

RESEARCH ARTICLE

A New Three-Dimensional Classification of Proximal Tibiofibular Fractures: A Multicenter Study

Li-ping Wu, MD¹ , Hermann O Mayr, MD², Qin Cai, MS³, Yuan-qiao Huan, MS¹, Xiao-hua Zhu, MS⁴, Yuan-zhuang Chen, BS¹, Yi-ping Tang, MS⁵, Xin-yu Huang, BS⁶

¹Department of Joint and Trauma Surgery, Jiangmen Central Hospital (Affiliated Jiangmen Hospital of Sun Yat-Sen University), ³Department of Orthopaedic Surgery, Jiangmen Wuyi Hospital of Traditional Chinese Medicine (TCM), (Affiliated Jiangmen TCM Hospital of JiNan University) and ⁶Department of Trauma Surgery, Jiangmen people's Hospital, (Affiliated Jiangmen Hospital of Southern Medical University), Jiangmen, ⁴Department of Orthopaedic Surgery, Zhongshang Xiaolang people's Hospital (Affiliated Xiaolang Hospital of Southern Medical University), Zhongshang and ⁵School of Foreign Languages, Southern Medical University, Guangzhou, China and ²Department of Orthopaedics and Trauma Surgery, Medical Center, Faculty of Medicine, Albert-Ludwigs-University of Freiburg, Freiburg, Germany

Objectives: To propose an updated definition of proximal tibia and fibula fracture (PTFF) and establish a three-dimensional (3D) structure-based classification of PTFF.

Methods: In total, 1358 adult patients (837 males and 521 females; 43.61 ± 15.13 years, 1364 affected knees) who were diagnosed with PTFF at the departments of orthopaedic surgery of four hospitals from January 2010 to December 2019 were enrolled. The new classification of PTFF, termed Wu classification, included three parts: classification of columns in the horizontal plane, regions in the frontal plane, and segments in the sagittal plane. All PTFFs were classified according to Schatzker, Luo, and Wu classification systems. Additionally, the incidence and characteristics of PTFFs were analyzed.

Results: The major internal structural fractures of PTFF were tibial plateau fracture (TPF) only (725, 53.15%), TPF and proximal fibular fracture (274, 20.09%), and isolated avulsion fracture of the posterior cruciate ligament (PCL) (189, 13.86%). Approximately a quarter of PTFF cases could not be classified using Schatzker or Luo classifications, but all PTFF cases could be classified using Wu classification. The most frequent PTFFs included all four columns in region IV, segment 2 (235, 17.23%); the posterolateral and posteromedial columns in region II, segment 2 (191, 14.00%); and the lateral and posterolateral columns in region IV, segment 2 (136, 9.97%). Isolated avulsion fracture of the anterior cruciate ligament (ACL) was categorized as three injury types, most of which involved the lateral and medial columns in region II, segment 1 (40/63, 64%). More than 97% of cases of isolated fractures of the PCL involved the posterolateral and posteromedial columns in region II, segment 2. The most frequent combined avulsion fracture of the ACL and PCL included all four columns in region II, segment 2 (18/24, 75%). All of the isolated avulsion fractures of the ACL were located in segment 1, and all those of the PCL in segment 2. The most common type of isolated proximal fibular fracture involved the posterolateral column in region III, segment 2 (23/26, 88%). The most frequent combined TPF and proximal fibular fracture involved all four columns in region IV, segment 2 (107/274, 39.05%).

Conclusions: All cases of PTFF could be classified by the new 3D Wu classification which should be beneficial for clinical diagnosis, guidance of treatment, statistical analysis, academic communication, and prognosis, and the most frequent PTFF involved all four columns in region IV, segment 2.

Address for correspondence Li-ping Wu, MD, Department of Joint and Trauma Surgery, Jiangmen Central Hospital (Affiliated Jiangmen Hospital of Sun Yat-Sen University), Jiangmen, China 529030; Tel: +86 13822415987; Fax: +86 0750 3375441; Email: 12303383@qq.com

Disclosure: No benefits in any form have been or will be received from a commercial party related directly or indirectly to the subject of this manuscript.

Received 18 August 2020; accepted 16 September 2021

Key words: Classification; Fibula; Fracture; Knee joint; Tibia

Introduction

Tibial plateau fractures (TPFs) are common and complicated injuries around the knee that result from high- or low-energy trauma, and an increasing number of studies are focused on TPF¹⁻⁴. Even though TPF and proximal fibula fracture are similar in terms of morphology, mechanism of injury, soft tissue damage, diagnosis, classification, treatment, and knee reconstruction, it has been recognized that the importance of fibular fractures helped us to treat tibial fractures easily⁵. Although more than 30.0% of TPFs co-occur with proximal fibular fractures⁶, and up to 63.4% of bicondylar TPFs co-occur with fibular-head fractures⁷, there is a lack of research focusing on combined proximal tibia and fibula fracture (PTFF). In 1986, Hall *et al.*⁸ reported a case with fracture of proximal part of tibia and fibula associated with an entrapped popliteal artery. Mendelson *et al.*⁹ reported on an 89-year-old woman with a proximal tibia and fibula fragility fracture in 2011. Cheung *et al.*¹⁰ reported on an 82-year-old man who experienced an insufficiency fracture of the proximal fibula and the tibia in 2013. There is a need for a clear definition of PTFF that accurately describes its anatomy and scope and is universally applicable in adults.

Although lacking for PTFF, the classification of TPF has been studied thoroughly and systematically. TPF can be classified either according to X-rays or according to computed tomography (CT). Based on X-rays, conventional classification systems (Hohl and Moore, Schatzker, Orthopaedic Trauma Association/Arbeitsgemeinschaft für Osteosynthesefragen [OTA/AO] 2007) have played significant roles in guiding surgical treatment¹¹⁻¹⁴. However, these classifications systems, which use X-ray, lack the terminology to accurately characterize fractures involving the posterior tibial plateau in the coronal plane. Furthermore, classification based on two-dimensional image results is limited, as it conveys incomplete fracture information that may lead to misdiagnosis of posterolateral TPF as well as intraoperative mistakes.

According to the horizontal plane in CT, Luo *et al.*¹⁵,¹⁶ proposed the three-column classification (medial, lateral, and posterior columns) system. Other researchers have further subdivided the three-column classification. Yang *et al.*¹⁷ divided the posterior column into the posteromedial and posterolateral columns. Wahlquist *et al.*¹⁸ divided the medial column into the medial, inter-, and lateral condyles, while Yang *et al.*¹⁹ divided it into anteromedial, total lateral, and posteromedial columns. Chen *et al.*²⁰ refined posterior-condyle fractures into five subtypes. Moreover, others have divided TPF into four to 10 subtypes. For example, Gicquel *et al.*²¹ revised the Duparc classification into four subtypes: unicondylar, bicondylar, spinocondylar, and posteromedial fractures, while Chang *et al.*²² divided it into two condyles

and four quadrants. Hoekstra *et al.*²³ classified TPF into seven types: lateral, medial, posterior, anterior, rim, bicondylar, and subcondylar. Gebel *et al.*²⁴ divided the joint surface into nine areas. Furthermore, Yao *et al.*⁶ classified TPF according to four columns and nine segments and proposed a new intermedial column concept (containing the tubercle area, bare area, and anterior/posterior cruciate ligament (ACL/PCL) insertion area). The most precise classification is that by Krause *et al.*^{25, 26}, mapping TPF to 10 segments. Although the Krause classification appears to be the most detailed system so far, we are convinced of that the fracture line distribution can be described more precisely and visually.

