BJR

■ **BONE FRACTURE**

Reliability and repeatability of tibial plateau fracture assessment with an injury mechanism-based concept

B-B. Zhang,
H. Sun,
Y. Zhan,
Q-F. He,
Y. Zhu,
Y-K. Wang,
C-F. Luo

Shanghai Jiao Tong University Affiliated Sixth People's Hospital, Shanghai, China

Objectives

CT-based three-column classification (TCC) has been widely used in the treatment of tibial plateau fractures (TPFs). In its updated version (updated three-column concept, uTCC), a fracture morphology-based injury mechanism was proposed for effective treatment guidance. In this study, the injury mechanism of TPFs is further explained, and its inter- and intraobserver reliability is evaluated to perfect the uTCC.

Methods

The radiological images of 90 consecutive TPF patients were collected. A total of 47 men (52.2%) and 43 women (47.8%) with a mean age of 49.8 years (SD 12.4; 17 to 77) were enrolled in our study. Among them, 57 fractures were on the left side (63.3%) and 33 were on the right side (36.7%); no bilateral fracture existed. Four observers were chosen to classify or estimate independently these randomized cases according to the Schatzker classification, TCC, and injury mechanism. With two rounds of evaluation, the kappa values were calculated to estimate the inter- and intrareliability.

Results

The overall inter- and intraobserver agreements of the injury mechanism were substantial ($\kappa_{inter} = 0.699$, $\kappa_{intra} = 0.749$, respectively). The initial position and the force direction, which are two components of the injury mechanism, had substantial agreement for both inter-reliability or intrareliability. The inter- and intraobserver agreements were lower in high-energy fractures (Schatzker types IV to VI; $\kappa_{inter} = 0.605$, $\kappa_{intra} = 0.721$) compared with low-energy fractures (Schatzker types I to III; $\kappa_{inter} = 0.81$, $\kappa_{intra} = 0.832$). The inter- and intraobserver agreements were relatively higher in one-column fractures ($\kappa_{inter} = 0.759$, $\kappa_{intra} = 0.801$) compared with two-column and three-column fractures.

Conclusion

The complete theory of injury mechanism of TPFs was first put forward to make the TCC consummate. It demonstrates substantial inter- and intraobserver agreement generally. Furthermore, the injury mechanism can be promoted clinically.

Cite this article: *Bone Joint Res* 2019;8:357–366.

Correspondence should be sent to C-F. Luo; email: congfengl@outlook.com

Article focus

■ In this paper we present an updated three-column concept based on injury mechanism to deal with tibial plateau fractures (TPFs), and good clinical results according to this concept have been reported.

■ The injury mechanism was not consummate, and its reliability and repeatability were unclear.

■ We further explained the injury mechanism according to two parameters from CT images, and evaluated its reliability and repeatability.

Key messages

■ A new approach to evaluating TPFs based on injury mechanism was proposed in this study.

■ Satisfactory reliability and repeatability of the injury mechanism were achieved.

Strengths and limitations

■ This is the first time that the injury mechanism of TPFs has been described in detail.

■ The primary limitation of this study is that the injury mechanism of TPFs was inferred from fracture morphology on the basis of our clinical experience and previous biomechanical studies.

Introduction

Tibial plateau fractures (TPFs) are complex intra-articular fractures that usually indicate the need for surgical intervention. In past decades, the Schatzker classification[1] and the AO/OTA classification[2] were the two most commonly used tools and were based on normal radiological images. With the wide use of CT scanning and image reconstruction in the diagnosis and treatment of TPFs, evaluation of the fracture pattern and morphology has become routine in current preoperative planning.[3] A reliability study concluded that CT scanning could improve the inter- and intraobserver reliability of the aforementioned classifications.[4]

To promote a more comprehensive understanding of TPFs, a theory of three-column classification (TCC) was proposed that particularly emphasized CT and image reconstruction as the basis of TPF classification.[5,6] Subsequently, CT-based TCC has shown advantages in analyzing the fracture pattern and deciding on subsequent treatment.[7-10] Furthermore, other studies have proposed or analyzed the concepts of four-column classification,[11-13] ten-segment classification,[14] and fracture mapping[15] of TPFs, among others, all of which being based on CT images, in order to profoundly realize the characteristics of TPFs. However, these innovative classifications or mappings have, to date, been focused on the morphology of TPFs, but from different angles. Besides fracture morphology, to determine the appropriate surgical approach, implant placement, and fixation sequence, a combination injury mechanism analysis for preoperative assessment is highly recommended. A literature review found that the description of the TPF injury mechanism in published reports is currently inconsistent,[16] and no reliability studies have been reported in the literature. Although we have already achieved good clinical outcomes with the use of the incomplete injury mechanism,[17] there is still much to be improved or completed, and the reliability of the injury mechanism of TPFs remains unclear. Thus, it is necessary to obtain the comprehensive injury mechanism of TPFs and evaluate its interobserver reliability and intraobserver reproducibility in order to guide effective treatment strategies. According to these requirements, TPF cases were retrospectively collected, and a reliability study was conducted.

