CLINICAL ARTICLE

Flexion Tibial Plateau Fractures: 3-dimensional CT Simulation-based Subclassification by Injury Pattern

Yaning Hu, MD[1], Aqin Peng, MD, PhD[1], Shuai Wang, MD[2], Shuo Pan, MD[3], Xiao Zhang, MD[1]

[1]*Hebei Medical University Third Affiliated Hospital,* [2]*The Chest Hospital of Hebei and* [3]*The First Hospital of Shijiazhuang, Shijiazhuang, China*

Objective: To identify different injury patterns of flexion tibial plateau fractures (FTPFs) with 3D CT simulation technology. The association between these hypothesized injury patterns and concomitant injuries was also investigated.

Methods: The tibial plateau fracture cases of 297 patients consecutively treated at our trauma center from August 2016 to December 2018 were reviewed retrospectively. A total of 108 patients with FTPFs were enrolled. 3D CT simulation technology was used to reconstruct the position of the knee joint at the time of tibial plateau fracture. The 3D segments for the tibia and femur were created separately, the tibial 3D segment was aligned with the articular surface of the femoral condyle, and then the corresponding injury patterns were deduced. The magnitudes of translation and rotation incurred after the segments were repositioned were calculated by Mimics software. The associations between the hypothesized injury patterns and concomitant injuries were compared.

Results: FTPFs were classified into two groups according to the fracture region: unicondylar FTPFs (type I) and bicondylar FTPFs (type II). According to the injury patterns simulated in this study, these two types of FTPFs were further subclassified into five subgroups. Type I FTPFs were categorized into two subtypes based on the degree of rotation in the coronal plane (varus $< 0°$; valgus $> 0°$): pure flexion-varus fractures (type IA, $-10.23° \pm 2.11°$, 3.7%, 4/108) and pure flexion-valgus fractures (type IB, $11.54° \pm 2.63°$, 26.9%, 29/108). Type II FTPFs were divided into three subgroups based on the degree of rotation in the axial plane (internal rotation $>10°$; flexion-neutral $-10°$ to $10°$; external rotation $<-10°$): flexion-neutral fractures (type IIA, $2.01° \pm 3.43°$, 13.0%, 14/108), flexion-internal rotation fractures (type IIB, $23.66° \pm 6.17°$, 35.2%, 38/108) and flexion-external rotation fractures (type IIC, $-16.23° \pm 4.27°$, 21.3%, 23/108). The incidence of posterolateral quadrant collapse fractures among type IIB fractures was significantly increased relative to that of type IIC fractures ($P < 0.001$). The incidence of posterolateral quadrant split fractures, anterolateral quadrant fractures and proximal fibular fractures among type IIC fractures was significantly higher than that among type IIB fractures ($P < 0.001$). The number of these concomitant injuries significantly differed between type IIB and type IIC fractures ($P < 0.001$).

Conclusion: 3D CT simulation-based subclassification according to the pattern of injury can help surgeons better understand FTPFs and select an appropriate treatment strategy.

Key words: Flexion tibial plateau fractures; Injury pattern; Simulation; Subclassification

Introduction

Tibial plateau fractures are associated with a variety of complex injury patterns that have been classified in different ways by many researchers. The current system that is widely recognized is the Schatzker classification system, which is based on two-dimensional X-ray imaging[1]. Luo *et al.* proposed the "three-column" concept, which is based on CT scans[2]. With the advancement of CT and 3D reconstruction technology, researchers have agreed that a three-dimensional comprehension of fractures is critical for understanding tibial plateau injury patterns[3–6]. However, the injury patterns of the tibial plateau are complex, and the existing classification systems involving injury patterns are imperfect and controversial.

Wang *et al.* categorized tibial plateau fractures according to the following four injury patterns identified in CT images: extension varus, extension valgus, flexion varus, and flexion

Address for correspondence Aqin Peng MD, Hebei Medical University Third Affiliated Hospital, Shijiazhuang, Hebei, China 050051 Tel: +8618533112802; Fax: +86031188603000; Email:pengaqin@126.com
Received 13 June 2020; accepted 19 November 2021

Orthopaedic Surgery
Open Access

valgus[3]. The updated Schatzker classification system also presents similar injury patterns[4]. Recently, the hyperextension injury pattern was identified, and Xie *et al*. proposed that the hyperextension-varus and hyperextension-valgus injury patterns should be included in the classification system[5]. However, limited information on the role of knee rotation in flexion injury patterns is available.

Flexion tibial plateau fractures (FTPFs) usually involve the posterior condyle of the tibial plateau, and they have received attention and have been reported by many authors[7,8]. The knee joint is more mobile in flexion than in extension and can perform many kinds of movements. Knee rotation often occurs when the knee joint is in a flexed position. Some authors have proposed that knee rotation is a minor force[5,6]. However, researchers specializing in sports medicine believe that rotational forces are very important and can cause ligament injuries. Flexion-varus injuries often involve internal rotation of the knee joint, whereas flexion-valgus injuries involve external rotation[9,10]. A comprehensive understanding of these injury patterns can help surgeons make accurate preoperative plans and choose optimal surgical strategies. Due to an inadequate understanding of these injury patterns, inappropriate treatment plans are often made, resulting in poor knee joint function postoperatively. Nevertheless, most researchers only focus on flexion-varus and flexion-valgus injury patterns in the clinical study of FTPFs, while the role of knee rotation in FTPFs has been ignored.

There are still limited data with respect to the classification system of FTPFs, including knee rotation. Pan *et al.*[11] recently investigated the injury patterns and fracture characteristics of complex tibial plateau fractures involving the posterior plateau with three-dimensional computed tomography, researching the injury patterns related to knee rotation. However, flexion injury patterns were not highlighted. Therefore, the existing research on flexion injury patterns is insufficient, especially that on knee rotation. To investigate the tibial plateau injury patterns that occur in flexion, a study on flexion injury patterns of tibial plateau fractures with CT images and 3D simulation technology was conducted. 3D CT simulation technology is a good tool to restore the position of the knee joint at the time tibial plateau fracture occurs and to simulate the corresponding injury patterns. In this study, morphological characteristics and concomitant injuries were found in the hypothesized injury patterns of knee rotation, and the importance of knee rotation was proposed, which helped us to fully understand FTPFs. Therefore, the purpose of this study was: (i) to propose a classification system based on simulated injury patterns for FTPFs; (ii) to describe the hypothesized knee rotation injury patterns; and (iii) to analyze their morphological characteristics and concomitant injuries.

Materials and Methods

Patient Selection

The tibial plateau fracture cases in 297 patients consecutively treated at our trauma center from August 2016 to December 2018 were reviewed retrospectively. A total of 108 patients with FTPFs were enrolled. The inclusion criteria were as follows: (i) an increased posterior tibial slope of the tibial plateau in CT images[5]; and (ii) flexion injury confirmed by medical record review and telephone follow-up. The exclusion criteria were as follows: (i) age younger than 18 years old; (ii) pathologic fractures; (iii) previous knee surgery and/or knee ligament malfunctions; and (iv) poor-quality CT images or digital imaging and communication in medicine (DICOM) files.

3D CT Simulation Technology

DICOM files were generated from the CT scans and imported into Mimics software (19.0, Materialise, Leuven, Belgium) to create 3D segments of the tibia and femur separately. The reference position was defined as full extension and then the tibial 3D segment was aligned with the articular surface of the femoral condyle. Adjustments were also made by using two-dimensional (2D) images to obtain the optimal alignment. The magnitudes of translation and rotation incurred after the segments were aligned were calculated by Mimics software.