Despite the large number of classifications of TPF according to CT, almost all are based on the horizontal plane rather than on three-dimensional (3D) space, which also includes the frontal and sagittal planes. Moreover, current TPF classifications place little emphasis on the proximal fibula and fail to evaluate the complexity of the fracture sufficiently for clinical and academic use²⁴. As Zeltser *et al.*²⁷ has stated, no classification method currently includes all patterns of TPF and that there is still no clear consensus available on how to treat TPFs due to the wide variety of classification systems, surgical approaches, and fixation methods²⁸. However, a better and more comprehensive understanding of the fracture line distribution and morphological features of major fragment is essential for therapeutic decision-making²⁹. So, an entire, accurate, and visual classification of fractures, including an appropriate summary and fracture mapping, will help surgeons better comprehend, document, and communicate information about fractures³⁰.

In the present study, our aims were to: (i) propose an updated definition of proximal tibia and fibula, and an updated definition of PTFF; (ii) develop a new classification method of PTFF based on its 3D structure; and (iii) analyze the incidence and fracture characteristics of PTFF using the new classification framework. In order to provide a morphological basis for the new classification system, radiological imaging, including X-ray imaging, CT, and 3D reconstruction, was used to measure and analyze the proximal tibiofibular morphology and 3D bone structure, and this was the fourth point of study. Before the study was initiated, ethical approval was obtained from the Human Research Ethics Committee in the first author's hospital. The research project conformed to the provisions of the Declaration of Helsinki.

Materials and Methods

Subjects

Inclusion criterion were as follows: (i) patients older than 18 years and diagnosed with PTFF; (ii) this study was

conducted at the departments of orthopaedic surgery of four hospitals. Patients had received complete radiological data including the standardized X-ray imaging, CT, and 3D reconstruction for both knees. All patients remained in the same position during CT machine examination (supine position with both knees straight). Relevant imaging parameters of patients were used for measurement and analysis. All PTFs were classified; (iii) all PTFs were classified according to Schatzker¹¹, Luo¹⁵, and new classification systems; (iv) the new classification of PTF was proposed and the incidence and characteristics of PTFs were analyzed; (v) a retrospective, multicenter study.

Exclusion criteria were as follows: (i) insufficient CT information; (ii) bullet wounds; (iii) bone defects; (iv) pathological or periprosthetic fractures; (v) congenital or acquired malformation of the tibial plateau; (vi) severe osteoporosis; (vii) the patient did not remain the supine position with both knees straight during CT machine examination. For example, the patient's knees were flexion during CT machine examination.

In total, 1358 patients (1364 affected knees) at the departments of orthopaedic surgery of four hospitals from January 2010 to December 2019 were enrolled in this study, including 402 patients from Jiangmen Central Hospital (Affiliated Jiangmen Hospital of Sun Yat-Sen University), 480 patients from Jiangmen Wuyi Hospital of Traditional Chinese Medicine (TCM) (Affiliated Jiangmen TCM Hospital of JiNan University), 118 patients from Zhongshang Xiaolang People's Hospital (Affiliated Xiaolang Hospital of Southern Medical University), and 358 patients from Jiangmen People's Hospital (Affiliated Jiangmen Hospital of Southern Medical University).

Definition of Proximal Tibia and Fibula

The proximal tibia was defined as the area between the highest point of the intercondylar eminence of the tibial plateau down to point G in Fig. 1. To determine point G, the width of the tibia, from the innermost point of the articular surface of the medial plateau to the outermost point of the articular surface of the lateral plateau, was measured. That measurement was used to draw a perpendicular line, inferiorly from the highest point of the intercondylar eminence; the end of the line was labeled point G. The proximal fibula was defined as the region of the fibula at the same level as the proximal tibia.

New Classification of PTF

Based on 3D structure, the new classification of PTF consisted of three parts: columns in the horizontal plane, regions in the frontal plane, and segments in the sagittal plane. Four columns were defined: the lateral, medial, posteromedial, and posterolateral columns. Each fracture is located in a minimum of one and a maximum of four columns according to the fracture line. For example, a complex fracture may be located in the lateral, medial, and posterolateral column.

Figure 2 illustrates the four columns in the horizontal plane on an axial CT image of the head of the fibula.

Four regions were defined: regions I, II, III, and IV. Figure 3 illustrates the four regions in the frontal plane of the proximal tibia and fibula.

Two segments were defined: segments 1 and 2. Figure 4 illustrates the two segments in the sagittal plane of the proximal tibia and fibula.

Taken together, PTF is classified in three planes, similar to the X-, Y-, and Z-axes of 3D coordinates. This new framework, termed "Wu classification," can be used for all patterns of PTF (including TPF and proximal fibula fracture). For example, the complex PTF displayed in Fig. 5 is located in the lateral and posterolateral columns in region IV, segment 2.

Radiological Measurements

All patients underwent standard anteroposterior and lateral X-ray imaging of both knee joints, tibias, and fibulas, as well as CT and 3D reconstruction of both knees. Three investigators measured the following lines independently in patients' non-injured knee.

Length of Line CD

Length of line CD in Fig. 1 (cm) was defined as the length from the innermost point C of the articular surface of the medial plateau to the outermost point D of the articular surface of the lateral plateau in anteroposterior X-ray of knee joint. Similarly, the length of line CD had to be measured on the frontal plane of CT. The length of line CD was measured to evaluate the width of the proximal tibia.

Length of Line OA

A CT image of the head of the fibula in the horizontal plane is indicated in Fig. 2. The length of line OA (cm) was defined as the length from the center point O of the tibial plateau to the most anterior point A of the proximal tibia (located in the anterior tibial tubercle). Similarly, the length of line OA had to be measured on the anteroposterior and lateral X-ray. The length of line OA was measured to evaluate the length of the medial column and lateral column.

Length of Line OB

A CT image of the head of the fibula in the horizontal plane is indicated in Fig. 2. The length of line OB (cm) was defined as the length from the center point O of the tibial plateau to the posteromedial point B of the proximal tibia. Similarly, the length of line OB had to be measured on the anteroposterior and lateral X-ray. The length of line OB was measured to evaluate the width of the medial column and posteromedial column. The area between line OA and line OB is the scope of the medial column.

