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Proximal avulsion of five ligaments and revised diagonal principle in tibial plateau fractures

Xiang Yao[a,1], Minjie Hu[a,b,1], Yutong Fu[c,1], Hongyuan Liu[a,b], Xiaohui Pan[a,*], Jiajun Zhao[d,*], Jilei Tang[e,*]

[a] Department of Orthopaedics, The Affiliated People's Hospital of Jiangsu University, Zhenjiang, Jiangsu, China
[b] Jiangsu University, Zhenjiang, Jiangsu, China
[c] Department of Acupuncture and Moxibustion Rehabilitation, Danyang Hospital of Traditional Chinese Medicine, Danyang, Jiangsu 212300, China
[d] Department of Orthopaedics, Nanjing Bond Department of Orthopedics Hospital, Nanjing, Jiangsu, China
[e] Department of Orthopaedics, Qidong Hospital of Traditional Chinese Medicine, Nantong, Jiangsu 226200, China

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ABSTRACT

Purpose: The aim of the study was to analyze the incidence of proximal avulsion of the five main ligaments and to revise the diagonal tension/compression concept in tibial plateau fractures.
Methods: Computed tomographic images of 1263 cases of tibial plateau fractures were retrospectively analyzed by the OTA/AO classification and four-column nine-segment classification. The correlation between proximal avulsion of five ligaments and the injury mechanism was analyzed.
Results: In total, 1263 tibial plateau fractures in 1253 patients were included. A total of 92 cases (7.3%) associated with proximal avulsions were identified among the 1263 tibial plateau fracture cases obtained from our institution's database. The 92 avulsions occurred in 82 patients, among whom 10 patients had two different avulsions in a single knee. The incidence of proximal avulsion fracture of the medial and lateral collateral ligament was 3.6% (45/1263) and 2.1% (26/1263), respectively. The incidence of avulsion of the anterior cruciate ligament and avulsion of the posterior cruciate ligament was much lower at 0.2% (2/1263) and 0.1% (1/1263), respectively. Proximal avulsion of the patellar ligament occurred in 18 cases (incidence rate = 1.4%). Several combinations of injuries, composed of distal tibial plateau fractures and proximal avulsion of ligaments, were identified.
Conclusions: Among the patients with tibial plateau fracture, the incidence of proximal avulsion of the five ligaments was 7.3% (92/1263). The four-column and nine-segment classification is an exhaustive method for recording injuries in these ligaments. The revised diagonal injury concept is useful for understanding the injury mechanism and choosing the appropriate surgical strategy.

Introduction

The knee joint contains five important ligaments: the medial and lateral collateral ligament (MCL and LCL), the anterior cruciate ligament (ACL), the posterior cruciate ligament (PCL), and the patellar ligament (PL). Each ligament is composed of a proximal (femoral/patellar) attachment, substance, and a distal (tibial/fibular) attachment (Fig. 1). Fracture of the tibial plateau is a severe compound trauma of the knee joint with a wide range of presentations, including cortical comminution, articular depression, and ligament and cartilage injuries. In the event of TPFs, ligament tear and avulsion at the distal and proximal side may occur. Mohamed et al. have reported the incidence of ligament injury associated with tibial plateau fractures in 98 cases, including one case of femoral avulsion of both the MCL and the LCL [1]. With the popularity of magnetic resonance imaging (MRI), ligament tear and avulsion at the distal (tibial/fibular) attachment have received more attention, but avulsion at the proximal (femoral/patellar) attachment has been discussed to a much lesser extent [2–4].

The commonly used fracture classification (Schatzker, three-column/four-column classification) only includes the structures of the proximal tibia and does not include proximal avulsion fractures [5,6]. The OTA/OA classification codes isolated avulsion of the medial and lateral femoral condyle as 33A1.2 and 33A1.1, respectively, but the classification of proximal tibial plateau (coded as 41) does not consider coexisting ligament femoral/patellar avulsion [7]. Further, the eight-column/ten-column classification and nine-

* Corresponding authors.
E-mail addresses: 16962775@163.com (J. Zhao), orthopedictang@126.com (J. Tang).
[1] Xiang Yao, Minjie Hu and Yuyong Fu contributed equally to this work.

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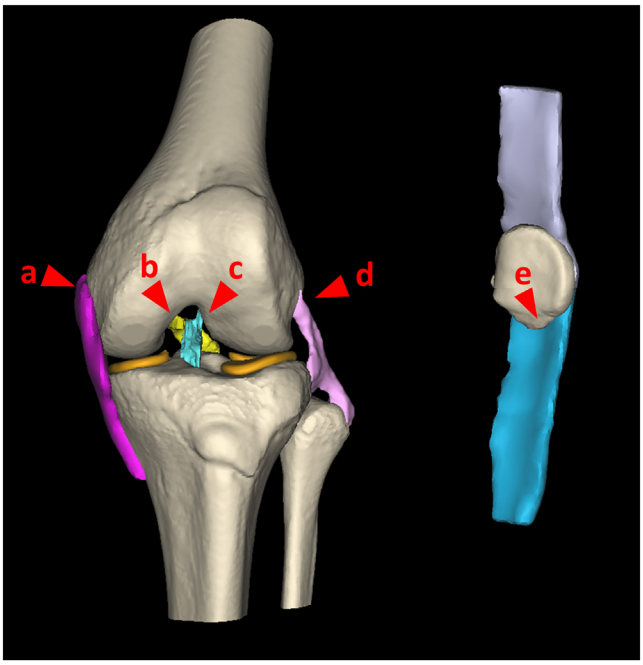