Study Design

Three observers were trained to view the CT images with the Picture Archiving and Communication System (PACS) and use 3D computer simulation technology with Mimics software. Then, FTPFSs were divided according to the fracture region and further subdivided according to the data from the simulated injury patterns. Varus and valgus were defined as the degree of rotation in the coronal plane (varus $<0°$; valgus$> 0°$), internal rotation and external rotation were defined as the degree of rotation in the axial plane (internal rotation $>10°$; flexion-neutral $-10°$-$10°$; external rotation $<-10°$). Interobserver reliability among the three observers was assessed in the first round, and another round of evaluation was performed among the same three observers after an interval of 8 weeks to evaluate the intraobserver reliability.

Statistical Analyses

All statistical analyses were performed using SPSS software (version 23.0; IBM, Armonk, NY, USA). Data are presented as mean values (SD) for continuous variables. The kappa statistic was used to analyze the reliability of the FTPFS classification and simulated injury patterns. The guidelines proposed by Landis and Koch[12] were used to categorize the levels of reliability based on the kappa values. The kappa values: 0.01 to 0.20 (slight agreement), 0.21 to 0.40 (fair agreement), 0.41 to 0.60 (moderate agreement), 0.61 to 0.80 (substantial agreement), and more than 0.81 (almost perfect agreement). Fisher's exact test was used to compare the incidence of concomitant injuries such as proximal fibular fractures, avulsion fractures of intercondylar eminence, anterolateral quadrant fractures, posterolateral quadrant split fractures and posterolateral quadrant collapse fractures among different types of FTPFS, and was also used to compare the incidence of proximal fibular fractures between posterolateral quadrant split fractures and posterolateral quadrant collapse fractures. Differences were considered significant if the P value was less than 0.05.

Results

Patient Characteristics

Among the 108 FTPFs, 65 (60.2%) and 43 (39.8%) fractures occurred in the left and right knees, respectively. There were 66 male patients (61.1%) and 42 female patients (38.9%); fractures occurred more frequently in males than in females. The causes of injury included electric bicycle traffic accidents for 40 cases (37.0%), car accidents for 25 cases (23.1%), crash injuries for 16 cases (14.8%), falls from a height for 15 cases (13.9%), and simple falls for 12 cases (11.1%). Electric bicycle traffic accidents are relatively common among the causes of injury (Table 1).

Fracture Types and Subclassification of FTPFs

FTPFs were classified into two groups according to the fracture region: unicondylar FTPFs (type I) and bicondylar FTPFs (type II). According to the injury patterns simulated in this study, the two types of FTPFs were further subdivided into five subgroups: pure flexion-varus fractures (type IA), pure flexion-valgus fractures (type IB), flexion-neutral fractures (type IIA), flexion-internal rotation fractures (type IIB) and flexion-external rotation fractures (type IIC). (Fig. 1). (Table 2). The most common type of fracture in this case series was type IIB (35.2%, 38/108), followed by type IB (,26.9%, 29/108), type IIC (21.3%, 23/108), type IIA (13.0%, 14/108) and type IA (3.7%, 4/108). Type IIB fractures were more common than type IIC fractures (35.2% *vs.* 21.3%). The average kappa value was 0.66 for interobserver reliability and 0.71 for intraobserver reliability, both representing substantial agreement according to the levels of agreement proposed by Landis and Koch.[12]

Type IA Pure Flexion-Varus Fractures

Obvious varus deformities in the coronal plane ($-10.23° \pm 2.11°$) were observed in patients with type IA pure flexion-varus fractures. The stress zone between the femoral condyle and the tibial plateau was located in the posteromedial plateau. When a pure varus force is applied to the posteromedial tibial plateau with the knee flexed, an isolated posteromedial tibial plateau fracture occurs. This is the rarest type of flexion tibial plateau fracture. Only four isolated posteromedial tibial plateau fracture cases were found among the 108 fracture cases (Fig. 2).

Type IB Pure Flexion-Valgus Fractures

Obvious valgus deformities in the coronal plane ($11.54° \pm 2.63°$) were observed in patients with type IB pure flexion-valgus fractures. The stress zone between the femoral condyle and the tibial plateau was located in the posterolateral plateau. When a pure valgus force is applied to the posterolateral tibial plateau with the knee flexed, an isolated posterolateral tibial plateau fracture occurs. Most of the posterolateral tibial plateau is depressed when a pure valgus force is incurred, which is often caused by low-energy trauma[13–15]. In this study, most of these types of fractures resulted from electric bicycle traffic accidents (Fig. 3).

Type IIA Flexion-Neutral Fracture

No obvious axial rotation deformities ($2.01° \pm 3.43°$) were observed in patients with type IIA flexion-neutral fractures. The contact zone between the lateral femoral condyle and the tibial plateau was located in the posterolateral plateau, and the contact zone between the medial femoral condyle and the tibial plateau was located in the posteromedial plateau. The main fracture plane starts from the

TABLE 1 Demographic and clinical data of patients enrolled

Parameter	Overall	Type IA	Type IB	Type IIA	Type IIB	Type IIC
Patients, n (%)	108	4(3.7)	29(26.9)	14(13.0)	38(35.2)	23(21.3)
Gender, n (%)						
Male	66(61.1)	2(3.0)	18(27.3)	9(13.6)	22(33.3)	15(22.7)
Female	42(38.9)	2(4.8)	11(26.2)	5(11.9)	16(38.1)	8(19.0)
Mean age (range),years	48(20–76)	45(30–65)	52(25–76)	47(28–59)	49(20–70)	46(34–52)
Knee, n (%)						
Right	43(39.8)	1(2.3)	13(30.2)	8(18.6)	14(32.6)	7(16.3)
Left	65(60.2)	3(4.6)	16(24.6)	6(9.2)	24(36.9)	16(24.6)
Causes of injury, n (%)						
Electric bicycle traffic accidents	40(37.0)	1(2.5)	15(37.5)	3(7.5)	15(37.5)	6(15.0)
Car accidents	25(23.1)	0(0.0)	3(12.0)	5(20.0)	10(40.0)	7(28.0)
Crash injuries	16(14.8)	2(12.5)	1(6.3)	2(12.5)	6(37.5)	5(31.3)
Falls from a height	15(13.9)	1(6.7)	4(26.7)	3(20.0)	3(20.0)	4(26.7)
Simple falls	12(11.1)	0(0.0)	6(50.0)	1(8.3)	4(33.3)	1(8.3)

n, number.