Length of Line OC

A CT image of the head of the fibula in the horizontal plane is indicated in Fig. 2. The length of line OC (cm) was defined

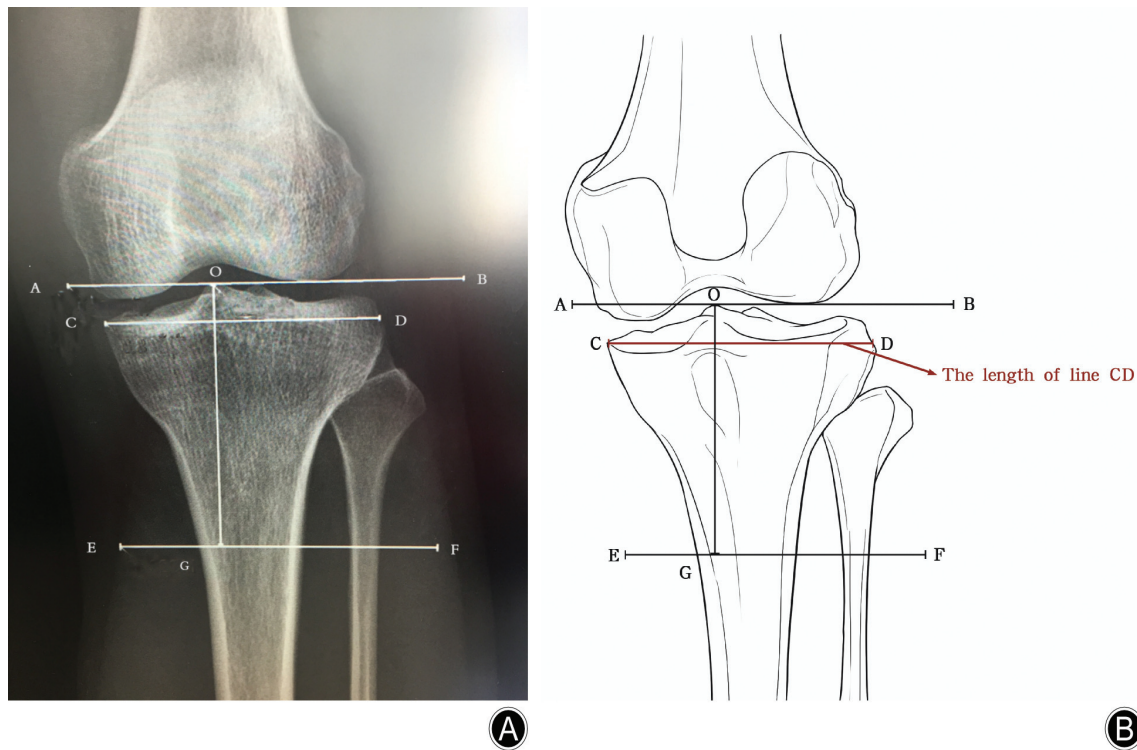


Fig. 1 An updated definition of the proximal tibia and fibula (image **A**). In the frontal view of the knee using anterior–posterior X-ray imaging, a straight line was drawn from the innermost point (C) of the articular surface in the medial plateau of the tibia to the outermost point (D) of the articular surface of the lateral plateau of the tibia. Line AB, which is parallel to line CD, passes through point O, the highest point of the intercondylar eminence of the tibial plateau. Line OG is a straight line, perpendicular to line AB, with the same length as line CD. Line EF, parallel to line AB, passes through point G. The areas of the tibia and fibula between lines AB and EF were defined as the proximal tibia and fibula, respectively, and a fracture in this area was defined as a proximal tibia and fibula fracture. The measure method schematic diagram in length of line CD (image **B**).

as the length from the center point O of the tibial plateau to the most anterior point C of the fibular head. Similarly, the length of line OC had to be measured on the anteroposterior and lateral X-ray. The length of line OC was measured to evaluate the width of the lateral column and posterolateral column. The area between line OA and line OC is the scope of the lateral column.

Length of Line OD

A CT image of the head of the fibula in the horizontal plane is indicated in Fig. 2. A straight line is drawn from point A to O, and extended. The intersection of this line with the posterior margin of the proximal tibia is point D. The length of line OD (cm) was defined as the length from the center point O of the tibial plateau to the posterior margin point D of the proximal tibia. Similarly, the length of line OD had to be measured on the anteroposterior and lateral X-ray. The length of line OD was measured to evaluate the length of the posteromedial column and posterolateral column. The area between line OB and line OD is the scope of the posteromedial column. The area between line OC and line OD is the scope of the posterolateral column.

Vertical Length of Point E and Point F on Coronal Plane Projection

In the posterior view of the proximal tibia and fibula of Figs 3,6, the vertical length of the point E and point F on the coronal plane projection (cm) was defined as the vertical length in the frontal plane from the coronal plane projection point E1 of point E to coronal plane projection point F1 of point F. At this time, the measurement was performed on anteroposterior X-ray and in the frontal plane of CT. The vertical length of point E and point F on the coronal plane projection was measured to evaluate the vertical length of region I. Region I in the frontal plane is the area between points E and F, consisting completely of the tibial intercondylar eminence.

Vertical Length of Point E and Point G on Coronal Plane Projection

In the posterior view of the proximal tibia and fibula of Figs 3,6, the vertical length of point E and point G on the coronal plane projection (cm) was defined as the vertical length in the frontal plane from coronal plane projection point E1 of point E to coronal plane projection point G1 of