Patients and Methods

Patients. The approval of the institution's ethical review board (ERB number: 2016-89-(1)) was obtained prior to initiation of the study. We included a total of 90 consecutive patients with TPF who were surgically treated in the department of orthopaedic surgery and trauma III at our hospital (level I trauma centre) between May 2016 and November 2017. All potential patients were screened by retrieving the following terms: TPF; proximal tibial fracture; knee joint fracture; or tibial fracture from the Medical Writing and Managing System, and by evaluating the radiographs in the Picture Archiving and Communication System. Three experienced orthopaedic surgeons were chosen to select and check patients. Exclusion criteria were as follows: 1) age less than 16 years; 2) incomplete CT images; 3) a history of knee trauma or surgery, including previous TPFs and/or existing knee deformity; 4) an open proximal tibial fracture; 5) fractures of intercondylar eminence of tibia, fractures of tibial insertions of cruciate ligaments, or subtle fractures or avulsion fractures of the plateau (Segond fractures); 6) articular cartilage denudation; and 7) pathological fractures. In addition, patients with concomitant proximal tibial diaphyseal fractures were also excluded to avoid interference with the alignment measurements and evaluations. Demographical and clinical data such as age, sex, affected side, and accompanying injuries were collected from the medical records department. A total of 47 men (52.2%) and 43 women (47.8%) with a mean age of 49.8 years (SD 12.4; 17 to 77) were enrolled in our study. Among them, 57 fractures were on the left side (63.3%) and 33 were on the right side (36.7%); no bilateral fracture existed.

Observers and survey. Four independent observers, including two orthopaedic traumatologists (QFH and HS) who specialized in knee joints, one attending doctor (YZ), and one senior resident (YKW), were recruited for study participation. No observer was involved in patient recruitment or exposed to the original patient documentation. All observers were asked to use the Schatzker classification[1] and the TCC.[5] To clarify these classifications, published documents that described the respective classification were supplied to the observers. Before the evaluation, all observers completed a training session, which elaborated the injury mechanism of TPFs with a diagrammatic sketch and a written or verbal description.

Two rounds of evaluation were performed. First, all observers evaluated the images of each patient according to the classifications and injury mechanism. Then, after an eight-week hiatus, patients were evaluated once again, with the previous evaluation blinded. The radiological images (radiograph and CT) of each patient were evaluated in a randomized fashion. The observers were not provided with any feedback after the initial viewing, and the images were not available between the viewings. The observers were given as much time as they needed to

Fig. 1a　　　　　　　　**Fig. 1b**　　　　　　　　**Fig. 1c**

Fig. 1d　　　　　　　　**Fig. 1e**　　　　　　　　**Fig. 1f**
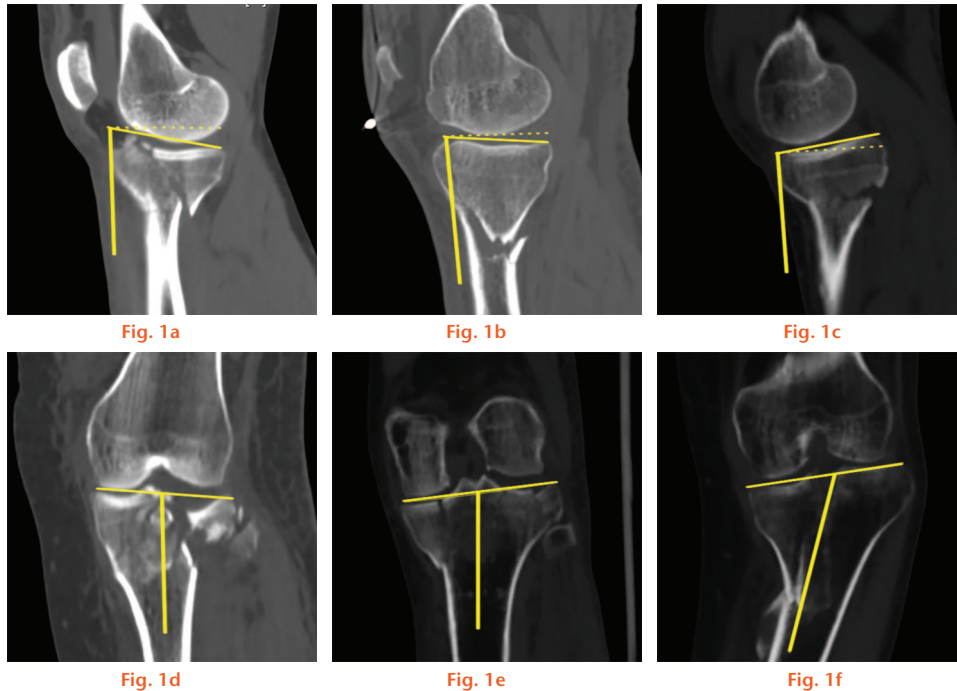
Parameters in CT reconstruction images for injury mechanism. a) to c): Posterior tibial slope angle (PTSA), defined as the angle created by the tibial plateau and the long axis of the tibia in the sagittal plane. a) The increased PTSA indicates a flexion mode of initial position of knee joint; b) the normal or unchanged PTSA indicates extension injury pattern; c) the decreased PTSA (or retroversion) means the injured knee in hyperextension pattern. d) to f): tibial plateau angle (TPA) defined as the angle created by the medial angle of tibial plateau surface and the long axis of the tibia shaft in the coronal plane. d) The increased TPA indicates a valgus force; e) the normal or unchanged TPA indicates axial force; f) the decreased TPA means a varus force.

evaluate the images accurately and independently. After the evaluation, the final and unique Schatzker classification and TCC and the injury mechanism of each case were determined by majority opinion and consultation with the corresponding author (CFL).