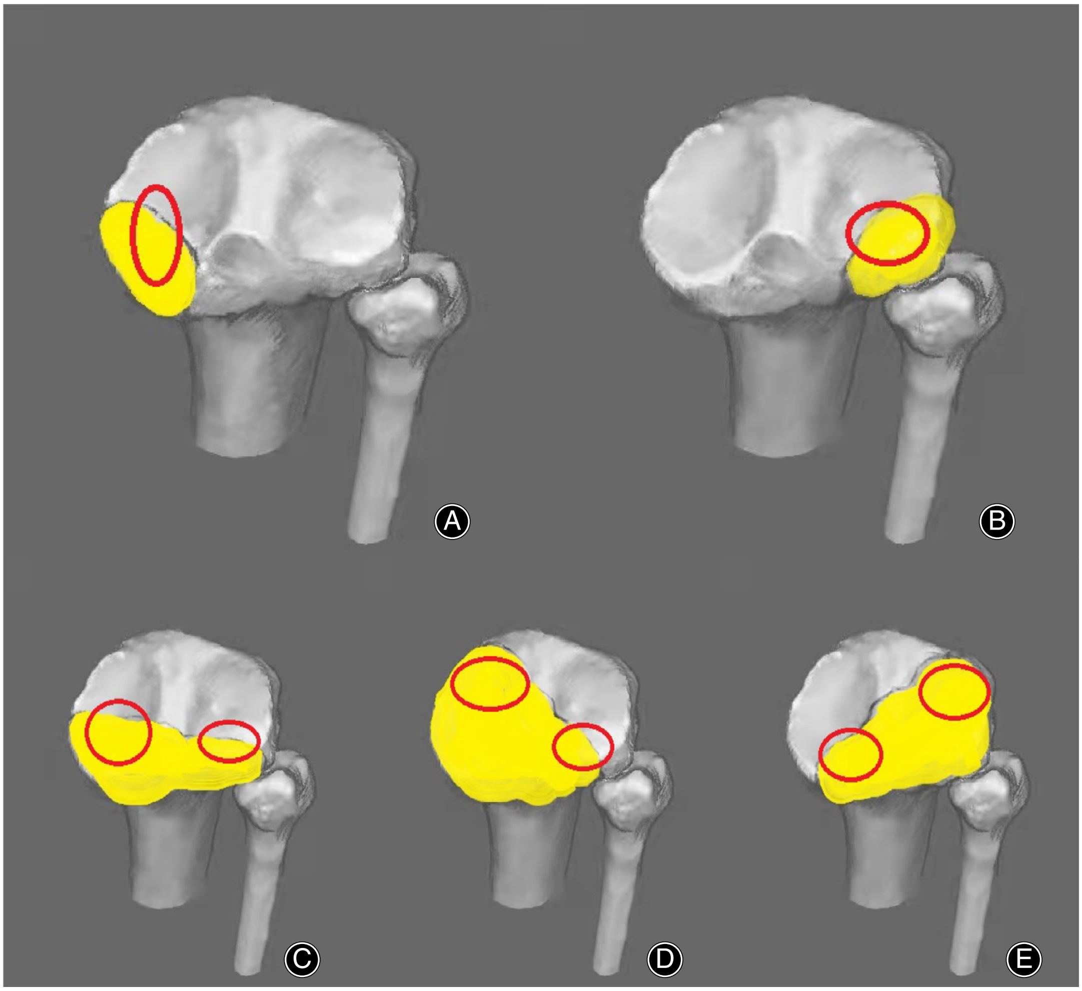

Fig 1 Classification of FTPFs. (A) type IA pure flexion-varus fractures, (B) type IB pure flexion-valgus fractures, (C) type IIA flexion-neutral fractures, (D) type IIB flexion-internal rotation fractures and (E)type IIC flexion-external rotation fractures. Yellow zone, fracture zone. Red oval, stress zone.

posteromedial region, passes through the center of the tibial plateau involving the tibial eminence, and ends in the posterolateral region. The posteromedial fracture fragment often involves approximately half of the medial condyle, and the posterolateral plateau fracture is often compressed. The knee joint is often anteriorly dislocated (Fig. 4).

Type IIB Flexion-Internal Rotation Fracture

Obvious axial internal rotation deformities (23.66° ± 6.17°) were observed in patients with type IIB flexion-internal rotation fractures. When forces were applied with the knee flexed and internally rotated, because the knee was internally rotated (internal rotation of the tibia, relative external rotation of the femur), the contact zone between the lateral femoral condyle and the tibial plateau was located in the centroposterior-lateral plateau, and the contact zone between the medial femoral condyle and the tibial plateau was located in the anteromedial plateau. The main fracture plane starts from the anteromedial region, passes through the center of the tibial plateau involving the tibial eminence and ends in the posterolateral region. The posteromedial fracture fragment often involves a large portion of the medial condyle, and centroposterior fractures of the lateral plateau often collapse and comminute (Fig. 5).

Type IIC Flexion-External Rotation Fracture

Obvious axial external rotation deformities (−16.23° ± 4.27°) were observed in patients with type IIC flexion-external rotation fractures. When forces were applied with the knee flexed and internally rotated, because the knee was externally rotated (external rotation of the tibia, relative internal rotation of the femur), the contact zone between the lateral femoral condyle and the tibial plateau was located in the anterolateral plateau, and the contact zone between the medial femoral condyle and the tibial plateau was located in the posteromedial plateau. The main fracture plane starts

TABLE 2 Fracture types and subclassification of FTPFs

Type	Fracture type	Morphological characteristics	Criteria	Patients, n (%)
Type IA	Pure flexion-varus fracture	The stress zone was located in the posteromedial plateau.	The degree of rotation in the coronal plane (varus < 0°)	4 (3.7)
Type IB	Pure flexion-valgus fracture	The stress zone was located in the posterolateral plateau.	The degree of rotation in the coronal plane (valgus > 0°)	29 (26.9)
Type IIA	Flexion-neutral fracture	Most of the posterolateral tibial plateau is depressed. The main fracture plane starts from the posteromedial region, ends in the posterolateral region. The posteromedial fracture fragment often involves approximately half of the medial condyle, and the posterolateral plateau fracture is often compressed.	The degree of rotation in the axial plane (flexion-neutral −10° to 10°)	14 (13.0)
Type IIB	Flexion-internal rotation fracture	The main fracture plane starts from the anteromedial region, ends in the posterolateral region. The posteromedial fracture fragment often involves a large portion of the medial condyle, and centroposterior fractures of the lateral plateau often collapse and comminute.	The degree of rotation in the axial plane (internal rotation > 10°)	38 (35.2)
Type IIC	Flexion-external rotation fracture	The main fracture plane starts from the anterolateral region, ends in the posteromedial region. Anterolateral fractures of the plateau are often split and collapsed, and the posteromedial fragment often involves a small portion of the medial condyle.	The degree of rotation in the axial plane (external rotation <−10°)	23 (21.3)

n, number.

from the anterolateral region, passes through the center of the tibial plateau involving the tibial eminence and ends in the posteromedial region. Anterolateral fractures of the plateau are often split and collapsed, and the posteromedial fragment often involves a small portion of the medial condyle (Fig. 6).

Concomitant Injuries of FTPFs

The incidence of posterolateral quadrant collapse fractures among patients with type IIB fractures is significantly increased relative to that among patients with type IIC fractures. The incidence of posterolateral quadrant split fractures, anterolateral quadrant fractures and proximal fibular fractures among patients with type IIC fractures is significantly higher than that among patients with type IIB fractures. A high incidence of avulsion fractures of the intercondylar eminence was found in this series of cases (72.2% 78/108). All type IIA and type IIB fractures are associated with avulsion fractures of intercondylar eminence, and 44.8% of type IB fractures and 56.5% of type IIC fractures are accompanied by avulsion fractures of intercondylar eminence. The number of these concomitant injuries significantly differed between patients with type IIB fractures and those with type IIC fractures ($P < 0.001$) (Table 3).

Discussion

Based on the injury patterns simulated in this study, FTPFs were classified into five subgroups: type IA pure flexion-varus fractures; type IB pure flexion-valgus fractures; type IIA flexion-neutral fractures; type IIB flexion-internal rotation fractures; and type IIC flexion-external rotation fractures. Each of the hypothesized injury patterns, especially rotation injury patterns, has distinctive morphological characteristics and is associated with specific concomitant injuries.