Fig. 1. Anatomical structure of the knee joint depicting the proximal attachment of the five ligaments.
The red triangles indicate the proximal attachment of the five ligaments: the medial and lateral collateral ligament (MCL and LCL), the anterior cruciate ligament (ACL), the posterior cruciate ligament (PCL), and the patellar ligament (PL).
a: MCL
b: PCL
c: ACL
d: LCL
e: PL.

segment classification also cover a wide range of fractures, but do not specifically include co-existing avulsion injuries [8–10]. In 2018, Yao et al. proposed a computed tomography (CT)-based four-column nine-segment classification system for TPF in which proximal avulsion of the five main ligaments was recorded as Extending type 2 (EX2) for the first time in the classification of TPF [11].

Diagonal tension/compression concept in TPF means combined injury pattern involving bipolar ligamentous tear/avulsion and bony compression [12]. The traditional diagonal principle is only based on the transverse plane like the anteromedial compression + posterolateral avulsion. However, there is no comprehensive study on proximal avulsion of the five ligaments and the corresponding injury mechanism associated with TPF.

The purpose of this study was to analyze in detail the incidence of proximal avulsion of the five ligaments and propose a revised diagonal tension/compression concept for TPF.

Patients and methods

This study was approved by the ethical committee of the *** Hospital, *** University. Between December 2007 and February 2022, we managed a total of 1300 adult (age ≥ 16 years) patients with proximal tibia closed fractures. Patients with isolated avulsion of ACL/PCL/PL tibial attachment were also enrolled. The exclusion criteria included isolated proximal fibular fracture, peri–prosthetic fractures, pathological fractures, bone defects, cutting, club violence, bullet wounds, congenital or non-congenital malformation of the tibial plateau, and insufficient CT data. Based on these criteria, a total of 1253 patients (663 males and 590 females) with 1263 affected knees were included.

3D CT images of the ligament injury with TPF were retrospectively reviewed. All cases were classified according to the OTA/AO and Yao classifications. All the columns and segments involving the proximal tibia and fibula were counted. All concomitant avulsion fractures of the distal femur and the inferior patellar pole were documented.

Table 1
Patients' biographical data and complexity of the fractures.

	Characteristics	
Patients (n = 82)	Sex ratio (male/female)	48/34 (1:0.708)
	Age (mean ± SD), y	52.1 ± 12.9
	Age (male/female)	49.9 ± 13.8/55.1 ± 10.8
Knees (n = 92)	Left	46 (50.0%)
n (%)	Right	46 (50.0%)
	Left/Right	46/46 (1:1)
OTA/AO classification	41.A	9 (9.8%)
n (%)	41.B	55 (59.8%)
	41.C	28 (30.4%)
Four-column nine-segment classification	1 column	31 (33.7%)
	2 columns	36 (39.1%)
	3 columns	20 (21.7%)
n (%)	4 columns	5 (5.4%)
Degree of comminution (TPII)	Mild comminution (2–5)	51 (55.4%)
		32 (34.8%)
n (%)	Moderate comminution (6–9)	9 (9.8%)
	Severe comminution (10–13)	

OTA/AO = Orthopaedic Trauma Association/AO Foundation; TPII = tibial plateau injury index.

Statistical analyses were performed using IBM SPSS Statistics 18 (SPSS Inc., Chicago, USA). Qualitative data are expressed as n (percentage), and quantitative data are expressed as mean ± SD values. The Student's t-test was used to analyze differences in continuous variables. p-values less than 0.05 were considered to indicate statistical significance.

Results

According to the statistical analysis, there were 92 cases of proximal origin avulsion, which corresponds to an incidence of 7.3% (92/1263) (Table 1). The 92 avulsions were recorded in 82 patients, among whom 10 patients had two different avulsions in a single knee. The mean age of the 82 patients was 52.1 ± 12.9 years, and they comprised 48 males and 34 females (mean age: 49.9 ± 13.8 vs. 55.1 ± 10.8, $P > 0.05$). According to the AO classification, type A, type B, and type C proximal avulsions were identified in 9 (9.8%), 55 (59.8%), and 28 (30.4%) of the 92 patients, respectively. As evident from the values, the incidence of type B proximal avulsion was the highest. According to the Yao classification, one-column, two-column, three-column, and four-column damage were identified in 31 (33.7%), 36 (39.1%), 20 (21.7%), and 5 (5.4%) of the 92 cases, respectively, and the incidence of two-column damage was the highest. According to the tibial plateau injury index, 51 (55.4%) exhibited mild comminution; 32 (34.8%), moderate comminution; and 9 (9.8%), severe comminution.

The incidence of proximal avulsion of the MCL and LCL was 3.6% (45/1263) and 2.1% (26/1263), respectively. The incidence of proximal avulsion of the ACL and PCL was much lower at 0.2% (2/1263) and 0.1% (1/1263), respectively. Proximal avulsion of the PL at the inferior pole of the patella occurred in 18 cases (1.4%). These values show that the incidence of proximal avulsion of the MCL was the highest, and it was followed by proximal avulsion of the PL at the inferior pole of the patella. However, proximal avulsion of ACL and PCL was rare.

