 80/100 (range 60–88). Physical examination did	Two partial and 12 total common peroneal nerve palsies. Two

(*continued on next page*)

Table 3 (*continued*)

Authors	Study design and number of hyperextension cases (N)	Approach	Reduction strategy	Fixation method	Outcomes	Complications
				shaped precontoured locking plates	not reveal anterior or posterior and varus or valgus instability of any affected knee. The average time to both clinical and radio- graphic union was 3.6 months (range 3–9 months, SD 8.5)	compartment syndromes. One vascular injury
Chanasit et al. [20]	Case report N = 1	Arthroscopicaly assisted	Arthroscopy with an additional anteromedial approach	Small fragment T-shaped plate	After three months, the fracture united uneventfully, and the knee stability tests were all equal to those of the uninjured side. Six months post-surgery, the patient was able to walk independently without pain and could participate in moderately strenuous sports activities	None
Campbell et al. [36]	Case series $N = 20$	The surgical approaches used for definitive fixation included combined anterolateral and medial or posteromedial (12 patients), medial only (6 patients), anterolateral only (1 patient), and posteromedial only in the prone position (1 patient).	A lamina spreader, stacked osteotomes, or screw or wire-based clamp can be used for reduction. Depending on the fracture pattern, it is useful to identify which area of the condyle has been compressed, and which failed in tension, and apply the reduction vector preferentially to the depressed, compression failure location. Occasionally, k-wires across the tension failure site can be used to allow this area to function as a hinge.	Mini-fragment plate, 2.0 (4), 2.4 (7), or 2.7 (4) mm (15/22); both “compression” or “strength” style plates and reconstruction style plates were used. In the other 7 cases, a one-third or one-quarter tubular plate was used. In all but 1 case, the shelf plate was used adjunctively, with other implants used on the same condyle. Bone void filler was used in all cases to pack residual metaphyseal defects.	The mean difference between contralateral slope and postoperative slope was 0.7 ° (range 0–3.7 ° [absolute values]). At the final follow-up, the mean posterior plateau slope was 6.5 °. The mean difference between plateau slope at the final follow-up and postoperative follow-up was 0.02 ° (range 0–1.7 ° [absolute values]). No patients experienced a change in slope measurement at the final follow-up more than 2 °. There were no instances of the shelf plate breaking, cata- strophic failure, or clinically relevant change in alignment. In 4 cases, patients experienced change in Kellgren–Lawrence scores from 0 to 1 at the final follow-up (20 %). All other patients had scores that remained unchanged from the injury date to the final follow-up.	One patient sustained a deep venous thrombosis. One patient developed postoperative stiffness and went onto manipulation under anesthesia. One patient sustained vascular and multiligamentous knee injuries at the time of the trauma in additional to the skeletal injury and went onto limb salvage and healing but required manipulation under anesthesia for stiffness. One other patient sustained a vascular injury requiring repair. One patient was reported as noncompliant and began weight-bearing within the 2 weeks postoperatively. This patient developed lateral rafting screw partial back out, but unchanged alignment. The fracture went on to heal with unchanged knee alignment.

reduction maneuver (identified in the lateral fluoroscopy view), we change the strategy, focusing initially on the posterior cortical, by approaching it directly via a posteromedial exposure, followed by the restoration of the continuity of the posterior cortical with plate and screws, then followed by the reduction of the anterior tibial rim. A posteromedial minifragment or 3.5 mm LCP plate are enough to maintain the reduction of the posterior hinge, preserving some degree of flexibility to not hinder the anterior reduction. In bicondylar fractures, after reducing one of the condyles, lateral or medial, we start the preparation for the insertion of an angle blade plate, from anterior to posterior. We use a thin chisel applied 5 to 7 mm below the osteochondral surface to create a path parallel to the joint line in the coronal and sagittal planes. We bend a mini-fragment 2.7 mm straight plate, in order to create an angle blade plate. We insert one of the arms of the plate into the path created by the chisel, making sure that it follows the same inclination as the tibial slope. Once one of the arms of the angle plate is completely buried into the bone, we fix the other arm to the anterior cortical of the respective tibial condyle, using bicortical screws. A second precontoured locking plate (2.7- or 3.5 mm) is placed orthogonally to enhance the mechanical properties of the construct, but with screws that don't extend to the remnant tibial condyle, which still needs to be reduced and fixed. The same sequence is applied to the remnant tibial condyle that has not been fixed yet. Depending on the magnitude of the subchondral wedge gap, bone quality, and fracture pattern a structural bone graft should reinforce the fixation, supporting the subchondral open wedge. (Figs. 4 and 5).