Hayes *et al.*[9] classified flexion rotation injuries on the basis of magnetic resonance imaging findings and proposed that flexion-varus injuries are often caused by internal rotational forces in the knee joint, whereas flexion-valgus injuries are caused by external rotational forces. Sheehan *et al.*[10] further presented a biomechanical approach to interpreting MRI scans of knee rotation injuries. Both research groups emphasized that knee rotation is a key factor in knee injuries. However, some authors regarded knee rotation as a minor force for tibial plateau fracture[5,6]. In this study, different morphological characteristics and concomitant injuries were observed among the rotation injury patterns, and knee rotation was considered a significant factor for tibial plateau fracture.

The direction of the force incurred (axial, varus, valgus, rotation) and the position of the knee (flexion, extension, hyperextension and knee rotation) may determine the fracture pattern. When the knee is fully extended, axial rotation of the knee is maximally restricted by passive tension in the stretched ligaments and parts of the capsule and increased bony congruity within the joint. When the knee joint is

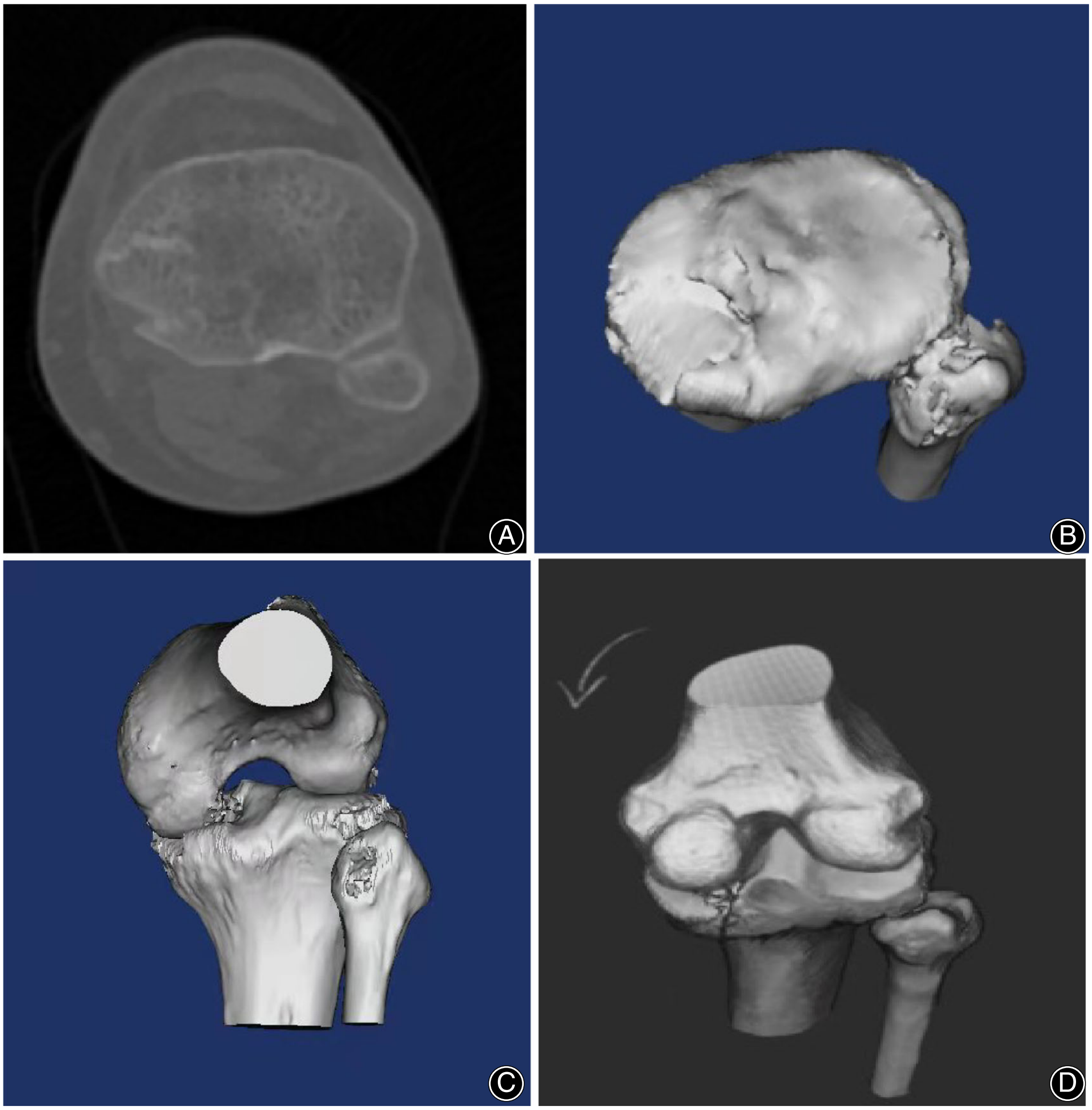

Fig 2 Type IA pure flexion-varus fractures. (A) CT image. (B) 3D CT simulated image. (C) 3D CT injury pattern simulated image. (D) injury pattern simulated hand drawing.

flexed to 90 degrees, it can perform approximately 40 to 45 degrees of axial rotation. Therefore, the knee may be internally or externally rotated when a force is incurred during flexion. Pan *et al.*[11] described the injury patterns of tibial plateau fractures involving the posterior plateau and proposed two injury patterns referring to knee rotation, namely, flexion-internal rotation and flexion-external rotation. In this study, the two injury patterns with fracture characteristics were similar to those of type IIB flexion-internal rotation fractures and type IIC flexion-external rotation fractures. Tibial plateau fractures involving the posterior plateau occurred in all knee positions, including extension, while our research emphasized knee rotation when the knee joint was flexed. Tibial plateau fractures are caused by an impact force from the femoral condyle. When the knee joint flexes, the contact zone between the femoral condyle and tibial plateau moves backward, and the contact zone between the lateral femoral condyle and the tibial plateau shifts significantly. When knee flexion is accompanied by internal rotation, the contact zone between the lateral femoral condyle and the tibial plateau is located in the centroposterior-lateral plateau, and the contact zone between the medial femoral condyle and the tibial plateau is located in the anteromedial plateau. When knee flexion is accompanied by external rotation, the contact zone between the lateral femoral condyle and the tibial plateau is located in the anterolateral plateau, and the contact zone between the medial femoral condyle and the tibial plateau is located in the posteromedial plateau. Thus,