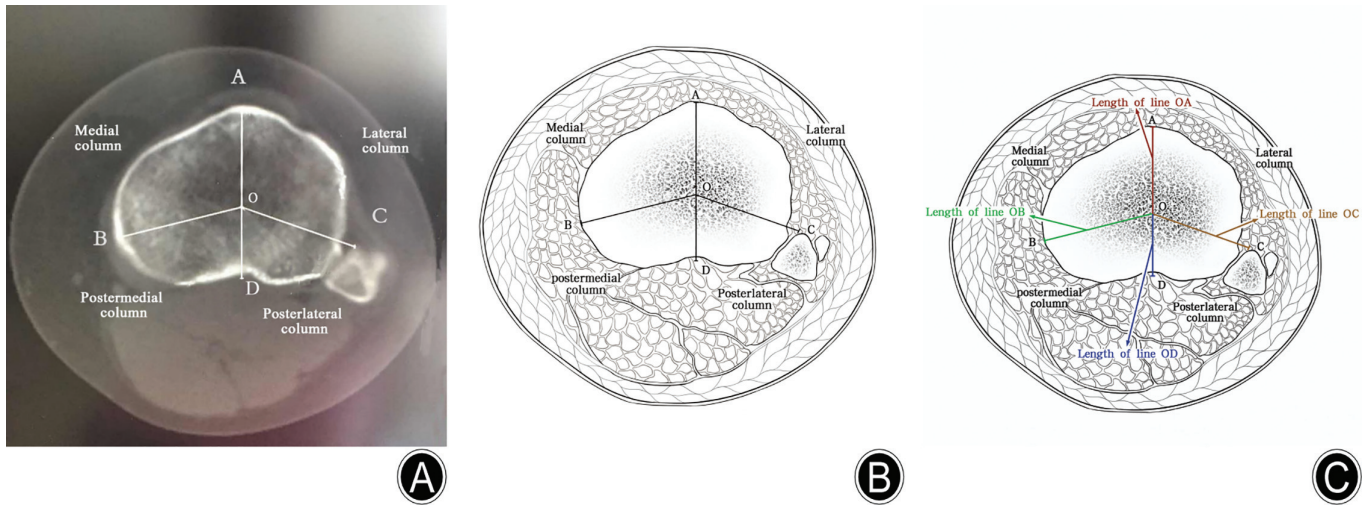


Fig. 2 Definition of columns in Wu classification. A computed-tomography image (image A) and freehand schematic diagram (image B) of the head of the fibula in the horizontal plane are indicated. Point O is the center of the tibial plateau. Point A represents the most anterior point of the proximal tibia, located in the anterior tibial tubercle. Point B is the posteromedial point of the proximal tibia. Point C is the most anterior point of the fibular head. A straight line is drawn from point A to O, and extended. The intersection of this line with the posterior margin of the proximal tibia is point D. Point O is also connected to points B and C using straight lines. As a result, the tibial plateau is divided into a lateral column (bordered by line AOC), a medial column (bordered by line AOB), a posteromedial column (bordered by line BOD), and a posterolateral column (bordered by line COD). The measure method freehand schematic diagram in length of line OA, OB, OC, and OD (image C).

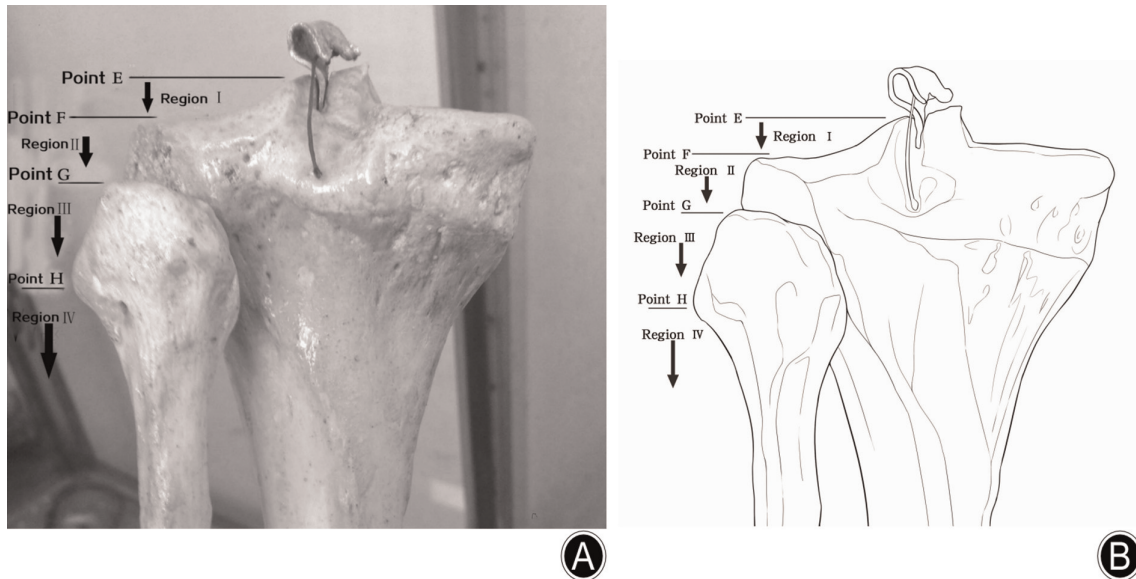


Fig. 3 Definition of regions in Wu classification. A photograph (image A) and freehand schematic diagram (image B) in the posterior view of the proximal tibia and fibula are indicated. Point E is the highest point of the intercondylar eminence in the tibial plateau. Point F is the outermost point of the cortical surface in the lateral tibial plateau. Point G is the highest point of the fibular head, and point H is outermost lateral point of the fibular head. Region I is the area between points E and F, consisting completely of the tibial intercondylar eminence. Region II is the area between points F and G. Region III is the area between points G and H. Region IV is the area below point H. The determination of the region is based on the lowest point of the fracture.

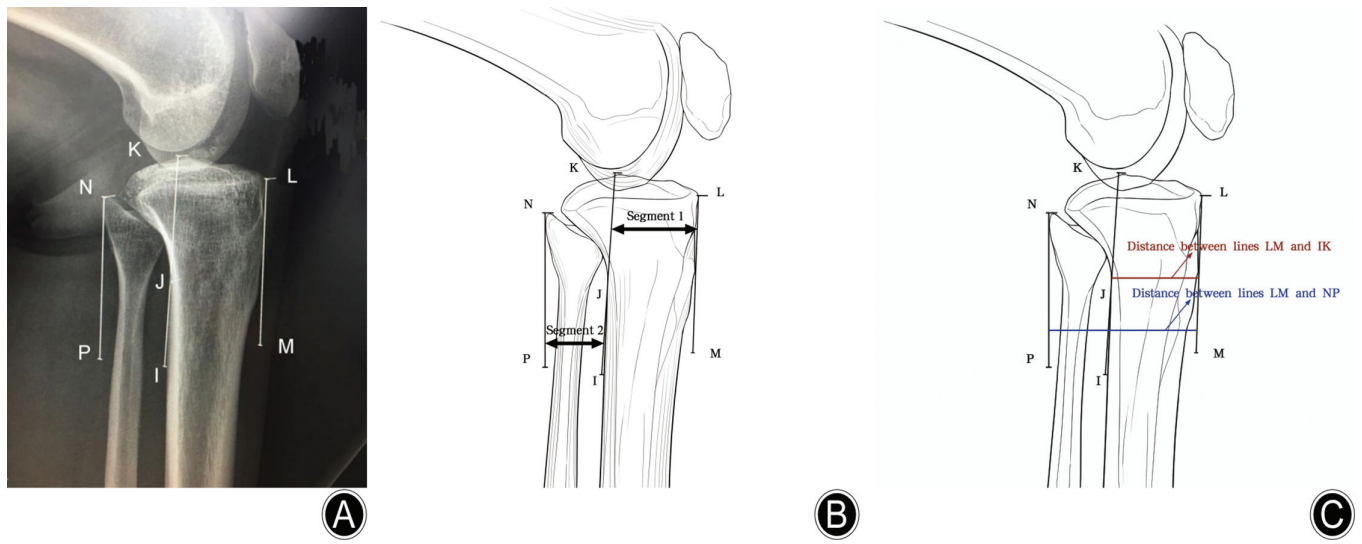


Fig. 4 Definition of segments in Wu classification. A lateral X-ray of the knee image (image A) and freehand schematic diagram (image B) in the sagittal plane of the proximal tibia and fibula are indicated. A straight line (IJ) is drawn along the posterior cortical margin of the tibia. When this line is extended superiorly, its intersection with the cortical surface of the tibial plateau is point K. Point L is the anterior point of the tibial tubercle. Line LM is parallel to line IK. Point N is the posterior point of the proximal fibula. Line NP is parallel to lines IK and LM. Segment 1 is the area between lines LM and IK, and segment 2 is the area between lines IK and NP. The determination of the segment is based on the posterior point of the fracture line. The measure method freehand schematic diagram in distance between lines LM and IK and distance between lines LM and NP (image C).

point G. At this time, the measurement was performed on anteroposterior X-ray and in the frontal plane of CT. The vertical length of the point E and point G on the coronal plane projection was measured to evaluate the vertical length of region I plus region II. Region II in the frontal plane is the area between points F and G.