Case 1 illustrates the fixation of a bicondylar hyperextension tibial plateau fracture using the abovementioned technique (Figs. 6, 7, and 8).

The use of subchondral rafting plates for the treatment of tibial plateau fractures is not new. Giordano et al. [35] previously reported the use of subchondral 1/3 tubular plates in four cases for fragmented articular central depression lateral tibial plateau fractures. The main reasons for applying a subchondral plate is the possibility of a larger footprint area to support the subchondral bone, as well as the link with

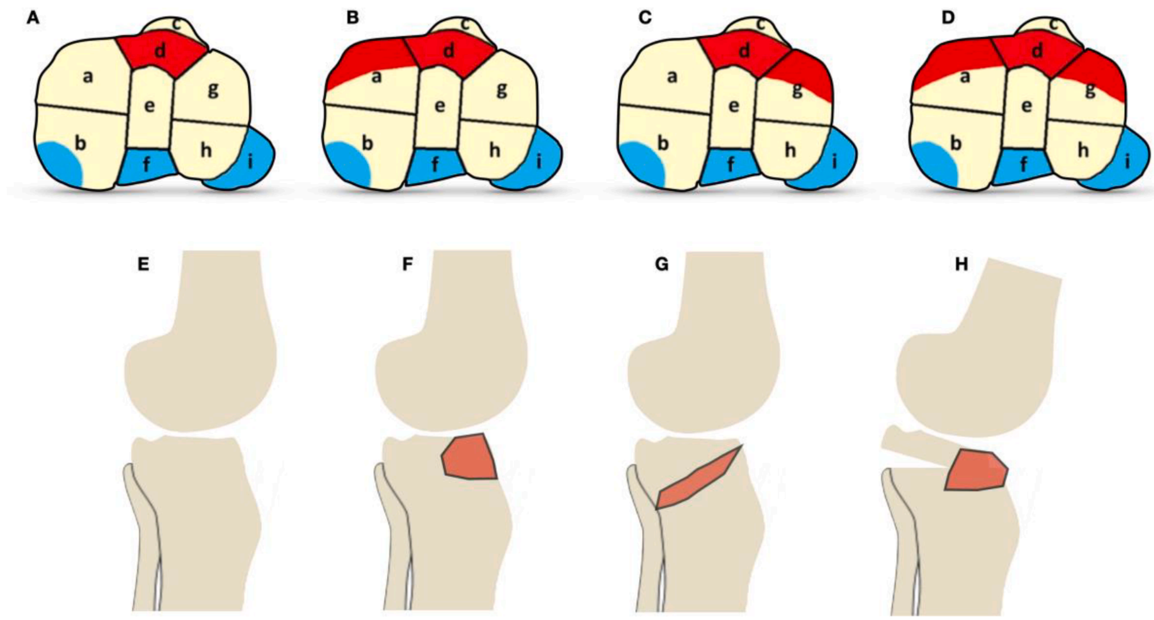

Fig. 2. The illustration depicts the Yao et al. [27,28] classification system for hyperextension fractures of the tibial plateau. A: pure hyperextension (segment d); B: hyperextension–varus (segments *a*+ *d*); C: hyperextension–valgus (segments *d*+ *g*); and D: hyperextension–bicondylar (segments *a*+ *d*+ *g*). Red shadow, compressed area. Blue shadow, avulsion area. Three types of hyperextension patterns in the sagittal plane. E, normal; F, type 1, pure depression of the bare area; G, type 2, cleavage extending to the posterior cortex with no displacement; H, type 3, cleavage extending to the posterior cortex with significant displacement. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