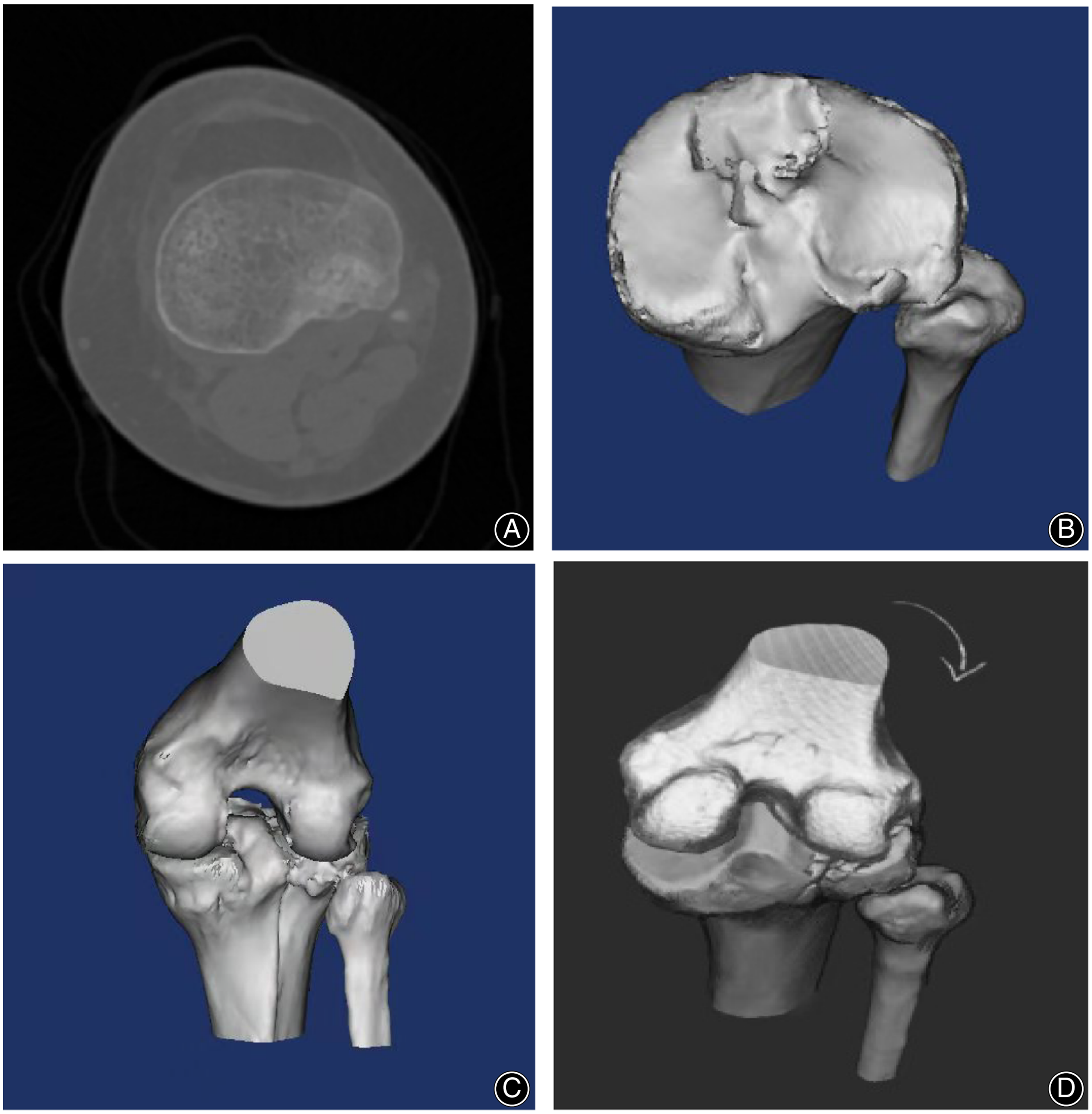

Fig 3 Type IB pure flexion-valgus fractures. (A) CT image. (B) 3D CT simulated image. (C) 3D CT injury pattern simulated image. (D) injury pattern simulated hand drawing.

the morphological characteristics of fractures are closely related to changes in the contact zone after knee flexion and rotation.

Zhu *et al.*[16] conducted biomechanical studies on cadavers and found that 30° and 60° of knee flexion with an axial force is highly likely to result in posterolateral split fractures, while posterolateral depression fractures occur more commonly with 90° of flexion. Posterolateral split fractures are often accompanied by anterolateral depression fractures with 30° of flexion. These results can be explained by the different tibiofemoral joint contact zones. In this study, the contact zone between the lateral femoral condyle and the tibial plateau was located in the anterolateral plateau for type IIC fractures, so type IIC fractures were often associated with anterolateral quadrant fractures and posterolateral quadrant split fractures; the contact zone between the lateral femoral condyle and the tibial plateau was located in the centro-posterior-lateral plateau for type IIB fractures, so type IIB fractures were more often accompanied by posterolateral quadrant collapse fractures.

Tibial plateau fractures are often accompanied by injuries such as meniscus injuries, cruciate ligament injuries and collateral ligament injuries, which have been widely reported by several authors[17–19], but the literature on injuries accompanied by proximal fibula fractures is very limited. Zheng *et al.*[20] proposed that the incidence of fibular fractures in tibial plateau fractures is 29.88% (150/502) and noted that fibular fracture reduction is helpful for performing minimally

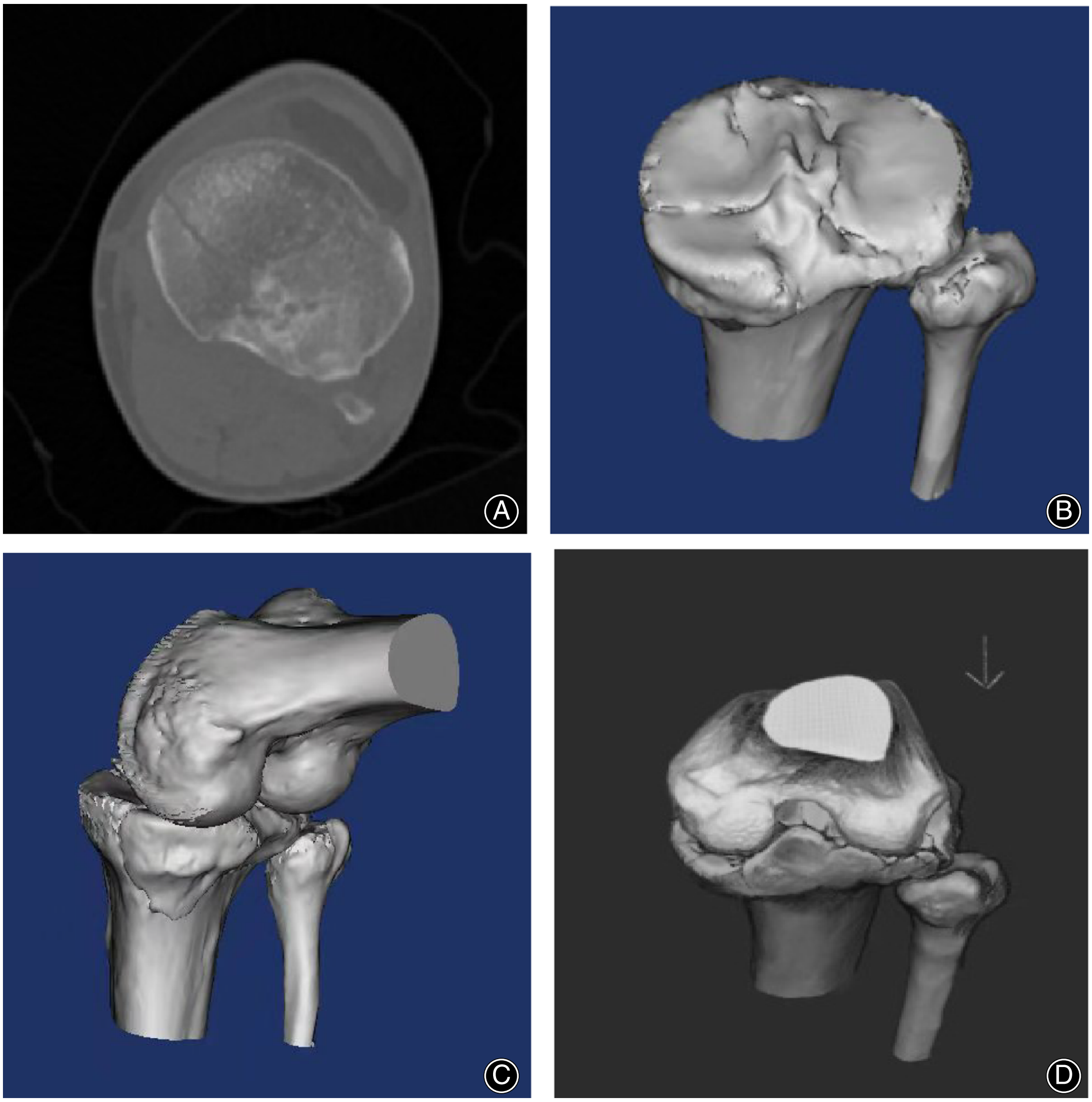

Fig 4 Type IIA flexion-neutral fractures. (A) CT image. (B) 3D CT simulated image. (C) 3D CT injury pattern simulated image. (D) injury pattern simulated hand drawing.