The CT images in three planes - horizontal (scanning images), sagittal, and coronal (2D reconstructions) - together with 3D reconstructions, were used for classification and assessment. The measurements and evaluation of the digital images were performed using Kingstar Winning TV view software (Shanghai Kingstar Winning Medical Information Technology Co., Ltd, Shanghai, China; precision within 0.01 mm).

Injury mechanism. Tibial plateau fractures often result from an applied axial load with the knee joint in various positions in conjunction with a varus or valgus deforming force.[17] The updated three-column concept (uTCC) system was developed on the basis of the fracture morphology (TCC) and mechanism of trauma, and the criteria to determine the appropriate injury mechanism consisted of two points: the position of the knee joint at the time of the traumatic event, at the exact relative position of the femur to the tibia (extension, flexion, hyperextension) as the initial position and the direction of the deforming force (valgus, varus, axial) as the force direction. Unfortunately, patients with a TPF are generally unable to provide the position of the knee joint at the time of the injury. Nevertheless, the specific location or appearance of the fracture and soft-tissue injuries at imaging allows

surgeons to translate imaging information into an injury mechanism.

Alignment of the proximal tibia has been considered to be one of the most important factors in determining the treatment effect of surgery for TPFs.[18] During flexion movement of the knee, the smaller radius of the femoral articular surface slides dorsally on the tibial plateau surface, which is relatively flat or slightly convex.[19] As the axial impact load is being transmitted from the femoral to the tibial articular surface, a fracture might be caused on the posterior plateau.[20] The changes in posterior tibial slope angle (PTSA) in the sagittal plane, formed by the medial/lateral tibial plateau line and the perpendicular line of the anterior tibial cortex in the sagittal plane, were used to represent the initial position. According to the results of cadaveric and radiological studies measuring the knees of Chinese and Asian patients,[21,22] the PTSA in the normal population is on average 11°, with a variable reference range. Meanwhile, the medial PTSA is slightly greater than the lateral one, and the association between the PTSAs of the medial and lateral tibial plateaus is not strong.[21] The initial position will be considered as hyperextension when the PTSA is reversed (less than 0°, indicating recurvation), as extension when the PTSA ranges from 0° to 11°, or as flexion when it is more than 11° (retroversion increased; Figs 1a to 1c).

Accordingly, the deforming force that was exerted on the tibial plateau could be predicated on the inclination tendency of the proximal tibia in the coronal plane, that

Table I. Injury mechanism of tibial plateau fractures (TPFs) with corresponding three-column classification (TCC) and Schatzker classification in detail

Initial position	Force direction	TCC*	Detail	Schatzker classification
Extension	Valgus	Two-column	Lateral column + posterolateral column (total lateral condylar fracture; depression located anteriorly)	I/II
		Zero-column	Depression located anteriorly	III
	Varus	Two-column	Medial column + posteromedial column (total medial condylar fracture)	IV
		Three-column	Medial column + posteromedial column fracture with lateral column split (sagittal fracture from anterior to posterior)	V/VI
	Axial	Three- column	Burst fracture; compression located centrally and tension side anterior and posterior	V/VI
Flexion	Valgus	One-column	Posterolateral subcolumn	I/II
		Two-column	Lateral column + posterolateral column (total lateral condylar fracture; depression located posteriorly)	I/II
		Zero-column	Depression located posteriorly	III
	Varus	One-column	Posteromedial column	IV
		Two-column	Medial column + posterolateral column	IV
	Axial	One-column	Posterior column (posteromedial + posterolateral columns)	VI
		Three-column	Compression side posterior; tension side anterior	V/VI
Hyperextension	Valgus	One-column	Lateral column	II
	Varus	One-column	Medial column	IV
	Axial	Two-column	Medial column + lateral column (anteriorly; no posterior cortex involved)	V
		Three-column	Compression side anterior; tension side posterior	VI

*In three-column classification, the posterior column is supposed to be a whole. The posterolateral and posteromedial columns are two subcolumns of the posterior column

is, the tibial plateau angle (TPA).[18] The TPA is the medial angle between the tangential line of the tibial plateau and the anatomical axis of the tibia, and its average is 85° in the Chinese population.[23] A decreased TPA indicates a primarily varus force, while an increased TPA indicates a primarily valgus force. With varying degrees of axial force (Figs 1d to 1f), a normal or unchanged TPA indicates a predominantly axial load. The analysis of force direction should not rely only on changes in TPA. If the TPA demonstrates little change, only the fracture side might imply the force direction. In some Schatzker type IV or V cases, the TPA may be almost normal or with a near-perpendicular angle, and the knee joint may be forced in an axial-load mechanism without distinct varus or valgus, such as bicondylar hyperextension fracture of the tibial plateau.[24]

For each case, two questions about the injury mechanism were presented to the observers: 1) What was the initial position of the knee joint?; and 2) What was the main direction of the force acting on the tibial plateau? All aforementioned measurements were used to assist in the observers' judgement. In addition to the quantitative measurements, fracture morphology was also used. Combining the results of these two questions, the injury mechanism of the TPFs could be divided into nine patterns: varus, valgus, and axial extension; varus, valgus, and axial flexion; and varus, valgus, and axial hyperextension (Table I).