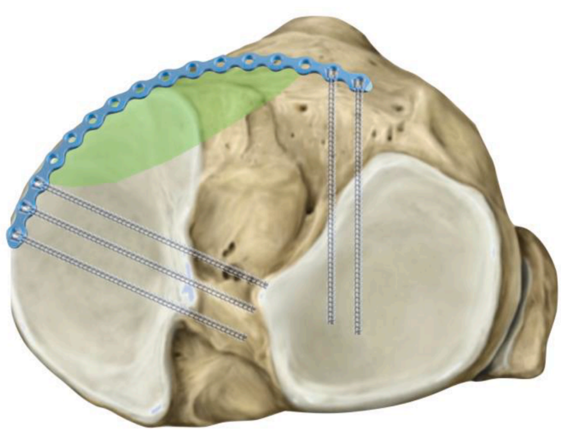

Fig. 3. Illustration of a hyperextension-varus pattern with impaction of the anteromedial perimeter of the tibial plateau (green zone). Observe the fixation of the fracture with a horizontal rim plate (2.7 mm minifragment plate). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

the metaphyseal zone using a unique implant. The major concern when using subchondral plates lies on the possibility of implants removal in cases of failure or need of an arthroplasty. Even though the implant removal can be challenging, we believe that applying the technique of using a thin osteotome above and below the plate to progressively release the plate from the subchondral bone can facilitate plate removal without major difficulties. Maybe, in the future, the development of small fragment angle blade plates, where the subchondral arm of the plate may not have any empty roles, may mitigate the concern of bone in growth through the plate, minimizing the risk of periarticular fractures at the time of implant removal. Campbell et al. [36] recently described intraosseous shelf plate fixation for depressed articular fragments in tibial plateau fractures, using a small or mini fragment plate contoured to function as an intraosseous shelf plate. This technique was applied mostly for hyperextension fractures of the tibial plateau in a multicentric case series. The authors highlighted several potential advantages of this strategy, including the use of the implant as a reduction tool, fragment-specific fixed-angle fixation, and the ability to place this implant above or within a bone void filler.

Outcomes and complications

Gonzales et al. [2], in a retrospective cohort study comparing 15 hyperextension with 69 non-hyperextension tibial plateau fractures, reported that hyperextension patterns presented worse functional outcomes and poorer radiographic results, being considered a predictor of poor prognosis for a tibial plateau fracture. Bu et al. [8], also in a retrospective cohort study comparing 17 hyperextension with 42 non-hyperextension tibial plateau fractures, reported a higher incidence of popliteal artery injury in the hyperextension group. The authors also reported that the range of motion and the Hospital for Special Surgery (HSS) score of the hyperextension group were significantly lower than those of the non-hyperextension group.

O'Neill et al. [12], in a retrospective case series, reported that the hyperextension varus fracture pattern, whether unicondylar or bicondylar, is associated with a higher rate of ligamentous and vascular injuries compared to non-hyperextension patterns and are also associated with worse health-related quality of life at mid-term follow-up. Injuries associated with hyperextension-varus fractures of the tibial plateau included popliteal artery damage, isolated lateral collateral ligament injuries, posterolateral corner multiligamentous injuries, meniscal tears, and peroneal nerve palsy.

Understanding the mechanism of injury and its complexity is paramount to avoid postoperative failures. The following case illustrates a varus-hyperextension injury of the tibial plateau, which was initially reduced but had a secondary loss of alignment in the sagittal plane. As a result, the patient developed instability while bearing weight (Figs. 9 and 10).