invasive fixation of tibial plateau fractures and releasing excessive local strain of the lateral tibial plateau. In this study, proximal fibular fractures had a high incidence in patients with type IIC fractures but a low incidence in patients with type IIB fractures and other flexion injury types. For type IIC fractures, the contact zone between the lateral femoral condyle and the tibial plateau is located in the anterolateral plateau. When flexion-external rotation injuries occur, high-energy forces are often transmitted to the fibula, so type IIC fractures are often accompanied by proximal fibular fractures, especially comminuted fractures of the fibular neck. However, for type IIB fractures, the contact point zone between the lateral femoral condyle and the tibial plateau is located in the centroposterior-lateral plateau, which is on the medial side of the fibular head; when even larger forces are incurred, the resultant forces caused by flexion-internal rotation injuries are often not transmitted to the fibula, so the incidence of proximal fibular fractures is significantly reduced. The incidence of posterolateral quadrant split fractures combined with proximal fibular fractures was significantly higher than that of posterolateral quadrant collapse fractures also found in this study (87.5% *vs.* 13.6%) ($P < 0.001$).

Tibial plateau fractures are often accompanied by avulsion fractures of intercondylar eminence, especially FTPFs. Hua *et al.*[7] reported that the incidence of avulsion fractures of intercondylar eminence in the flexion neutral position was 92.86%. In this study, all type IIA and type IIB fractures were

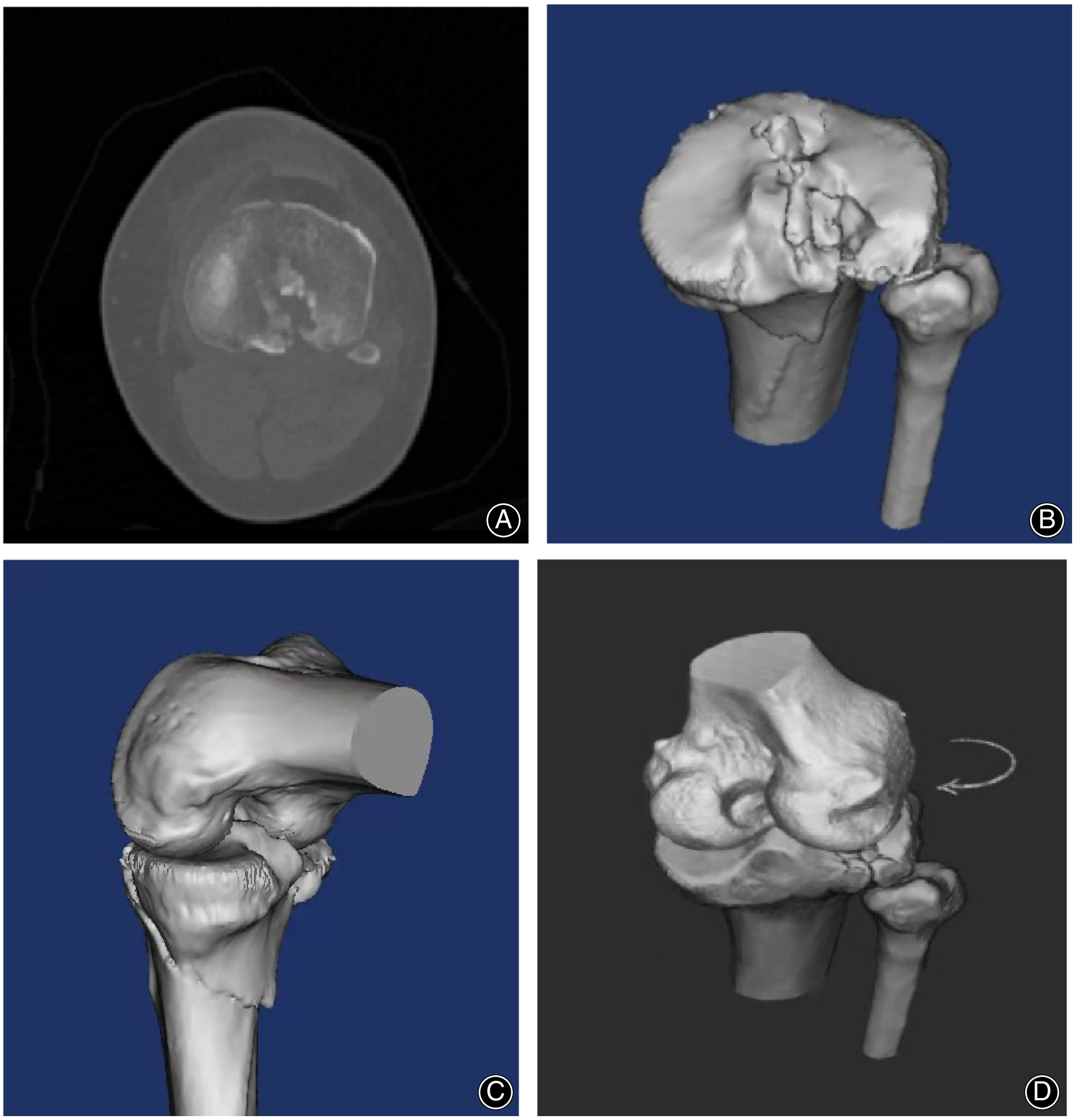

Fig 5 Type IIB flexion-internal rotation fractures. (A) CT image. (B) 3D CT simulated image. (C) 3D CT injury pattern simulated image. (D) injury pattern simulated hand drawing.

associated with avulsion fractures of intercondylar eminence, and 44.8% of type IB fractures and 56.5% of type IIC fractures were accompanied by avulsion fractures of intercondylar eminence. However, not every anterior cruciate ligament (ACL) avulsion fracture needs to be fixed. Regarding the different injury patterns, some avulsion fractures of intercondylar eminence were more likely to be caused by comminution fractures than ligamentous bone avulsions. The anterior drawer test was performed under anesthesia to determine whether the knee joint was unstable after fracture reduction and plate fixation. If the knee joint was slack, two screws or steel wires, depending on the size of the fracture fragment, were used to reduce and fix the ACL avulsion fracture.