Statistical analysis. SPSS Statistics 24.0 software (IBM SPSS Inc., Armonk, New York) was used for the statistical analyses. Data are presented as mean values (SD) for continuous variables. The kappa statistic was used to analyze the reliability of the fracture classification and injury mechanism made by different observers on the same occasion (interobserver reliability) or by the same observer on separate occasions (intraobserver reliability).[25] The kappa is a chance-corrected measure of agreement, comparing the observed measure of agreement with the level of agreement expected by chance alone.[26] The analysis of interobserver reliability was based on the first rounds of observations to prevent recall bias. The second round of observations was used only to determine intraobserver reliability. The guidelines proposed by Landis and Koch[27] were used to categorize the levels of reliability based on the kappa values. The kappa values, which range from +1 to −1, were assigned a subdivision based on the strength of agreement: 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). Zero represents no agreement, and 1.00 represents perfect agreement.[28]

Results
Schatzker type I to VI fractures accounted for 10, 30, 6, 12, 12, and 20 of all cases, respectively (Fig. 2). In addition, according to the TCC, five cases were zero-column fractures, 28 cases were one-column fractures, 30 cases were two-column fractures, and 27 cases were three-column fractures (Fig. 3). By consultation, the distribution of the injury mechanism of patients is shown in Figure 4. The morbidity rates of the hyperextension, extension, and flexion injuries were 21%, 46%, and 33%, respectively.
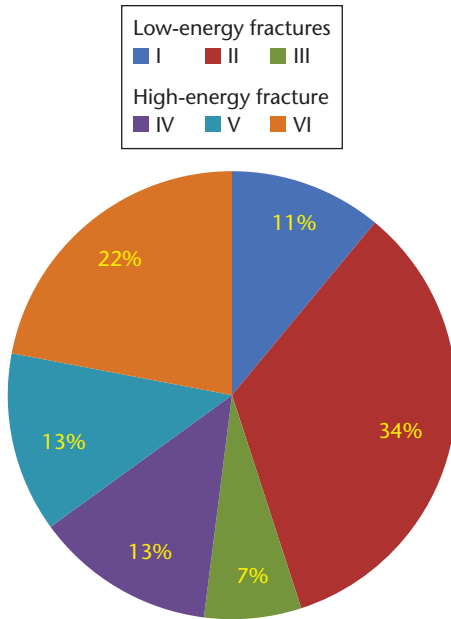
Low-energy fractures
■ I ■ II ■ III
High-energy fracture
■ IV ■ V ■ VI

Fig. 2

Population distribution of Schatzker classification in 90 patients.

Hyp-val **Hyp-var** Hyp-ax
Ext-val Ext-var Ext-ax
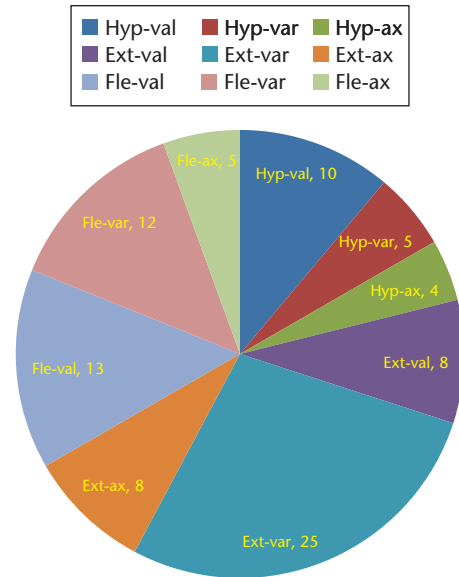Fle-val **Fle-var** Fle-ax

Fig. 4

Population distribution of injury mechanism in 90 patients. Hyp, hyperextension; Ext, extension; Fle, flexion; val, valgus; var, varus; ax, axial.
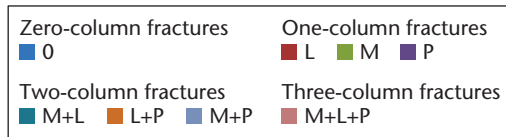
Zero-column fractures   One-column fractures
■ 0   ■ L ■ M ■ P
Two-column fractures   Three-column fractures
■ M+L ■ L+P ■ M+P   ■ M+L+P

Fig. 3

Population distribution of three-column classification (TCC) in 90 patients. 0 in TCC indicates zero-column fractures (fr); L, lateral one-column fr; M, medial one-column fr; P, posterior one-column fr; M+L, medial and lateral two-column fr; L+P, lateral and posterior two-column fr; M+P, medial and posterior two-column fr; M+L+P, three-column fr, medial, lateral and posterior all involved.