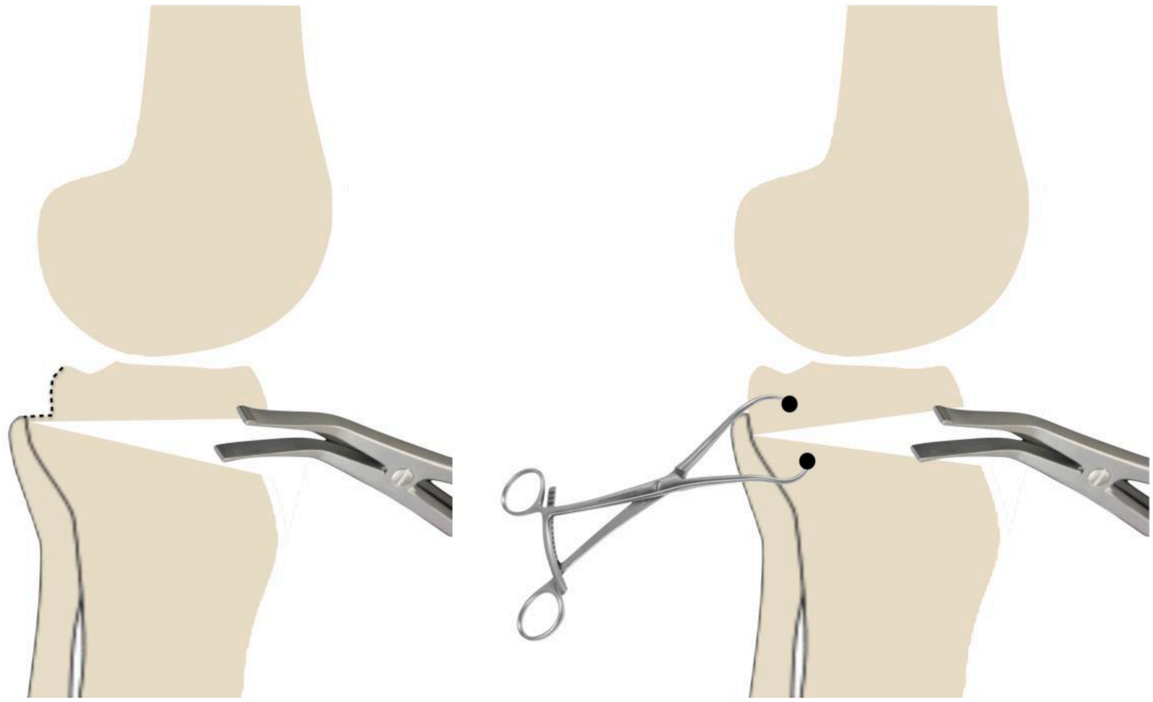

Fig. 4. Illustration depicting the reduction maneuver with a lamina spreader applied to the anteromedial quadrant of the tibial plateau. Observe that the posterior hinge is displaced. In this situation, it is indicated to perform a posteromedial approach and reduce the posterior tension hinge with a pointed clamp. The concept is to restore the continuity of the tibial plateau rim, which once is achieved, may be supported by plates that buttress the tibial condyle, containing it.

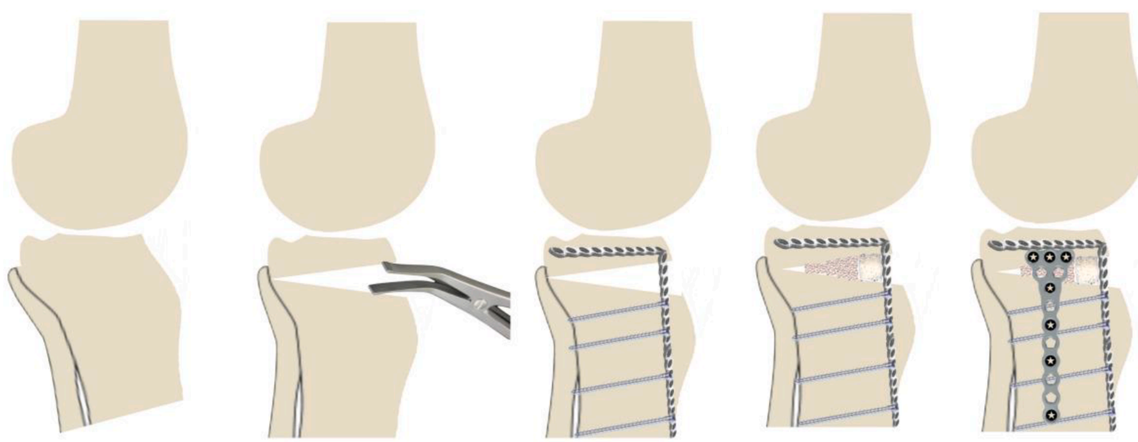

Fig. 5. Illustration of a hyperextension tibial plateau fracture. Observe the application of a lamina spreader to restore the tibial slope. Fixation was performed with a minifragment 2.7 mm plate that was bent to follow the articular joint line and the anterior surface of the proximal tibia. The intraosseous plate was positioned parallel to the articular surface, following the pathway created by the osteotome. Supplemental fixation is illustrated with an orthogonal locking plate, in addition to bone graft augmentation.