Vertical Length of Point E and Point H on Coronal Plane Projection

In the posterior view of the proximal tibia and fibula of Figs 3,6, the vertical length of point E and point H on the coronal plane projection was defined as the vertical length in the frontal plane from the coronal plane projection point E1 of point E to coronal plane projection point H1 of point H. At this time, the measurement was performed on anteroposterior X-ray and in the frontal plane of CT. The vertical length of point E and point H on the coronal plane projection was measured to evaluate the vertical length of region I plus region II plus region III. Region III in the frontal plane is the area between points G and H. Region IV in the frontal plane is the area below point H.

Distance between Lines LM and IK

On the lateral X-ray of the knee in Fig. 4, distance between lines LM and IK (cm) was defined as the shortest distance between two parallel lines LM and IK in the sagittal plane of the knee. Similarly, the distance between lines LM and IK had been measured on the sagittal plane of CT. The distance between lines LM and IK was measured to evaluate the

length of segment 1. Segment 1 in the sagittal plane is the area between lines LM and IK.

Distance between Lines LM and NP

On the lateral X-ray of the knee in Fig. 4, distance between lines LM and NP (cm) was defined as the shortest distance between two parallel lines LM and NP in the sagittal plane of the knee. Similarly, the distance between lines LM and NP had been measured on the sagittal plane of CT. The distance between lines LM and NP was measured to evaluate the length of segment 1 plus segment 2. Segment 2 in the sagittal plane is the area between lines IK and NP.

All data were measured in the measurement system of X-ray and CT machine. To determine the actual lengths of the lines, account had to be taken for the zoom ratios in the X-ray and CT images. Each measurement was averaged for the three investigators. Patients with bilateral PTF were excluded for this part of the research.

Statistical Analysis

Statistical analysis was carried out using IBM SPSS Statistics for Windows, version 22.0 (IBM Corp., Armonk, NY, USA). Quantitative data were presented as the mean \pm standard deviation. Qualitative data were indicated as frequency (percentage). An independent, two-sided *t*-test was used to determine whether there were statistically significant differences in PTF locations between patients of different genders. $P < 0.05$ was considered statistically significant.

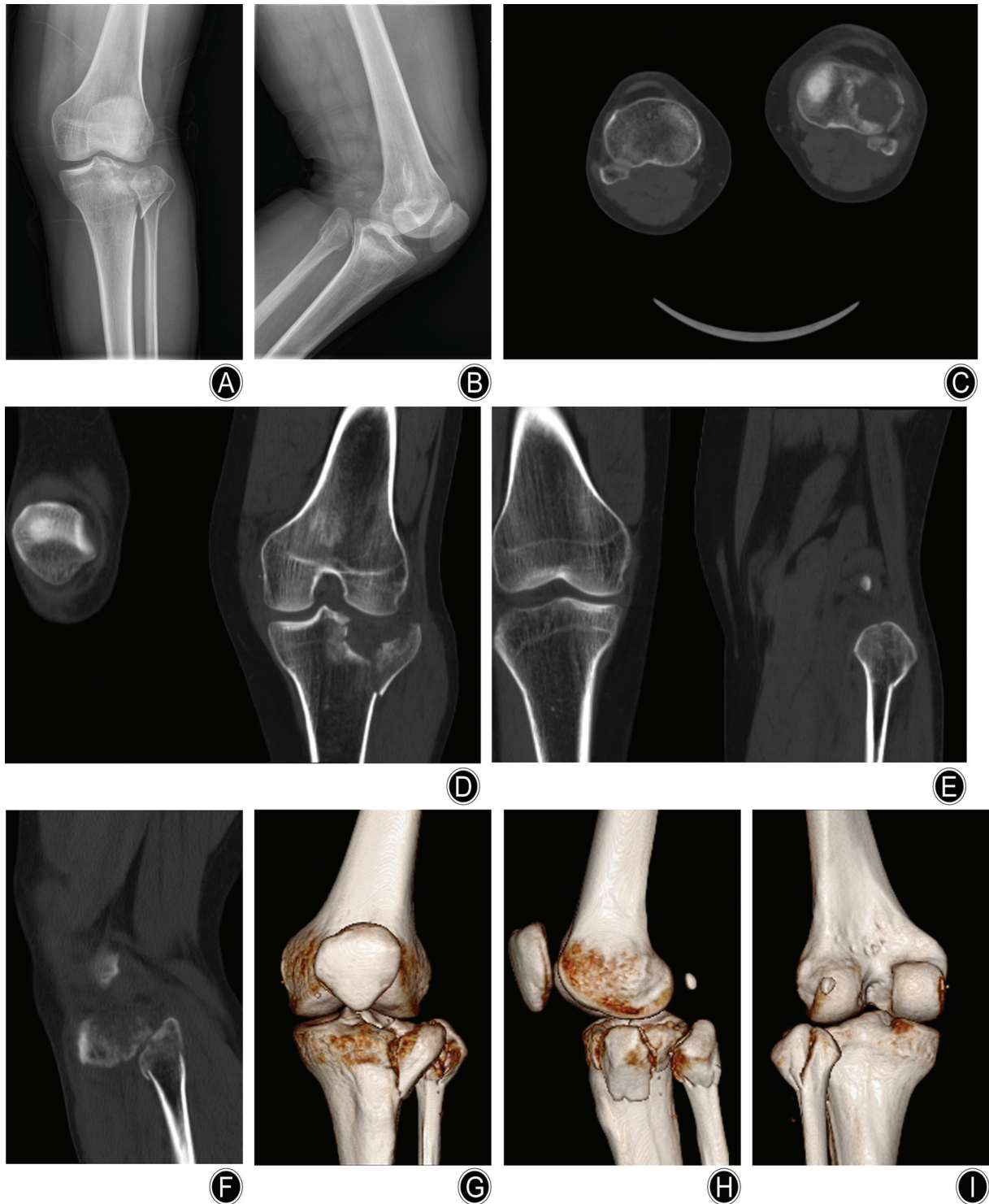


Fig. 5 Wu Classification of a complex proximal tibia and fibula fracture. A 41-year-old female patient sustained fractures of the left tibial plateau and proximal fibula due to a traffic accident in February 2019. There is type II of Schatzker classification from X-ray imaging (A, B), lateral and poster columns of Luo classification from CT (C). According to the Wu classification, based on results of CT (C, D, E, F), and 3D reconstruction (G, H, I), the fracture was located in the lateral and posterolateral columns, region IV, and segment 2.