With regard to the segments, segment g (61.4%, 775/1263) and segment h (61.7%, 779/1263) were the most affected; segment a (24.1%, 304/1263) and segment b (24.6%, 311/1263) were less likely

Table 2
Proportion of columns, segments, and EX2 in 1253 knees.

Four columns	n	Affected segments	EX2	%
Medial	417	a (n = 304)	45	3.6
		b (n = 311)		
Intermedial	959	c (n = 137)	18	1.4
		d (n = 487)	/	
		e (n = 581)	2	0.2
		f (n = 623)	1	0.1
Lateral	989	g (n = 775)	/	
		h (n = 779)	/	
Fibular	406	i (n = 406)	26	2.1

EX2 = extending type 2; / = not available.

to be injured; and segment c (10.8%, 137/1263) had the lowest probability of injury (Table 2).

Discussion

In this study, we analyzed the incidence of tibial plateau fractures with proximal avulsion and created a database with the largest sample size. The incidence and mechanism of proximal avulsion of the five ligaments are described below.

Proximal avulsion of the MCL (avulsion of medial femur condyle) is the most common injury that occurs around the distal femur and is associated with valgus injury. Stieda first reported this MCL injury, which was later named Pellegrini-Stieda fracture in 1808 [13]. Stevens and other scholars reported small samples of cases of MCL proximal avulsion [14–16]. Additionally, McCarthy reported an unusual adult case of MCL proximal avulsion along with posterior cruciate ligament avulsion fracture (segment f type 2 + medial column EX2 in Yao classification) [17]. In the present cohort, the incidence of proximal avulsion of the MCL was 3.6% (45/1263), which is significantly higher than the incidence reported in the literature. A possible reason for this is that none of the previous classifications included this injury, exception for the Yao classification. Surgeons have focused on bony injury of the tibial plateau, and seldom reported proximal avulsion of the MCL. Fig. 2 depict a typical TPF case along with proximal avulsion of the MCL. Nonoperative treatment, anchors, and cannulated screw fixation are the treatment options for such injury.

Proximal avulsion of the LCL (avulsion of lateral femur condyle) originates from the attachment of the LCL/PLC(posterolateral ligament complex) and is mainly caused by the varus/extension mech-