The average inter- and intraobserver reliabilities of the Schatzker classification system and TCC were 0.686, 0.743 and 0.739, 0.724, representing substantial agreement. The inter- and intraobserver agreements regarding the injury mechanism were substantial (κ_{inter} = 0.699, κ_{intra} = 0.749) without grouping. The initial knee position

and the force direction, which are two components of injury mechanism, had substantial agreement (κ_{inter} = 0.742, κ_{inter} = 0.782), respectively (Fig. 5; Table II).

After grouping the fractures based on the Schatzker classification, the inter- and intraobserver reliabilities of the group with low-energy fractures showed almost perfect agreement with regard to injury mechanism (κ_{inter} = 0.81, κ_{intra} = 0.832). However, the interobserver reliability of the group with high-energy fractures showed moderate agreement (κ_{inter} = 0.605), and the intraobserver agreement was substantial (κ_{intra} = 0.721). Furthermore, the relatively lower reliability in the group of high-energy fractures was caused by the subgroup of Schatzker type IV (κ_{inter} = 0.495) and type V (κ_{inter} = 0.486) fractures (Fig. 6; Table III). By grouping the fractures according to TCC, the interobserver reliabilities of groups with one column, two columns, and three columns were substantial (κ_{inter} = 0.759, 0.642, 0.627); meanwhile, the intraobserver agreement in the three groups was substantial (κ_{intra} = 0.801, 0.770, 0.708; Fig. 7; Table III). Certainly, the reliabilities, whether interobserver or intraobserver, of the one-column group were relatively higher than those of the other two groups.

Discussion

Tibial plateau fractures are common articular fractures with a complex injury mechanism. A literature review found a few studies mentioning the injury mechanism of a TPF,[20,29-31] however, most provided only brief and ambiguous descriptions. At present, the vast majority of TPF classifications are based on fracture morphology, and the difference between these classifications is in the level of detail. In 2018, a systematic review identified and
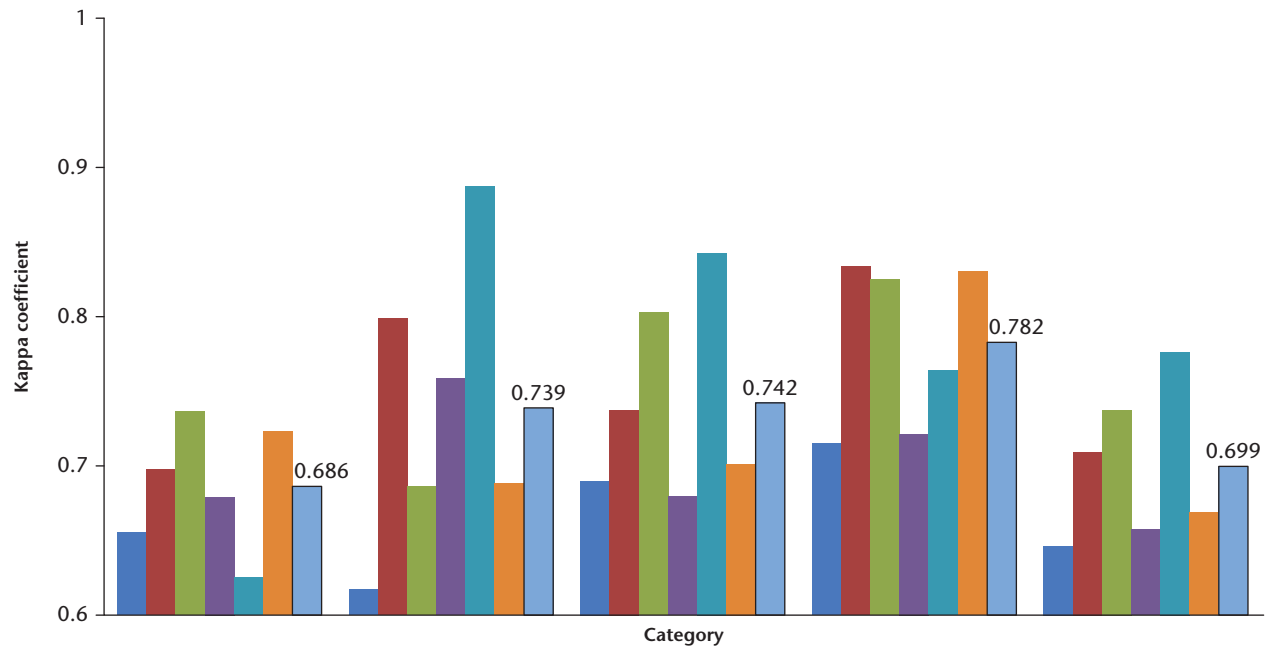
	Schatzker	TCC	Initial position	Deforming force	Injury mechanism
■ Observer 1/2	0.655	0.617	0.690	0.715	0.646
■ Observer 1/3	0.697	0.799	0.737	0.834	0.709
■ Observer 1/4	0.737	0.686	0.803	0.825	0.737
■ Observer 2/3	0.679	0.759	0.679	0.722	0.658
■ Observer 2/4	0.625	0.887	0.843	0.764	0.777
■ Observer 3/4	0.723	0.688	0.701	0.830	0.669
▩ Mean	0.686	0.739	0.742	0.782	0.699

Fig. 5

Kappa coefficients for the interobserver reliabilities of the Schatzker classification, three-column classification (TCC), and injury mechanisms of tibial plateau fractures (TPFs).