Limitations and strengths

This study presents limitations. In this systematic review of the literature, we found just 22 studies that specifically addressed hyperextension fractures of the tibial plateau, none prospectively randomized, which justifies the inclusion of non-randomized studies. We applied the Cochrane Risk of Bias in Non-Randomized Studies of Interventions (ROBINS-I) to stratify the quality of the presented evidence. A meta-analysis was not possible due to the heterogeneity of the included studies. Although we believe the proposed treatment protocol is a helpful guide for the management of hyperextension fractures of the tibial plateau, it is essential to highlight that it reflects the current and limited evidence and the authors' perspective. Therefore, more studies are needed to validate the use of the technique we emphasized. To our knowledge, this is the first systematic literature review on the unique characteristics of hyperextension fractures of the tibial plateau. We aimed to share a decision-making rationale relying primarily on the fundamental work of the classification and management of tibial plateau fractures, proposed by Schatzker and Kfuri, which essentially defines the critical elements for joint stability in the setting of tibial plateau fractures [23,29].

Conclusion

Hyperextension tibial plateau fractures are inherently unstable injuries that require the restoration of the continuity of the tibial plateau rim by reducing the inclination of the tibial slope, correcting the height of the anterior tibial cortical, maintaining the continuity of the tibial

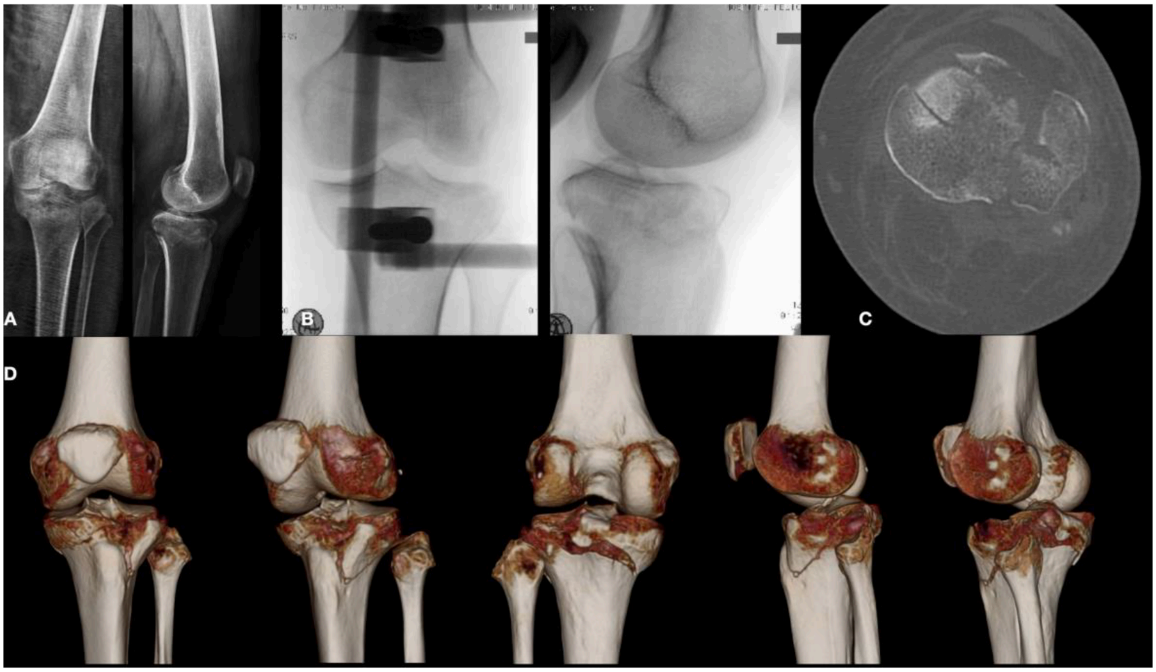

Fig. 6. A 58-year-old female patient, physical education teacher, fell down the stairs and presented a bicondylar tibial plateau fracture. A: Radiographs in anteroposterior and lateral projections showing the hyperextension mechanism. B: Intraoperative fluoroscopy images after spanning the fracture. C: Axial projection in the CT-scan showing the involvement of the anteromedial and posteromedial quadrants of the tibial plateau. D: 3D reconstruction of the computed tomography. Observe the impacted area at the anterolateral surface of the tibial plateau, associated with split wedge fragments located in the anteromedial and anterolateral quadrants. Observe the loss of the posterior medial hinge (tension failure). This injury was classified as a tibial plateau fracture dislocation Type V AL + AM + PM [23,29].