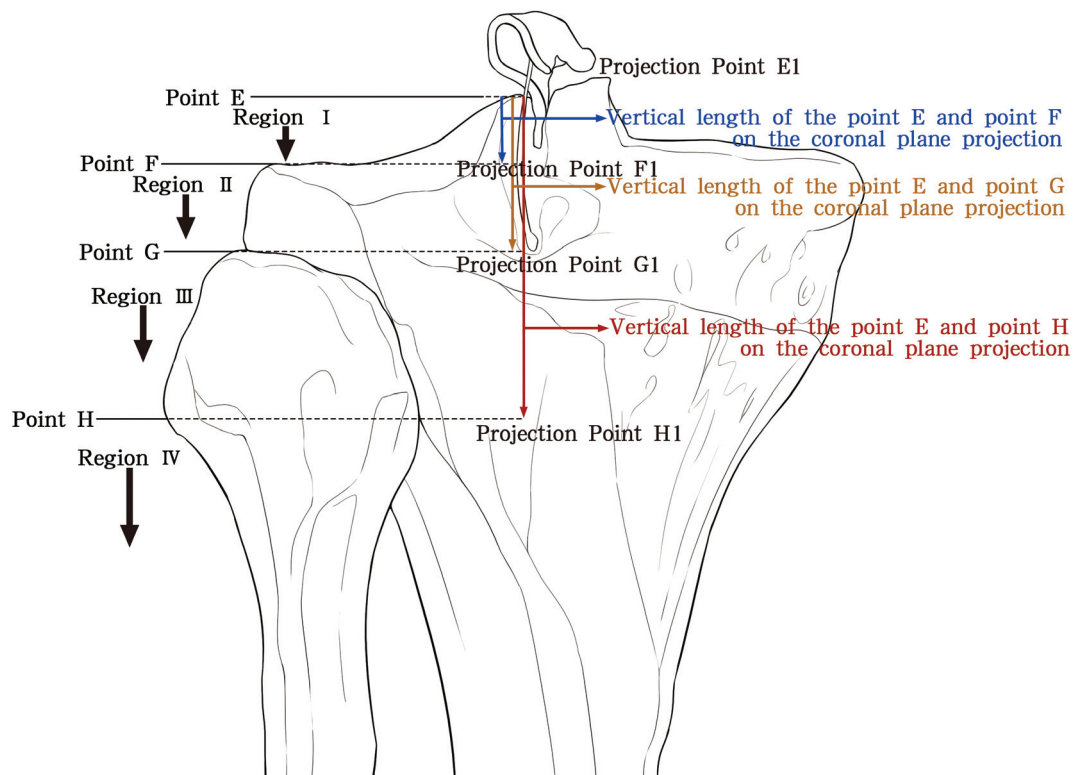


Fig. 6 Measure method freehand schematic diagram in vertical length of the point E and point F, point E and point G, point E and point H on the coronal plane projection. In the posterior view of the proximal tibia and fibula, point E1 is the projection point of point E on the coronal plane, point F1 is the projection point of point F on the coronal plane, point G1 is the projection point of point G on the coronal plane, and point H1 is the projection point of point H on the coronal plane. The vertical length of point E and point F, point E and point G, point E and point H on the coronal plane projection (cm) was to measure the distance between point E1 and point F1, point E1 and point G1, point E1 and point H1.

Results

Demographic Data of Radiological Measurements

For the radiological measurements, 1352 adult patients (834 males, 518 females; 749 left knees, 603 right knees) were included. The average age of these patients was 43.61 ± 15.12 years (range, 18–84 years).

Result of Radiological Measurements

The results of the radiological measurements using X-ray imaging and CT are summarized in Table 1. The length of line CD were 7.25 ± 0.79 cm in X-ray and 7.26 ± 0.83 cm in CT, and there was no statistical difference between the two measurements ($t = 0.259$, $P = 0.899$). And similarly, there was no statistical difference in the length of line OA between 2.56 ± 0.31 cm in X-ray measurement and 2.58 ± 0.29 cm in CT measurement ($t = 0.452$, $P = 0.717$). Moreover, the length of line OB was 3.49 ± 0.41 cm in X-ray and 3.46 ± 0.39 cm in CT, and no statistical difference between the two measurements ($t = 0.496$, $P = 0.688$) could be found. Furthermore, the measurement results in length of line OC on X-ray (3.53 ± 0.51 cm), which was similar to those measured on CT (3.51 ± 0.48 cm) ($t = 0.434$, P

$= 0.788$). And there was no statistical difference in the length of line OD between 2.10 ± 0.41 cm in X-ray measurement and 2.11 ± 0.35 cm in CT measurement ($t = 0.406$, $P = 0.804$).

The vertical length of point E and point F on the coronal plane was 0.79 ± 0.15 cm in X-ray and 0.82 ± 0.13 cm in CT, and there was no statistical difference between the two measurements ($t = 0.512$, $P = 0.672$). And similarly, there was no statistical difference in vertical length of point E and point G on the coronal plane between 2.12 ± 0.38 cm in X-ray measurement and 2.14 ± 0.33 cm in CT measurement ($t = 0.439$, $P = 0.701$). Moreover, the vertical length of point E and point H on the coronal plane were 3.69 ± 0.55 cm in X-ray and 3.68 ± 0.51 cm in CT, and no statistical difference between the two measurements ($t = 0.355$, $P = 0.843$) could be found. Furthermore, the measurement results in the distance between lines LM and IK on X-ray (3.73 ± 0.48 cm) were similar to those measured on CT (3.75 ± 0.42 cm) ($t = 0.421$, $P = 0.791$). There was no statistical difference in the distance between lines LM and NP between 5.42 ± 0.66 cm in X-ray measurement and 5.43 ± 0.64 cm in CT measurement ($t = 0.339$, $P = 0.876$).

TABLE 1 The result of radiological measurement

Radiological measurement	X-ray (cm)	CT (cm)	Test statistic	P value
Length of line CD	7.25 ± 0.79	7.26 ± 0.83	0.259	0.899
Length of line OA	2.56 ± 0.31	2.58 ± 0.29	0.452	0.717
Length of line OB	3.49 ± 0.41	3.46 ± 0.39	0.496	0.688
Length of line OC	3.53 ± 0.51	3.51 ± 0.48	0.434	0.788
Length of line OD	2.10 ± 0.41	2.11 ± 0.35	0.406	0.804
Vertical length of the point E and point F on the coronal plane	0.79 ± 0.15	0.82 ± 0.13	0.512	0.672
Vertical length of the point E and point G on the coronal plane	2.12 ± 0.38	2.14 ± 0.33	0.439	0.701
Vertical length of the point E and point H on the coronal plane	3.69 ± 0.55	3.68 ± 0.51	0.355	0.843
Distance between lines LM and IK	3.73 ± 0.48	3.75 ± 0.42	0.421	0.791
Distance between lines LM and NP	5.42 ± 0.66	5.43 ± 0.64	0.339	0.876

CT, computed tomography.