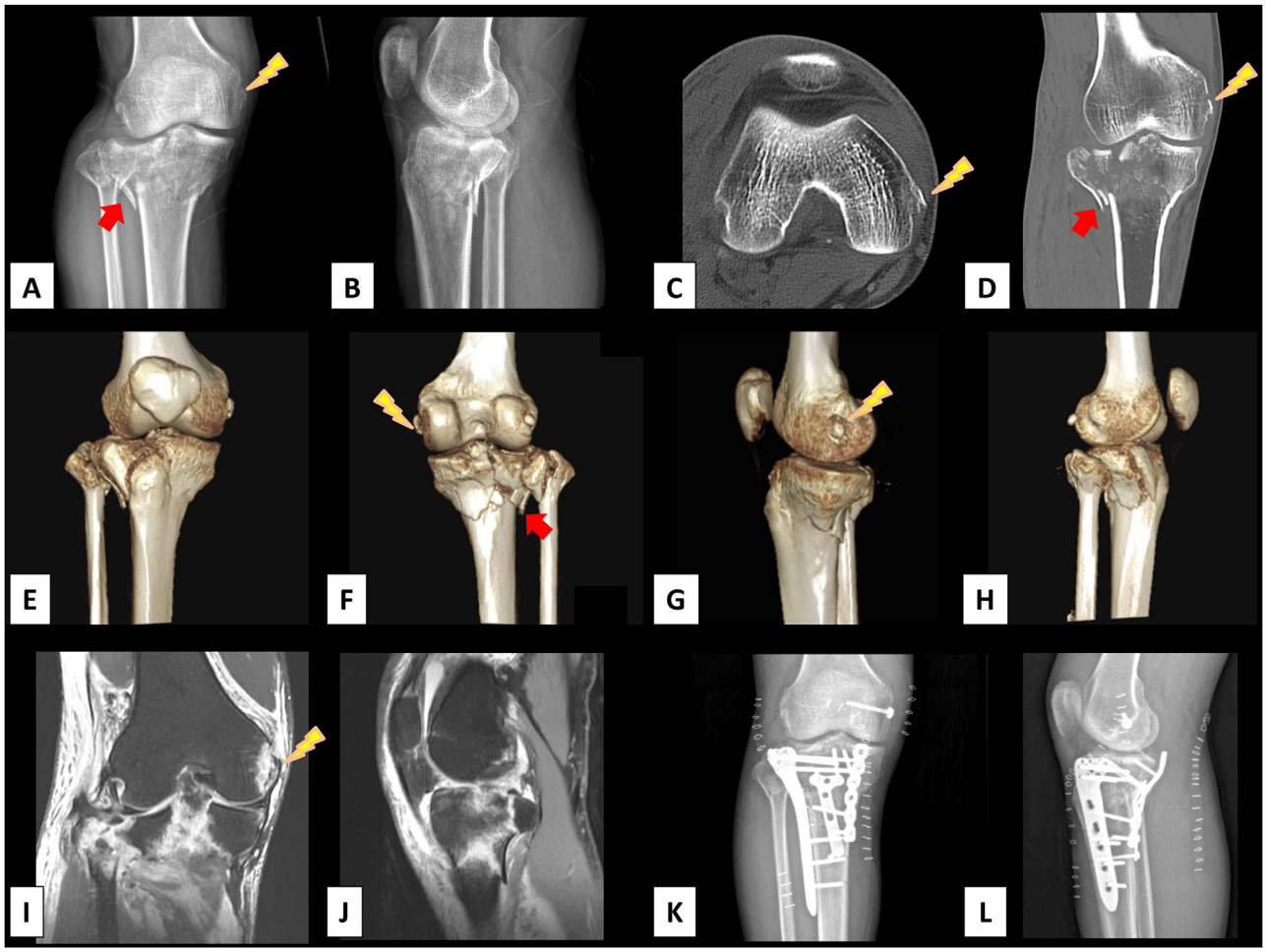

Fig. 2. Images depicting segment f type 2 along with medial column EX2 injury according to the Yao classification.
Lateral tibial plateau collapse (red arrow) along with femoral avulsion of the MCL (yellow polyline)
A & B: Preoperative radiograph
C & D: 2D-CT image
E–H: 3D-CT image
I & J: MR image
K & L: Postoperative radiograph.

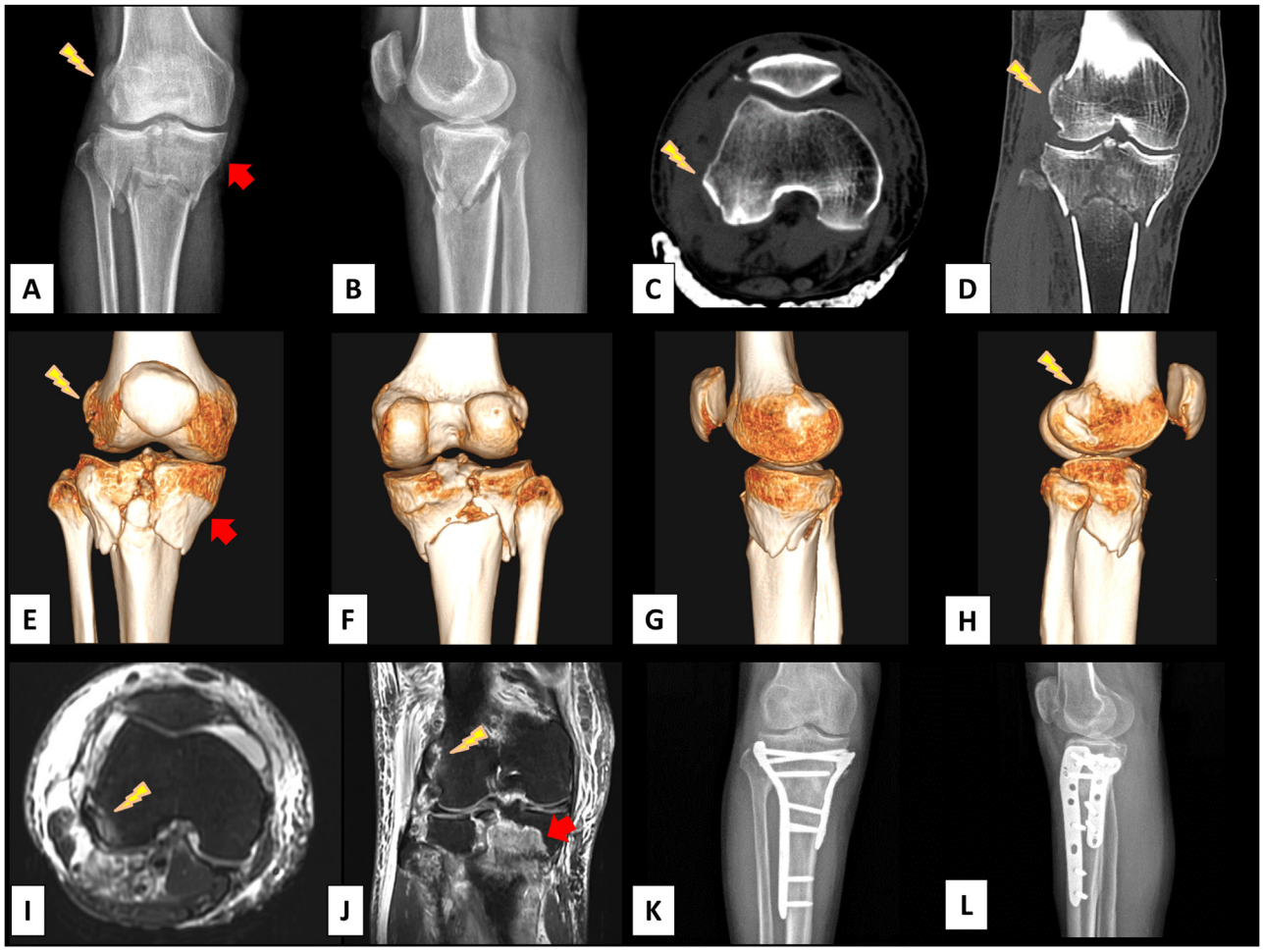

Fig. 3. Images of a case of comminution of the tibial attachment of the ACL and PCL along with avulsion of the lateral femoral condyle (yellow polyline), medial tibial plateau collapse (red arrow) classified as segment e injury type 3, segment f injury type 3, and fibular column EX2.
A & B: Preoperative radiograph
C & D: 2D-CT image
E–H: 3D-CT image
I & J: MR image
K & L: Postoperative radiograph.