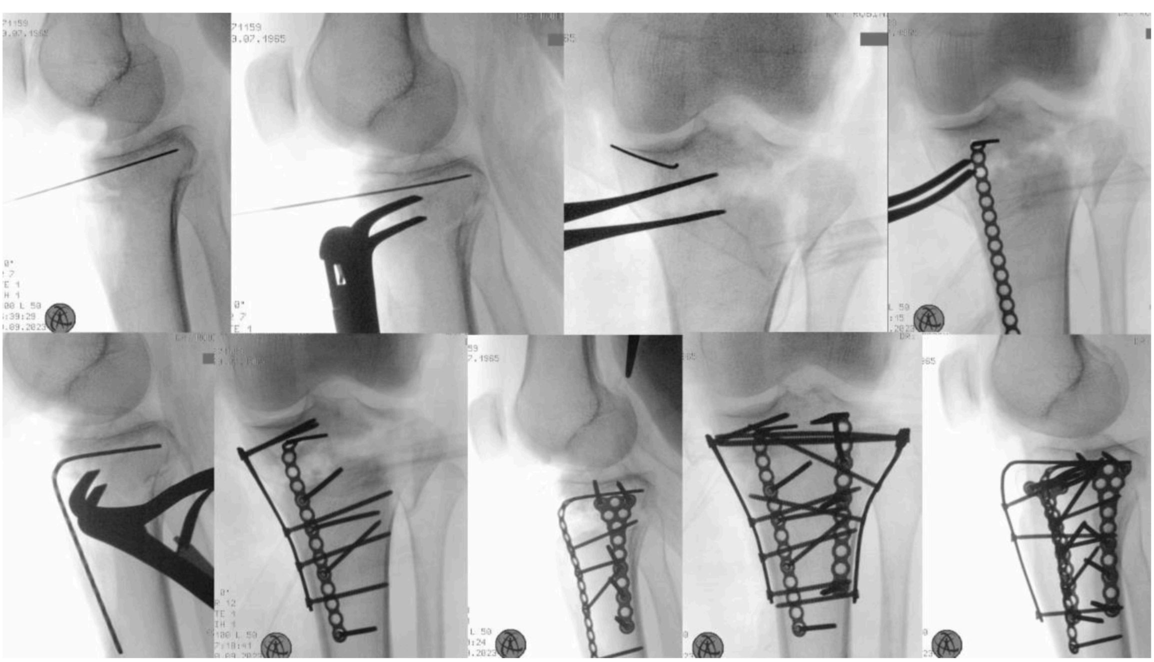

Fig. 7. Intraoperative fluoroscopy images showing the described fixation technique using minifragment bent plates. Observe the restoration of the tibial slope and the stability of the construct using orthogonal implants with restoration of both columns of the tibial plateau. Bone graft was not used due to the achieved stability. A posteromedial approach was not necessary, since the posterior tension hinge indirectly reduced with the placement of the lamina spreader to restore the tibial slope.

posterior cortical, and whenever possible reducing anatomically the crushed cartilage on the articular surface. We propose a detailed assessment of these patients and a treatment algorithm restoring the anatomy of the rim of the tibial plateau, the inclination of the tibial slope, and a biplanar orthogonal fixation method, using a pre-contoured plate angle blade plate to raft the previously depressed and impacted articular surface. We emphasize that the anatomy of the tibial plateau rim, usually assessed in the coronal plane, should be critically analyzed in the sagittal plane, as the inclination of the tibial slope may have devastating implications for the joint's stability. We recognize that this

Fig. 8. A and B: Immediate postoperative radiographs in anteroposterior and lateral views showing fracture reduction and fixation using minifragment plates. C and D: Radiographs in anteroposterior and lateral views after 6 months of fixation. Observe the complete fracture healing with maintenance of the reduction, without evidence of hardware failure.