Basic Data of PTFF Classification

For classification of PTFF, 1358 adult patients (837 males, 521 females; 1364 affected knees) were included. The rate of PTFF was higher in males than in females (ratio = 1:0.62). There were no statistically significant differences in the mean age of males (42.02 ± 14.21 years; range, 18–84 years) and females (44.94 ± 15.48 years; range 19–80 years) ($t = 0.332$, $P = 0.883$). Only the left knee was involved in 749 (54.91%) cases, and the right in 603 (44.21%) cases; six (0.44%) patients sustained bilateral injuries. Traffic accidents (669, 49.26%) were the biggest cause of PTFF, followed by falls (573, 42.19%), falls from heights (103, 7.58%), crushing injury (6, 0.44%), kick injury (5, 0.37%), and gas explosion (2, 0.15%).

The major internal structural fractures of PTFF were TPF only (725, 53.15%), TPF and proximal fibular fracture (274, 20.09%), isolated avulsion fracture of the PCL (189, 13.86%), isolated avulsion fracture of the ACL (63, 4.62%), isolated proximal fibular fracture (26, 1.91%) and avulsion fractures of the ACL and PCL (24, 1.76%). The minor internal structural fractures of PTFF were isolated tibial tubercle fracture (4, 0.29%), tibial plateau fracture and avulsion fracture of the PCL (5, 0.37%) and tibial plateau fracture and avulsion fracture of the ACL (12, 0.88%). In addition, there were 42 (3.08%) cases in other complicated fractures.

Results of PTFF Classification

Approximately a quarter of cases could not be classified using the Schatzker classification. The most frequent types were types II (296, 21.70%), VI (225, 16.50%), and IV (148, 10.85%), and the least frequent types were type III (97, 7.11%), V (112, 8.21%), and I (146, 10.70%) in the remaining 1024 knees.

Similar to using the Schatzker classification, approximately a quarter of knees could not be classified using Luo classification. In the remaining 1035 knees, the most common types were lateral and posterior column (378, 27.71%);

lateral, medial, and posterior column (259, 18.99%); lateral column only (131, 9.60%); and medial and posterior columns (114, 8.36%). The least common types were medial column only (34, 2.49%); lateral and medial columns (39, 2.86%); and posterior column only (80, 5.87%).

Unlike the above two classification methods, Wu classification could be used to categorize all PTFF cases. The most frequently affected columns were the lateral and posterolateral columns (320, 23.46%); all four columns (268, 19.65%); and the posterolateral and posteromedial columns (212, 15.54%). The least frequently affected columns were lateral and posteromedial columns (4, 0.29%); lateral, medial, and posteromedial columns (4, 0.29%) and posteromedial columns only (14, 1.03%). The frequently affected regions were regions IV (663, 48.61%), II (455, 33.36%), III (232, 17.01%), and I (14, 1.03%). Segment 2 (1009, 73.97%) was more commonly involved than segment 1 (355, 26.03%). Overall, there were 45 types of the 1364 PTFF cases in this multicenter study according to Wu classification (Table 2). The most frequent Wu classification types were as follows: all four columns in region IV, segment 2 (235, 17.23%); the posterolateral and posteromedial columns in region II, segment 2 (191, 14.00%); and the lateral and posterolateral columns in region IV, segment 2 (136, 9.97%).

Fracture Characteristics of PTFF Classification

Certain internal structural fractures of PTFF cannot be classified using the Schatzker and Luo classification systems, including isolated avulsion fracture of the anterior cruciate ligament (ACL), isolated avulsion fracture of the PCL, combined avulsion fracture of the ACL and PCL, isolated proximal fibular fracture, and isolated tibial tubercle fracture. However, all of these internal structural fractures can be classified using the Wu classification system. For isolated avulsion fracture of the ACL, the most frequent injury type involved the lateral and medial columns in region II, segment 1 (40/63, 64%), more than triple that of fractures involving the lateral and medial column in region I, segment 1 (12/63, 19%),

TABLE 2 Wu classification results of all 1364 PTFFs

Column	Region	Segment	Number
Lateral only	IV	1	30 (2.20%)
Lateral only	II	1	63 (4.62%)
Lateral only	III	1	35 (2.57%)
Medial only	II	1	18 (1.32%)
Medial only	III	1	18 (1.32%)
Medial only	IV	1	6 (0.44%)
Posteromedial only	II	2	10 (0.73%)
Posteromedial only	IV	2	4 (0.29%)
Posterolateral only	II	2	20 (1.47%)
Posterolateral only	III	2	30 (2.20%)
Posterolateral only	IV	2	12 (0.88%)
Lateral and medial	II	1	40 (2.93%)
Lateral and medial	III	1	14 (1.03%)
Lateral and medial	I	1	12 (0.88%)
Lateral and medial	IV	1	10 (0.73%)
Medial and posteromedial	II	1	4 (0.29%)
Medial and posteromedial	III	1	2 (0.15%)
Medial and posteromedial	III	2	2 (0.15%)
Medial and posteromedial	IV	1	4 (0.29%)
Medial and posteromedial	II	2	6 (0.44%)
Medial and posteromedial	IV	2	34 (2.49%)
Lateral and posteromedial	IV	2	4 (0.29%)
Lateral and posterolateral	II	1	28 (2.05%)
Lateral and posterolateral	II	2	44 (3.23%)
Lateral and posterolateral	III	1	29 (2.13%)
Lateral and posterolateral	III	2	51 (3.74%)
Lateral and posterolateral	IV	1	32 (2.35%)
Lateral and posterolateral	IV	2	136 (9.97%)
Posterolateral and posteromedial	II	2	191 (14.00%)
Posterolateral and posteromedial	III	2	3 (0.22%)
Posterolateral and posteromedial	IV	2	17 (1.25%)
Posterolateral and posteromedial	I	2	2 (0.15%)
Lateral, medial, and posterolateral	III	2	12 (0.88%)
Lateral, medial, and posterolateral	IV	1	9 (0.66%)
Lateral, medial, and posterolateral	IV	2	25 (1.83%)
Lateral, medial, and posterolateral	II	2	5 (0.37%)
Lateral, medial, and posteromedial	IV	2	4 (0.29%)
Lateral, posteromedial, and posterolateral	II	2	6 (0.44%)
Lateral, posteromedial, and posterolateral	III	2	22 (1.61%)
Lateral, posteromedial, and posterolateral	IV	2	61 (4.47%)
Medial, posteromedial, and posterolateral	III	2	4 (0.29%)
Medial, posteromedial, and posterolateral	IV	2	38 (2.79%)
Lateral, medial, posteromedial, and posterolateral	III	2	10 (0.73%)
Lateral, medial, posteromedial, and posterolateral	IV	2	235 (17.23%)
Lateral, medial, posteromedial, and posterolateral	II	2	22 (1.61%)

as well as those of the lateral column in region II, segment 1 (11/63, 17.5%). Notably, 184/189 (97.35%) isolated avulsion fractures of the PCL involved the posterolateral and posteromedial columns in region II, segment 2 (Fig. 7).