anism. This proximal (femoral) avulsion is a counterpart of the LCL distal (fibula) avulsion (arcuate sign). There are only a few reports of this injury in the previous literature. Abdel-Hamid et al. reported one LCL proximal avulsion fracture in 98 cases of TPFs [1]. Yoo et al. reported a unique adult case of lateral epicondylar femoral avulsion along with complete tear of the PCL [18]. In the present cohort, the incidence of LCL/PLC avulsion was 2.1% (26/1263), and it was mainly associated with varus/extension injury. Based on this finding, it is recommended that orthopedic doctors look for avulsion of the lateral femoral condyle when they encounter varus/extension TPFs (Fig. 3). Images of proximal avulsion of the LCL are presented in Fig 3. Similar to treatment options for proximal avulsion of the MCL, this injury can also be repaired with anchors, screws, and washers.

TPF along with tibial attachment injury and substance tear of the ACL are common [2–4]. Several immature cases of isolated proximal avulsions of the ACL have been recorded in the literature, but there was no adult case of TPF along with ACL femoral avulsion [19–22]. In the present cohort, two rare adult cases of femoral avulsion of the ACL were found in 1263 TPFs. This complex combination of injuries cannot be accurately classified by the Schatzker, three-column/four-column, or AO classifications. The illustrated case in Fig. 4 can be precisely classified as medial column EX2 along with segment g injury type 3, segment e EX2 (ACL avulsion), and segment f injury type 3 according to the Yao classification. Surgeons mostly repair proximal avulsion of the ACL with the arthroscopy technique. As the fragment was too small to fix, two cases in the present cohort received nonoperative treatment.

Isolated proximal avulsion of the PCL is rare, and less than 10 cases have been reported in the literature [23,24]. Only one case of TPF along with proximal avulsion of the PCL was found in the present cohort (Fig. 5). This confirms the low incidence of this injury. In addition, this combination of injury (TPF + proximal avulsion of the PCL) is possibly being reported for the first time. Proximal avulsion of the PCL can be classified as segment f EX2 according to the Yao classification, which cannot be coded by any other known femur/tibia classifications. Arthroscopic repair is the main treatment for this rare injury in literature. The present patient received nonoperative treatment.

The present cohort included 18 cases (1.4%, 18/1263) of proximal avulsion fracture of the PL. This extraarticular avulsion of the inferior patellar pole was coded as 34A1 (qualification b) in the OTA/AO classification and segment c EX2 in the Yao classification. Fig 6 presents a case of a special TPF along with inferior and lateral patellar avulsion. Treatment of avulsion of the proximal PL attach-