The postoperative protocol included progressive range of motion of the knee after pain control. Progressive weight bearing (proprioceptive) was allowed using crutches. After complete fracture healing (12 weeks), total weight bearing was allowed. After 6 months, the patient evolved without pain and presented a range of motion of 0–120°, and absence of local or systemic complications.

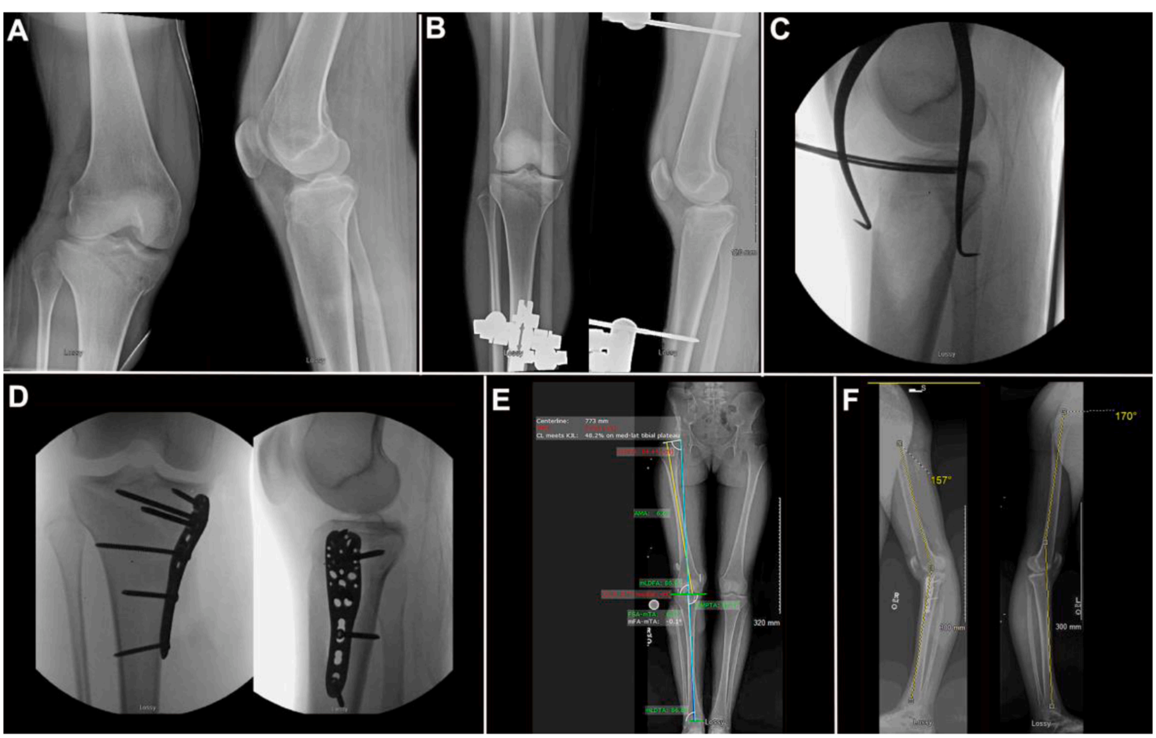

Fig. 9. A: Right knee radiographs at admission illustrating a type IVA tibial plateau fracture; B: Radiographs obtained after the implantation of a spanning external fixation demonstrates improvement of alignment in the coronal plane, but an inverted tibial slope on the sagittal plane; C: Intraoperative fluoroscopy revealing the insertion two Kirschner wires from anterior to posterior, parallel to the articular surface, and then mobilized cranially to reduce the tibial slope; D: Immediate postoperative radiographs show an acceptable reduction of the fracture and proper placement of a direct anteromedial locking plate; E; Extremity alignment study shows neutral alignment of the right lower extremity; F: Comparative extremity alignment study show bilateral knee hyperextension, worse at injured side.

technique needs further clinical validation.