Table II. Kappa coefficient for the intraobserver reliability of the Schatzker classification, three-column classification (TCC), and injury mechanism of tibial plateau fractures (TPFs)

Observers	Schatzker	TCC	Initial position	Deforming force	Injury mechanism
1/1'	0.779	0.788	0.768	0.739	0.735
2/2'	0.749	0.736	0.822	0.792	0.777
3/3'	0.751	0.749	0.769	0.783	0.749
4/4'	0.694	0.622	0.802	0.779	0.736
Mean	0.743	0.724	0.790	0.773	0.749

appraised the previously established classification systems for TPFs and determined their reliability for fracture classification. It concluded that using a fracture classification based on imaging findings to predict clinical outcome was not a commonly reported goal of newly developed systems.[32] To date, only one study has updated the TCC classification of TPF injury mechanism in relative detail.[17] Four kinds of injury mechanism, including extension-varus/-valgus and flexion-varus/-valgus, were proposed in the uTCC, which combined fracture morphology with injury mechanism. Under uTCC guidance, good clinical results of TPFs have been achieved. However, we think the definition of injury mechanism in the uTCC is not sufficiently comprehensive or detailed. Nonetheless, it is the first detailed description

and evaluation of the reliability of the injury mechanism of a TPF.

Classification of fractures is aimed at guiding treatment and estimating prognosis. However, classification does not comprise all of the information about the fracture. In clinical practice, the principal reduction and fixation of fracture should be performed and followed through the converse injury mechanism. In particular, the tibial plateau should always be obeyed. For flexion-varus injury, successful early reduction can be achieved by keeping the knee in extension-valgus with axial traction.[16] In Schatzker type V or VI fractures, the reduction and fixation methods will certainly differ for distinct injury mechanisms: for extension-axial injury, the rafting plate should be implanted for the major articular surface
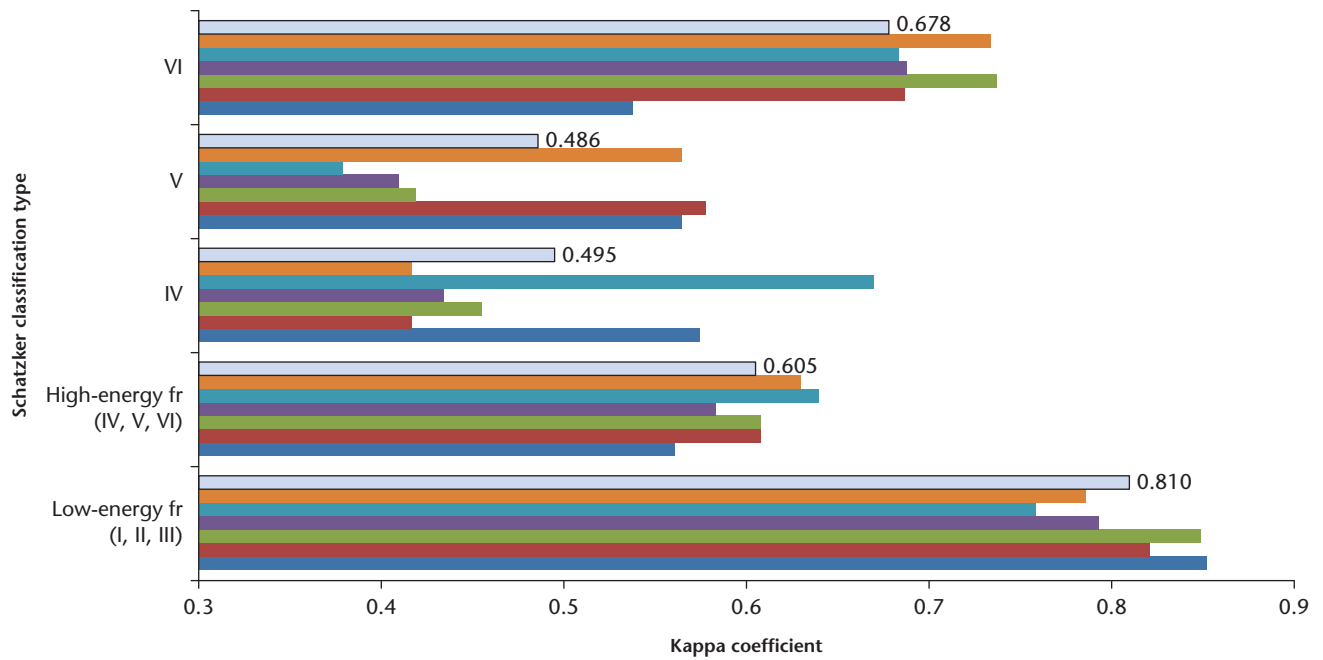
	Low-energy fr (I, II, III)	High-energy fr (IV, V, VI)	IV	V	VI
☐ Mean	0.810	0.605	0.495	0.486	0.678
■ Observer 3/4	0.786	0.630	0.417	0.565	0.734
■ Observer 2/4	0.759	0.640	0.670	0.379	0.684
■ Observer 2/3	0.793	0.583	0.434	0.410	0.688
■ Observer 1/4	0.849	0.608	0.455	0.419	0.737
■ Observer 1/3	0.821	0.608	0.417	0.578	0.687
■ Observer 1/2	0.852	0.561	0.575	0.565	0.538

Fig. 6

Kappa coefficients for interobserver reliabilities of different groups based on Schatzker classification. The low-energy fracture group includes types I to III, and the high-energy fracture group includes types IV to VI. fr, fracture.