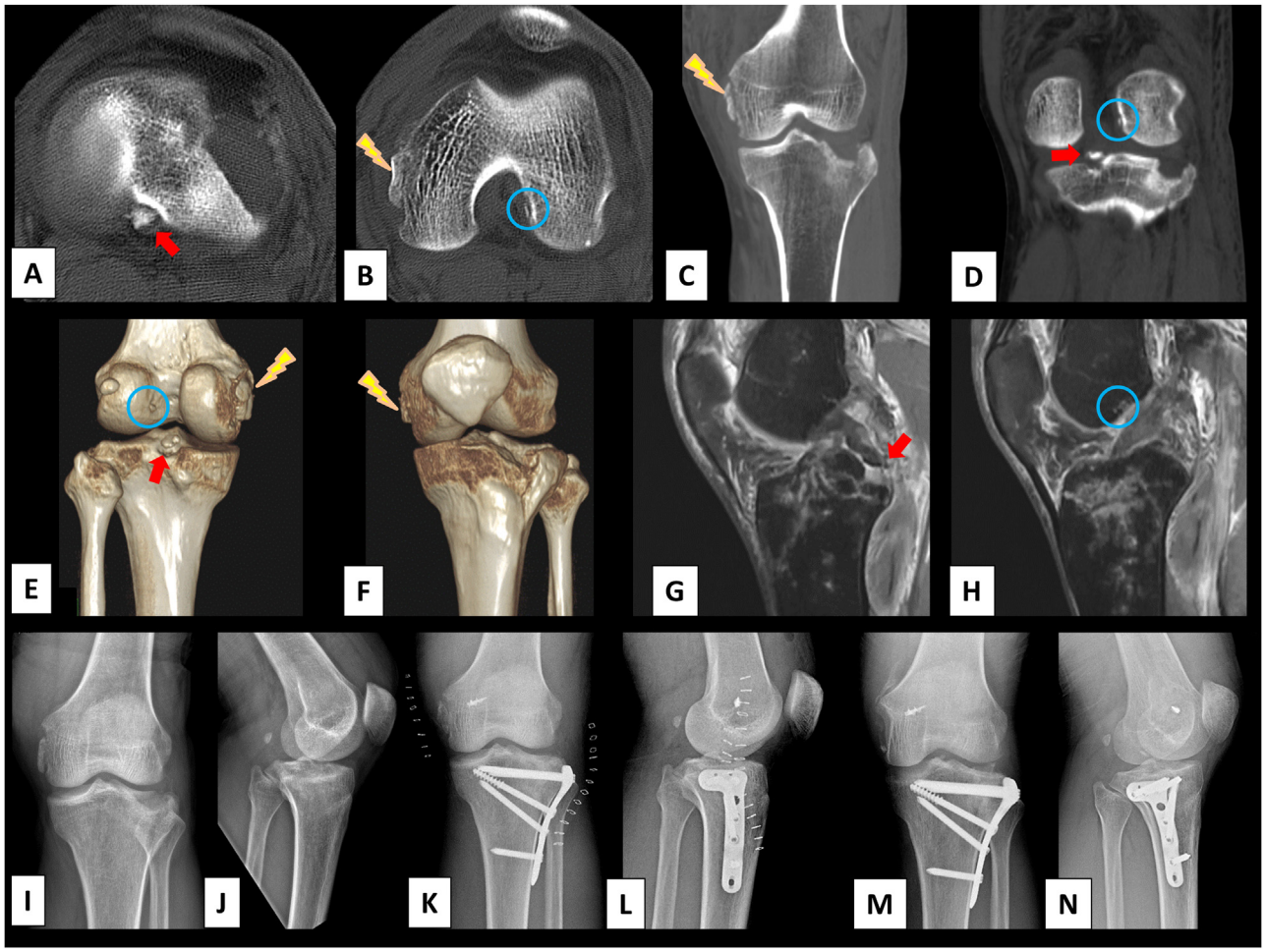

Fig. 4. Images of a complex case of hyperextension-valgus tibial plateau fracture.
The images depict collapse of the anterolateral platform along with femoral fracture of the medial collateral ligament (yellow polyline), femoral small avulsion fracture of the anterior cruciate ligament (blue circle), and tibial partial avulsion fracture of the posterior cruciate ligament (red arrow).
A–D: 2D-CT image
E & F: 3D-CT image
G & H: MR image
I & J: Preoperative radiograph
K & L: Postoperative radiograph
We used anchors to repair the femoral avulsion of the MCL.
M & N: Six months after surgery, unfortunately, the bone mass of the MCL femoral attachment was absorbed.

ment is relatively simple, as it can be fixed with a lag screw and a tension reducing wire.

The traditional diagonal principle is only based on the transverse plane. The most typical clinical manifestations are anteromedial margin compression and posterolateral aspect tear or avulsion that is usually found in hyperextension-varus TPF. Several similar injury combinations, composed of distal TPF and proximal avulsion of a ligament, were found in this study. That is, 45 MCL proximal avulsions were accompanied by 39 lateral column injuries (segment g/h), and the probability of both occurring at the same time was 86.7%. Proximal avulsion of the MCL along with compression of the lateral articular surface (segment g/h) represents typical valgus injury. In this cohort, 26 LCL proximal avulsions were accompanied by 16 medial column injuries (segment a/b)/bare area injuries (segment d), and the probability of both occurring at the same time reached 61.5%. This incidence is typical of varus/hyperextension injury. Proximal avulsion of the LCL along with compression of the medial articular surface (segment a/b) represents typical varus injury. Both valgus and varus injury are depicted in Fig 7. Avulsion of the inferior pole of the patella may result from tension injury during knee flexion or direct impact during knee extension/overextension (Fig. 7). There is no clear association between proximal avulsion of the PL and concomitant segment injury. ACL/PCL tear/avulsion could be caused by several types of injury mechanisms. As proximal avulsion of the ACL/PCL is extremely rare, we will not discuss it any further. These findings imply that the diagonal principle is applicable not only in the transverse plane, but also in the coronal and sagittal plane, especially in the context of proximal avulsion of ligaments. These revised diagonal injury combinations are important to understanding injury mechanisms around the knee and provide a theoretical basis for reverse injury mechanism fixation strategies.

Although the value of repairing proximal avulsions for functional recovery needs further investigation, the authors recommend that proximal avulsions be fixed if possible. In cases with large and displaced avulsions, it is easy to perform open reduction and fix the fragment with anchors, lag screws, wire, or suture. This procedure will add additional stability to the injured knee joint and contribute to early functional exercise ability. However, treatment of this proximal avulsion with arthroscopic techniques still