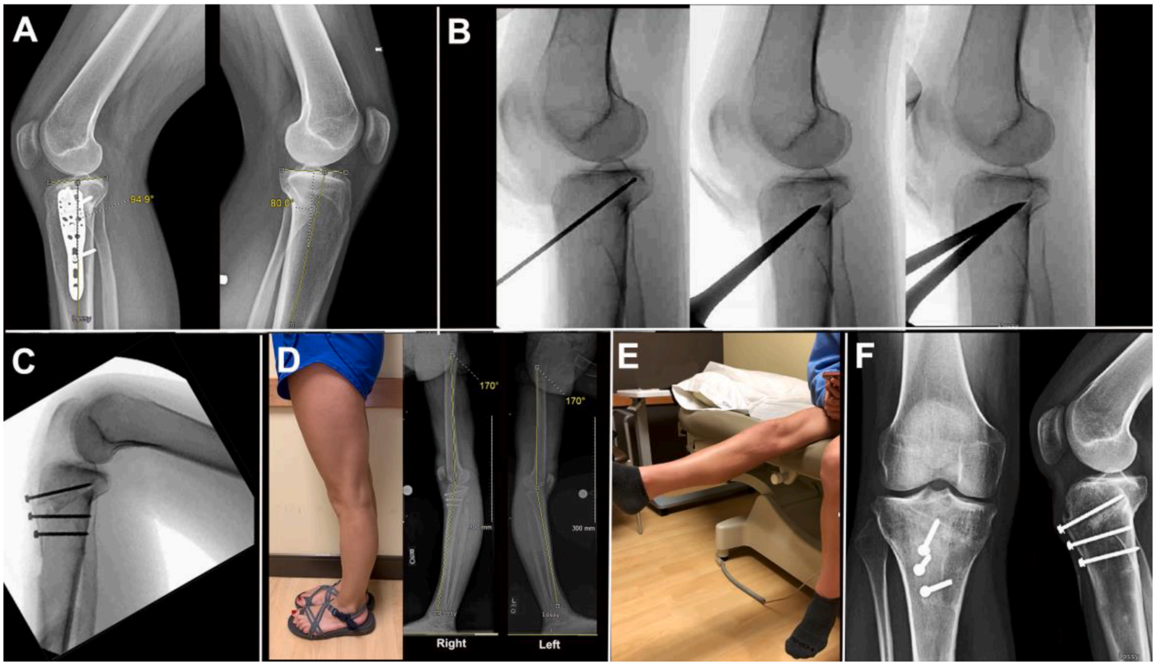

Fig. 10. Postoperative comparative measurements of the tibial slope show a decreased right tibial slope; B: Intraoperative fluoroscopy illustrating the steps of an anterior open wedge osteotomy, after performing an anterior tibial tubercle osteotomy. Note that the osteotomy aims a hinge at the attachment of the posterior cruciate ligament; C: Intra-operative radiograph shows a metaphyseal wedge of 17 mm, spaced by a tricortical bone allograft wedge. The anterior tibial tubercle is fixed with three cortical lag screws; D: Lateral view of the lower extremities showing symmetrical knee extension, confirmed by extremity alignment study in the sagittal plane; E: Intact right knee extensor mechanism; F: One-year postoperative radiographs showing complete integration and healing of the tricortical bone graft with neutral tibial slope.

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Code availability

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Consent for publication

Informed consent was obtained from the patient. The authors confirm the manuscript is sufficiently anonymized in line with the anonymization policy stated in the "Guide for Authors" and does not contain personal and/or medical information about any identifiable individual.

CRediT authorship contribution statement

Robinson E. Pires: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Project administration, Methodology, Data curation, Conceptualization. **Vincenzo Giordano:** Writing – review & editing, Visualization, Methodology. **Fernando Bidolegui:** Writing – review & editing, Visualization. **Rodrigo Pesántez:** Writing – original draft, Visualization, Validation. **Mauricio Kfuri:** Writing – review & editing, Visualization, Validation, Supervision, Methodology, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

REP has received honoraria from Zimmer Biomet, Johnson & Johnson, and Smith & Nephew for educational activities. VG has received honoraria from Zimmer Biomet for educational activities. RP has received honoraria from Johnson & Johnson for educational activities. FB and MK declare that they have no conflict of interest.

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