Table III. Kappa coefficient for the intraobserver reliability of different groups based on Schatzker classification and three-column classification (TCC)

Observers	Schatzker classification type					TCC		
	Low-energy fractures (I, II, III)	High-energy fractures (IV, V, VI)	IV	V	VI	One-column	Two-column	Three-column
1/1'	0.847	0.703	0.673	0.585	0.737	0.825	0.788	0.755
2/2'	0.849	0.796	0.771	0.714	0.844	0.833	0.731	0.701
3/3'	0.745	0.706	0.640	0.597	0.792	0.723	0.821	0.724
4/4'	0.887	0.680	0.692	0.684	0.695	0.825	0.743	0.655
Mean	0.832	0.721	0.685	0.645	0.767	0.801	0.770	0.708

involvement, and in flexion-axial injury, the buttress plate should be implanted posteroanteriorly to antiglide. The best implantation position (slightly anterior or lateral) for the hyperextension-axial pattern has not been tested in biomechanical research. Implant design should be advanced to allow for maintenance of mechanical stability after fracture reduction,[17] such as for the hyperextension injury pattern. The injury mechanism can also help us to determine the related soft-tissue injuries. In each kind of fracture, there is a compression side and a tension side. Ligamentous structures are more likely to be injured in the tension side, while the meniscus is more easily

injured in the compression side. For example, in a hyperextension-varus fracture, the tension side is in the posterior-lateral corner and the compression side is in the anterior-medial articular surface, so the ligamentous structures in the posterior-lateral corner and the medial meniscus are more likely to be injured. Thus, it is necessary to analyze the injury mechanism, which could be an effective complement to the classification, in order to recognize the fracture characteristic.

The hyperextension fracture of the tibial plateau is a unique injury pattern. The possible associated injury that accompanies this fracture must be identified.[33]
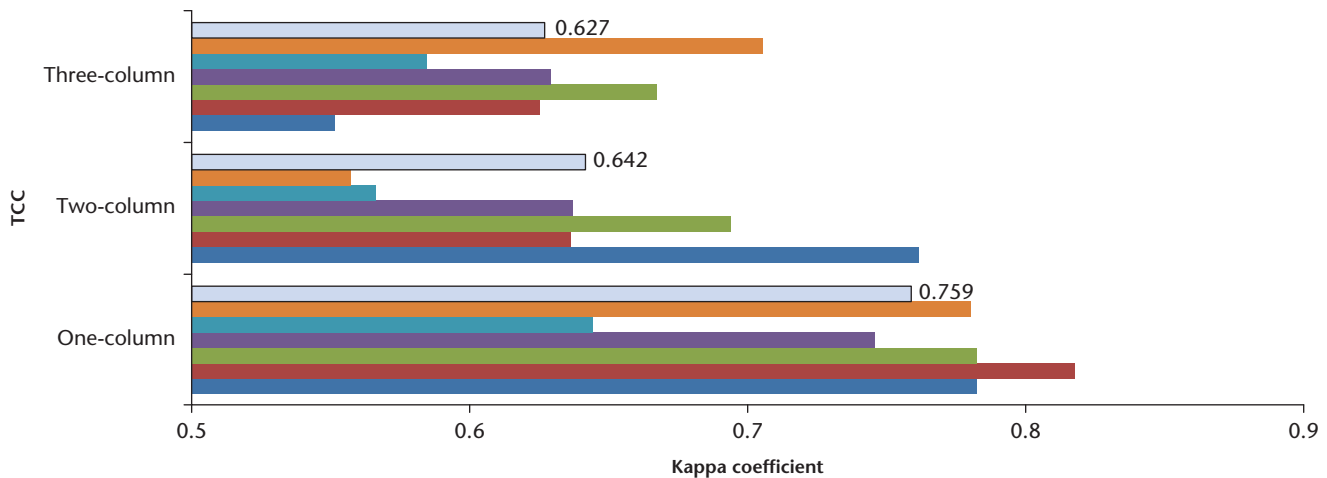
	One-column	Two-column	Three-column
☐ Mean	0.759	0.642	0.627
■ Observer 3/4	0.781	0.557	0.706
■ Observer 2/4	0.645	0.567	0.585
■ Observer 2/3	0.746	0.638	0.629
■ Observer 1/4	0.783	0.694	0.668
■ Observer 1/3	0.818	0.637	0.626
■ Observer 1/2	0.783	0.762	0.552

Fig. 7

Kappa coefficients for interobserver reliabilities of different groups based on three-column classification (TCC). The one-column fractures include lateral (L), medial (M), and posterior (P), and the two-column fractures include M+L, L+P, and M+P.