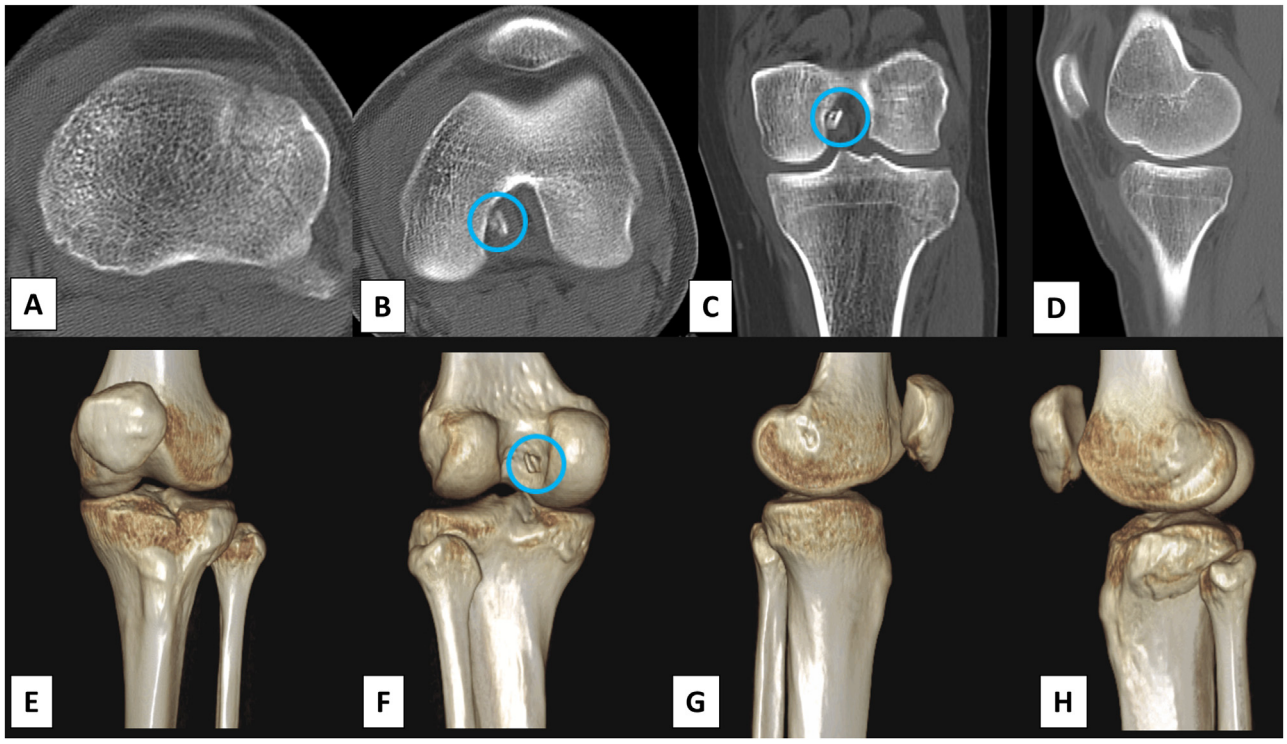

Fig. 5. Avulsion fracture of femoral attachment of the PCL (blue circle) in a tibial plateau fracture case.
A–D: 2D-CT image
E–H: 3D-CT image.

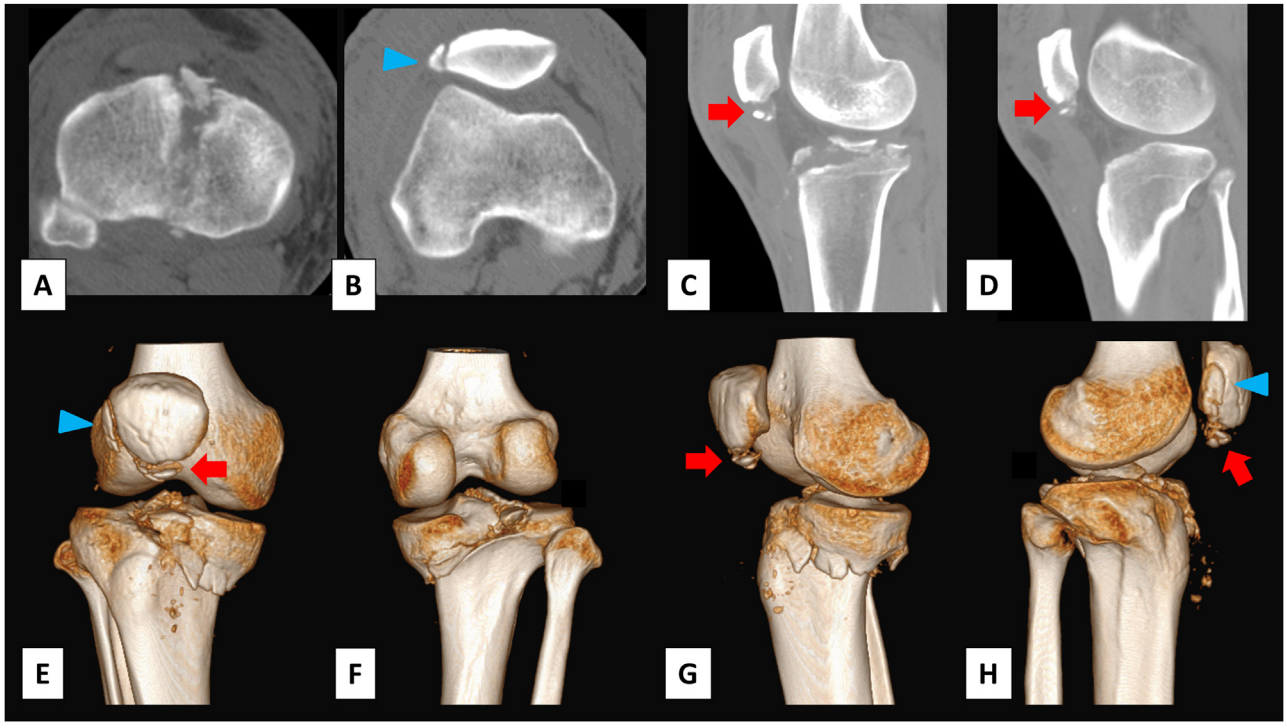

Fig. 6. Images of a case of tibial plateau comminution fracture.
The images depict collapse of the lateral platform along with proximal avulsion of the patellar ligament (red arrow, blue triangle).
A–D: 2D-CT image
E–H: 3D-CT image.