Tibial plateau fractures are considered a major risk factor for posttraumatic osteoarthritis and develop in 9%–44% of injured patients[21]. Initial trauma of the tibial plateau cartilage may be the first cause of the development of osteoarthritic problems[21]. Biz *et al.*[22] reported that AO 41-C (complete articular fractures) tibial plateau fractures tended to develop posttraumatic osteoarthritis more frequently than AO 41-B (partial articular fractures) tibial plateau fractures, while AO 41-C tibial plateau fractures had the worst clinical outcomes. According to the subclassification system of FTPFs, type I FTPFs belong to AO 41-B tibial plateau fractures, while type II FTPFs belong to AO 41-C tibial plateau fractures, so patients with type II FTPFs have a greater risk of developing posttraumatic osteoarthritis and having worse

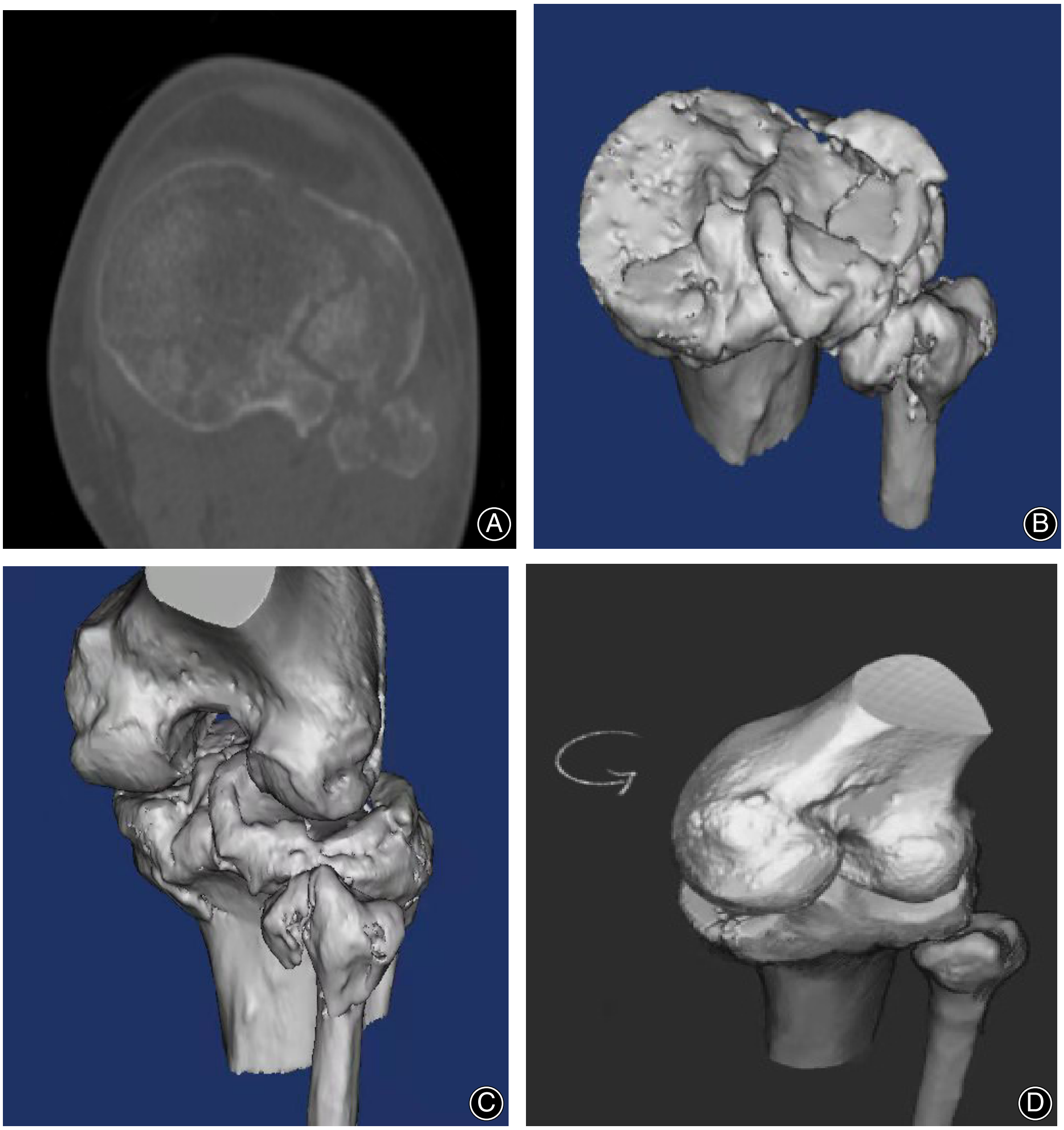

Fig 6 Type IIC flexion-external rotation fractures. (A) CT image. (B) 3D CT simulated image. (C) 3D CT injury pattern simulated image. (D) injury pattern simulated hand drawing.

TABLE 3 A comparison of the incidence of concomitant injuries between type IIB and type IIC fractures

Concomitant injury	Type IIB (n = 38)	Type IIC (n = 23)	*P* value*
Proximal fibular fractures, n (%)	5 (13.2)	15 (65.2)	<0.001
Avulsion fractures of intercondylar eminence, n (%)	38 (100)	13 (56.5)	<0.001
Anterolateral quadrant fractures, n (%)	2 (5.3)	21 (91.3)	<0.001
Posterolateral quadrant split fractures, n (%)	0 (0)	16 (69.6)	<0.001
Posterolateral quadrant collapse fractures, n (%)	38 (100)	7 (30.4)	<0.001

n, number.; * Fisher test.

clinical outcomes. Snoeker *et al.*[23] reported that in young adults, cruciate ligament injury increased the risk of future diagnosed knee osteoarthritis. In this study, all type IIA and type IIB fractures were accompanied by avulsion fractures of intercondylar eminence, which have a high risk of developing posttraumatic osteoarthritis.

In a clinical setting, it is critically important to recognize knee flexion rotation injury patterns, as they all have their own morphological characteristics and require different approaches and treatment strategies. Type IIA fractures are equivalent to Chen *et al.*'s[24] type V fractures (posteromedial split combined with posterolateral depression). There are many surgical approaches available that can be used to expose the posteromedial and posterolateral quadrants for this type of fracture. Bhattacharyya *et al.*[25] described a midline S-shaped posterior approach. Carlson[8] introduced dual posteromedial and posterolateral curvilinear S-shaped approaches separately for posterior bicondylar tibial plateau fractures. The posterior inverted L-shaped approach was proposed by Luo *et al.*[2] For type IIB fractures, "medial dislocation-type fracture" of the proximal tibia was described by Primoz *et al.*[26] As they have a unique fracture pattern, posterolateral fractures are located in the central part of the tibial plateau, and the anterolateral plateau cortex is intact. In addition to the above approaches, the anterolateral approach with intra-articular osteotomy of the lateral tibial plateau described by Sciadini *et al.*[27] is recommended, which facilitates the visualization and reduction of articular impaction and displaced lateral meniscus tears. Primoz *et al.*[26] also presented a single larger medial approach that can be used to repair most tibial plateau injuries. Nearly all type IIC fractures are accompanied by anterolateral quadrant fractures and posterolateral quadrant split fractures, so surgical approaches that can expose the anterolateral, posterolateral and posteromedial quadrants are required. An extended anterolateral approach that can easily expose, reduce and fix the posterolateral split fragment is recommended[28].

FTPFs usually involve the posterior tibial condyle, so the surgical approaches are different from the conventional anterolateral or anteromedial incision, which are often posterolateral or posteromedial incisions. According to the subclassification of FTPFs, the position of patient and the surgical approach can be better predicted during preoperative planning, and the location of the incision and the selection of internal fixation can be better estimated. One surgical incision and single plate fixation can be adopted in the simple unicondylar FTPFs (type I), while more surgical incisions and multiple plates fixation can be chosen in the complex bicondylar FTPFs (type II). The location of the main plate and the direction of screws are selected according to the main fracture plane, and further research is needed in future clinical studies.