Meanwhile, patients with hyperextension mechanisms have, however, been shown to have lower functional scores and a trend of higher pain scores, indicating worsened functional outcomes. They are also more likely than their counterparts with non-hyperextension mechanism to have associated soft-tissue damage and to develop post-traumatic osteoarthritis.[24] The axial load of the lower extremity is an important injury mechanism in trauma that is responsible for severe injuries, such as pilon comminuted fractures, without suffering obvious valgus and varus force.[34,35] Similarly, it is sometimes difficult to distinguish between valgus or varus force for TPFs when the knee is in the neutral position. Thus, to make the injury mechanism of TPFs more thorough and intact, the hyperextension injury and axial force should be taken into consideration.

A good injury mechanism system should be repeatable, comprehensive, and easily memorized.[32] In this study, the inter- and intraobserver reliabilities for the Schatzker classification and TCC were similar to those of previous studies.[32,36-39] The results of reliability for the Schatzker classification and TCC may be vastly different among studies because of heterogeneous observers, sample size, and different case load proportions.[32,39] Encouragingly, the inter- and intraobserver reliabilities regarding the injury mechanisms of TPFs represent substantial agreement. By grouping the patients on the Schatzker classification and TCC, it was found that the reliability of injury mechanism of TPFs was mainly affected by the group of high-energy fractures or three-column fractures. In the low-energy fractures (Schatzker types I to III), the deforming force was relatively clear; the initial position of the knee joint needs to be considered, especially when the PTSA is near the critical value. However, both the deforming force and initial position would be debatable in high-energy fractures. The main fracture fragment should be helpful in determining the injury mechanism in one-column and two-column fractures; however, it is difficult to determine the main fragment in three-column fractures. Injury mechanism evaluation for TPFs is a synthetic assessment of fracture characteristics. When estimating high-energy TPFs, 3D reconstructed images can help. From the 3D reconstructed images, we can obtain the shift trend of the main fracture fragments, which gives an overall view of the fractures. Then, combined with the two parameters (PTSA and TPA), the injury mechanism of high-energy TPFs can be estimated more accurately. Therefore, we consider the injury mechanism system of TPFs to be sufficiently reproducible and suggest applying it in further clinical practice.

Although the injury mechanism of TPFs proposed in this study included the most dominant elements of injury, including the initial position and force direction, the rotatory force was not added, which was obviously different from the malleolar fracture.[40] The rotational force often occurs when the knee joint is in the flexion position. The flexion-varus injury often combines with

the internal rotation force in the knee joint, whereas the flexion-valgus combines with the external rotation force.[41] However, the rotation force always results in soft-tissue injuries and/or tiny marginal fractures, such as Segond fracture with anterior cruciate ligament injury.[42,43] Thus, to make the discussion on the injury mechanism of TPFs succinct, it was not included.

The primary limitation of this study is that the injury mechanism of TPFs was ascertained from fracture morphology on the basis of our clinical experience and previous biomechanical studies.[5,17,38] Although attempts have been made,[20] it is difficult to simulate the injury mechanism of TPFs in various specimens using existing experimental conditions, whether quantitative analysis or even qualitative description. In addition, in a clinical setting, it is critically important to recognize the concurrent soft-tissue injuries in TPFs[29] as they may require different approaches and treatment strategies.[17] It is believed that a particular injury mechanism may cause a specific soft-tissue injury in TPFs (e.g. knee injury).[41] Due to the inadequate MRIs of these patients, the study was too underpowered to identify a relationship between the injury mechanisms of TPFs and soft-tissue injuries. This leaves room for further research.

In conclusion, the proposal of the complete theory of the injury mechanism of TPFs helps to make TCC consummate. It demonstrates a substantial inter- and intra-observer agreement generally. In the future, the injury mechanism may help orthopaedic trauma surgeons to make the optimal preoperative plan by selecting the appropriate approach, guiding the reduction technique, determining the function of fixation plates, and forecasting the injuries of related soft tissue. Further studies are needed to confirm its practical clinical value.

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Author information
- B-B. Zhang, MD, Resident Doctor,
- H. Sun, PhD, MD, Attending Doctor,
- Y. Zhan, MD, Resident Doctor,
- Y. Zhu, PhD, MD, Attending Doctor,
- Y-K. Wang, MD, Resident Doctor,

- C-F. Luo, PhD, MD, Senior Doctor, Department of Orthopaedic Surgery, Shanghai Jiao Tong University Affiliated Sixth People's Hospital, Shanghai, China.
- Q-F. He, PhD, MD, Attending Doctor, Department of Orthopaedic Surgery, Zhejiang University School of Medicine Affiliated Hangzhou First People's Hospital, Shanghai, China.

Author contributions
- B-B. Zhang: Designed the study, Collected and analyzed the data, Drafted the manuscript.
- H. Sun: Designed the study, Attended the two-turn classification process, Drafted the manuscript.
- Y. Zhan: Collected and analyzed the data.
- Q-F. He: Attended the two-turn classification process, Drafted the manuscript.
- Y. Zhu: Attended the two-turn classification process, Drafted the manuscript.
- Y-K. Wang: Attended the two-turn classification process, Drafted the manuscript.
- C-F. Luo: Proposed this concept, Designed the study, Drafted the manuscript.

- B-B. Zhang and H. Sun contributed equally to the paper.

Ethical review statement:
- The approval of the institution's ethical review board (ERB number: 2016-89-(1)) was obtained prior to initiation of the study.