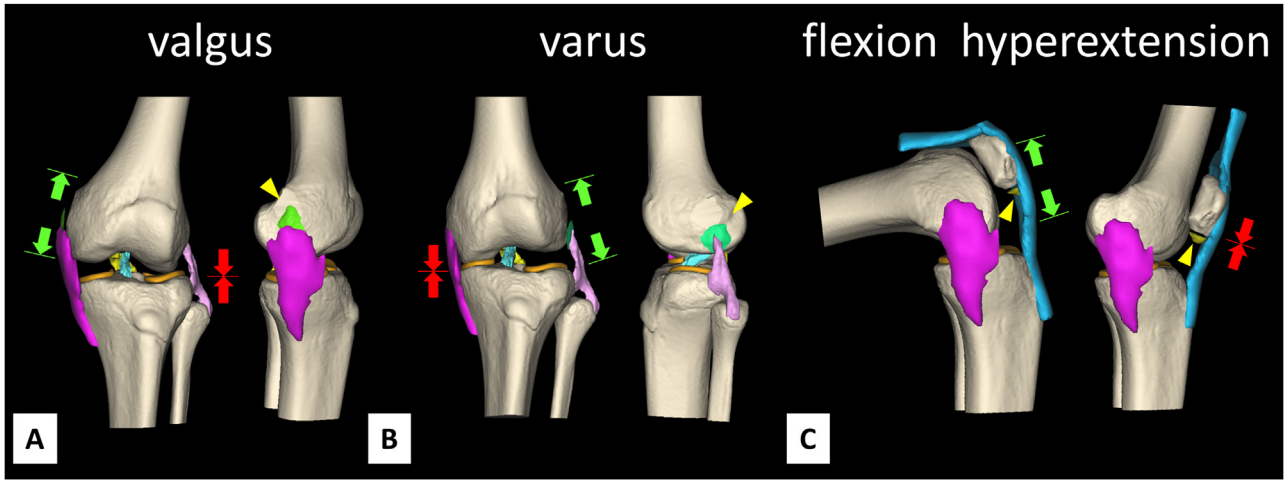

Fig. 7. Images of valgus, varus, flexion and hyperextension injury mechanisms. A: Valgus injury mechanism of proximal avulsion of MCL. B: Varus injury mechanism of proximal avulsion of LCL. C: Flexion and hyperextension injury mechanism of proximal avulsion of PL. Red arrow indicates compression injury. Green arrow indicates tension injury. Yellow triangle indicates avulsions of MCL, LCL and PL.

needs further study. Nonoperative treatment seems to be a good option for small or non-displaced fragments.

So far, about 40 classification systems have been proposed to classify the morphology and assess the prognosis of TPFs [25,26]. Among these, the four-column and nine-segment classification was pathbreaking as it facilitated the classification of the injury type of TPF and fibula, as well as the classification of ligament tears as EX1 and proximal avulsions as EX2. These categorizations were not possible with the other classifications. When applied to the classification of injuries on the horizontal plane, the four-column and nine-segment classification has obvious advantages in terms of coverage and comprehensiveness.

Limitations

One of the main limitations of this study is that only CT images of the tibial plateau injuries were analyzed. MRI would reveal more information about the ligament substance and bone contusion and should be considered in future analyses. This is a single-center study, while multi-center study with larger samples will provide a more reliable incidence. Finally, only five ligaments were analyzed, but other ligaments and soft tissue structures in the knee joint may also be torn or avulsed and must be examined in the future.

Conclusion

Among the patients with tibial plateau fracture in the present cohort, the incidence of proximal avulsion of the five ligaments was 7.3% (92/1263). It was possible to comprehensively classify these injuries using the four-column and nine-segment classification system. The revised diagonal tension/compression concept could be useful for understanding the mechanism of injury and choosing the appropriate reduction strategy.

Declaration of Competing Interest

We declare that we do not have any commercial or associative interest that represents a conflict of interest in connection with the work submitted.

CRediT authorship contribution statement

Xiang Yao: Funding acquisition, Methodology, Writing – original draft. **Minjie Hu:** Data curation, Funding acquisition, Software, Writing – review & editing. **Yutong Fu:** Data curation. **Hongyuan Liu:** Data curation. **Xiaohui Pan:** Conceptualization. **Jiajun Zhao:** Project administration. **Jilei Tang:** Visualization.

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Abbreviations

CT Computed tomography; MRI Magnetic resonance imaging; MCL Medial collateral ligament; LCL Lateral collateral ligament; ACL Anterior cruciate ligament; PCL Posterior cruciate ligament; PL Patellar ligament; PLC Posterolateral ligament complex; TPF Tibial plateau fracture; Fig. Figure; EX1 Extending type 1; EX2 Extending type 2; OTA/AO Orthopaedic Trauma Association/AO Foundation

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Ethical approval

This retrospective study has been approved by the ethical committee of the Affiliated People' s Hospital of Jiangsu university(K-20210041-Y).

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