FTPFs are divided into simple unicondylar fractures (type I) and complex bicondylar fractures (type II) according to the subclassification, which have the advantage of being easy to remember and understand. Other types (such as AO) were classified based on morphology, which were difficult to comprehend and memorize and required long time training. Wang *et al.*[3] proposed flexion-varus and flexion-valgus injury patterns of tibial plateau fractures, however FTPFs have not been classified comprehensively until now. Limited information on the role of knee rotation in flexion injury patterns is available in other types of tibial plateau fractures. In this type, FTPFs are categorized in detail involving knee rotation, which is a thorough classification of the flexion injury patterns of tibial plateau fractures. Fractures can be reduced according to the type of injury mechanism, which has guiding significance for operative treatment.

There are also several limitations to this study. First, the classification system proposed in this study is for flexion tibial plateau injuries and does not cover all tibial plateau fractures. Second, bicondylar fractures are usually caused by axial, varus and valgus forces rather than a single force, so varus and valgus forces are not clearly described in bicondylar flexion fractures. Finally, the injury patterns found in this study, especially the rotation patterns, are based on 3D CT simulations; additional research about biomechanical experiments is needed.

Conclusion

In this study, a novel subclassification system of flexion tibial plateau fractures based on 3D CT simulation technology was proposed. The association between these hypothesized injury patterns and concomitant injuries was also analyzed. This subclassification system can help surgeons better understand FTPFs and rotation injury patterns, allowing them to make suitable preoperative plans and choose optimal surgical strategies.

References

1. Markhardt K, Gross JM, Monu JU. Schatkzker classification of tibial plateau fractures: use of CT and MR imaging improves assessment. Radiographics, 2009, 29: 585–597.
2. Luo C-F, Sun H, Zhang B, Zeng B-F. Three-column fixation for complex tibial plateau fractures. J Orthop Trauma, 2010, 24: 683–692.
3. Wang Y, Luo C, Zhu Y, *et al*. Updated three-column concept in surgical treatment for tibial plateau fractures - a prospective cohort study of 287 patients. Injury, 2016, 47: 1488–1496.
4. Kfuri M, Schatzker J. Revisiting the Schatzker classification of tibial plateau fractures. Injury, 2018, 49: 2252–2263.
5. Xuetao Xie Y, Zhan YW, Lucas JF, Zhang Y, Luo C. Comparative analysis of mechanism-associated 3-dimensional Tibial plateau fracture patterns. J Bone Joint Surg Am, 2020, 102: 410–418.
6. Zhang B-B, Sun H, Zhan Y, *et al*. Reliability and repeatability of tibial plateau fracture assessment with an injury mechanism-based concept. Bone Joint Res, 2019, 8: 357–366.
7. Kehan H, Xieyuan J, Yejun Z, Chen C, Bosong Z, Yujiang M. Retrospective analysis of 514 cases of tibial plateau fractures based on morphology and injury mechanism. J Orthop Surg Res, 2019, 14: 267.
8. Carlson DA. Posterior bicondylar tibial plateau fractures. J Orthop Trauma, 2005, 19: 73–78.
9. Hayes CW, Brigido MK, Famadar DA, Propeck T. Mechanism-based pattern approach to classification of complex injuries of the knee depicted at MR imaging. Radiographics, 2000, 20: 121–134.
10. Sheehan SE, Khurana B, Gaviola G, Davis KW. A biomechanical approach to interpreting magnetic resonance imaging of knee injuries. Magn Reson Imaging Clin N Am, 2014, 22: 621–648.

11. Pan S, Peng A-Q, Hu Y-N, *et al*. Injury pattern simulation and mapping of complex tibial plateau fractures that involve the posterior plateau with three-dimensional computed tomography. Ann Transl Med, 2021, 9: 302.
12. Landis JR, Koch GG. The measurement of observer agreement for categorical data. Biometrics, 1977, 33: 159–174.
13. Yu GR, Xia J, Zhou JQ, Yang YF. Low-energy fracture of posterolateral tibial plateau: treatment by a posterolateral prone approach. J Trauma Acute Care Surg, 2012, 72: 1416–1423.
14. Zhang Y, Song L, Li X, Fang J. Flexion-valgus unicondylar tibial plateau depression fracture pattern: classification and treatment. Injury, 2018, 49: 852–859.
15. Chang SM, Zheng HP, Li HF, *et al*. Treatment of isolated posterior coronal fracture of the lateral tibial plateau through posterolateral approach for direct exposure and buttress plate fixation. Arch Orthop Trauma Surg, 2009, 129: 955–962.
16. Zhu Y, Meili S, Dong M-J, *et al*. Pathoanatomy and incidence of the posterolateral fractures in bicondylar tibial plateau fractures: a clinical computed tomography-based measurement and the associated biomechanical model simulation. Arch Orthop Trauma Surg, 2014, 134: 1369–1380.
17. Xingguang T, Nong C, Fugen P, Cheng B. External fixation combined with delayed internal fixation in treatment of tibial plateau fractures with dislocation. Medicine (Baltimore), 2017, 96: e8221.
18. Mthethwa J, Chikate A. A review of the management of tibial plateau fractures. Musculoskelet Surg, 2018, 102: 119–127.
19. Keightley AJ, Nawaz SZ, Jacob JT, Unnithan A, Elliott DS, Khaleel A. Ilizarov management of Schatzker IV to VI fractures of the tibial plateau: 105 fractures at a mean follow-up of 7.8 years. Bone Jt J, 2015, 97: 1693–1697.
20. Zheng Z-l, Yi-yang Y, Chang H-r, Liu H, Zhou H-l, Zhang Y-z. Establishment of classification of tibial plateau fracture associated with proximal fibular fracture. Orthop Surg, 2019, 11: 97–101.
21. van Dreumel RL, van Wunnik BP, Janssen L, Simons PC, Janzing HM. Mid-to long-term functional outcome after open reduction and internal fixation of tibial plateau fractures. Injury, 2015, 46: 1608–1612.
22. Biz C, Maso G, Gambato M, *et al*. Challenging surgical treatment of displaced articular tibial plateau fractures: do early knee radiographic features have a predictive value of the mid-term clinical functional outcomes. Orthop Surg, 2019, 11: 1149–1162.
23. Snoeker B, Tukiewicz A, Magnusson K, *et al*. Risk of knee osteoarthritis after different types of knee injuries in young adults: a population-based cohort study. Br J Sports Med, 2020, 54: 726–730.
24. Chen HW, Chen CQ, Yi XH. Posterior tibial plateau fracture: a new treatment-oriented classification and surgical management. Int J Clin Exp Med, 2015, 8: 472–479.
25. Bhattacharyya T, McCarty LP 3rd, Harris MB, *et al*. The posterior shearing tibial plateau fracture: treatment and results via a posterior approach. J Orthop Trauma, 2005, 19: 305–310.
26. Potocnik P, Acklin YP, Sommer C. Operative strategy in postro-medial fracture-dislocation of the proximal tibia. Injury, 2011, 42: 1060–1065.
27. Sciadini MF, Sims SH. Proximal Tibial intra-articular osteotomy for treatment of complex Schatzker type IV tibial plateau fractures with lateral joint line impaction: description of surgical technique and report of nine cases. J Orthop Trauma, 2013, 27: e18–e23.
28. Cho J-W, Kim J, Cho W-T, *et al*. Approaches and fixation of the posterolateral fracture fragment in tibial plateau fractures: a review with an emphasis on rim plating via modified anterolateral approach. Int Orthop, 2017, 41: 1887–1897.