For combined avulsion fractures of the ACL and PCL ($n = 24$), three cases (13%) involved the lateral, medial, and posterolateral columns in region II, segment 2, and a further three cases involved the lateral, posteromedial, and posterolateral columns in region II, segment 2. However, the most frequent injury type for combined avulsion fractures of the ACL and PCL involved all four columns in region II, segment 2 (18/24, 75%).

For isolated proximal fibular fractures, 23/26 (88%) cases involved the posterolateral column in region III, segment 2, whereas 3/26 (12%) cases involved the posterolateral column in region IV, segment 2 (Fig. 8). Interestingly, only

four cases (0.29%) of isolated tibial tubercle fracture were observed, of which the most frequent injury type was that of the lateral column in region III, segment 1 (3/4, 75%); the remaining case involved the lateral and medial columns in region IV, segment 1.

Among cases of combined TPF and avulsion fracture of the ACL, lateral and medial columns in region III, segment 1 (4/12, 33%) was the most frequent Wu classification. Moreover, among knees with combined TPF and avulsion fracture of the PCL, the most frequent Wu classifications were the posterolateral and posteromedial columns in region IV, segment 2 (2/5, 40%), and the posteromedial column in region III, segment 2 (2/5, 40%). The remaining Wu classification among such fractures was the medial, posterolateral, and posteromedial columns in region IV, segment 2.

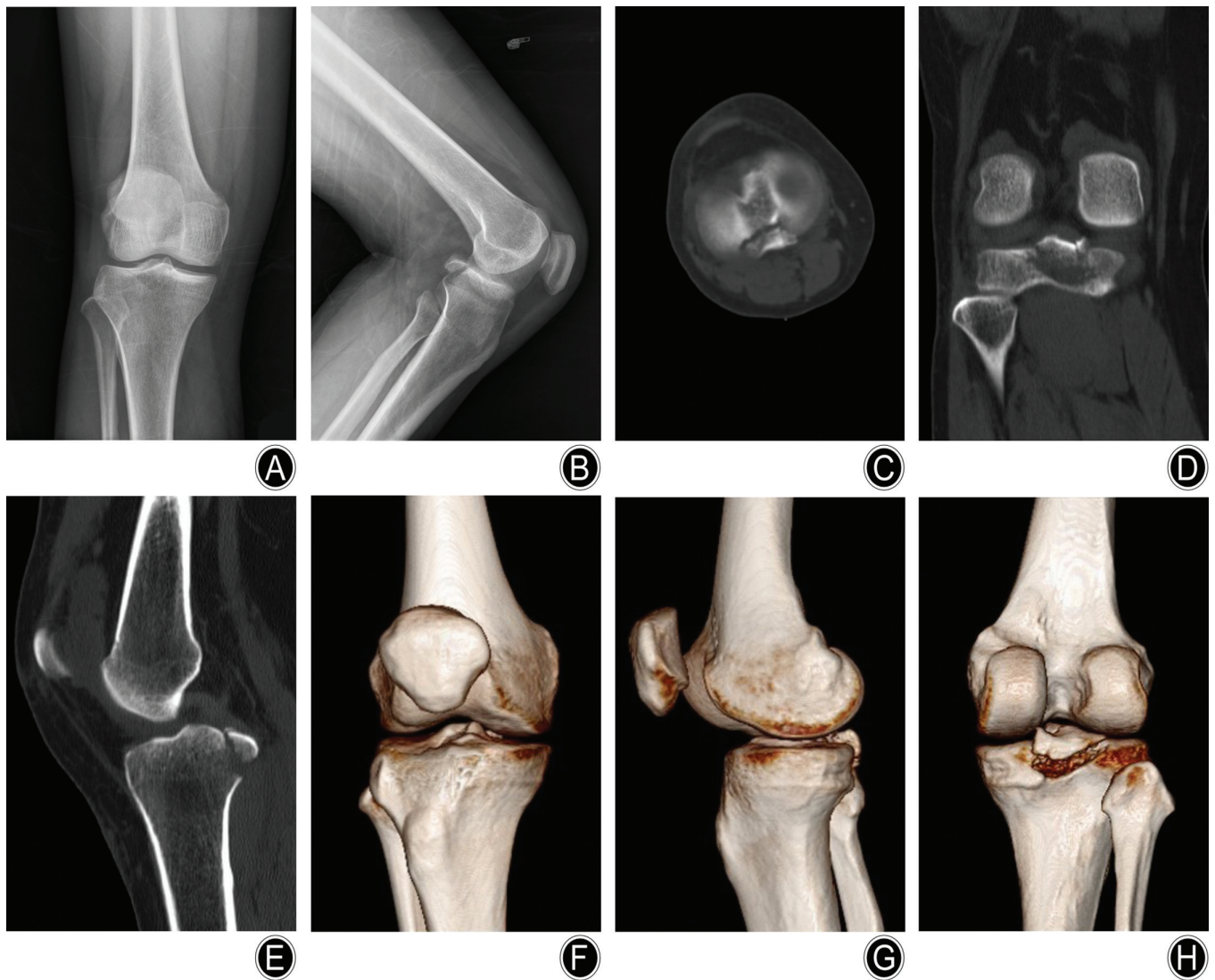


Fig. 7 Wu Classification of isolated avulsion fracture of the PCL. A 40-year-old female patient sustained fractures of the right isolated avulsion fracture of the PCL due to fall from bicycle in September 2018. It cannot be classified using the Schatzker classification from X-ray imaging (A, B), poster column of Luo classification from CT (C). According to the Wu classification, based on results of CT (C, D, E) and 3D reconstruction (F, G, H), the fracture was located in the posterolateral and posteromedial columns in region II, segment 2.

Interestingly, of the more than 20% of cases of combined TPF and proximal fibular fracture, the most frequent injury type involved all four columns in region IV, segment 2 (107/274, 39.05%). These were followed by those involving the lateral and posterolateral columns in region IV, segment 2 (43/274, 15.69%), and those involving the lateral, posterolateral, and posteromedial columns in region IV, segment 2 (20/274, 7.30%).

Discussion

An Updated Definition of Proximal Tibia and Fibula, and PTFF, and a New Classification Method of PTFF

To our knowledge, this was not only the first study to put forward an updated definition of the proximal tibia and

fibula, and PTFF, but also the first PTFF-classification system based on the 3D structure of the tibia and fibula. Wu classification has a morphological basis, supported by radiological measurements. The use of 3D reconstruction enabled us to refine PTFF and TPF classification; we used Wu classification to determine the incidence and fracture characteristics of PTFF.

Previously established classification systems of TPF (Hohl and Moore, Schatzker, OTA/AO 2007) are based on plain X-ray imaging¹¹⁻¹⁴, which provides incomplete, two-dimensional fracture information. Luo *et al.*^{15, 16} put forward the three-column classification concept and laid the fundamentals for several revised column classifications, the major shortcomings of which are insufficient coverage and column

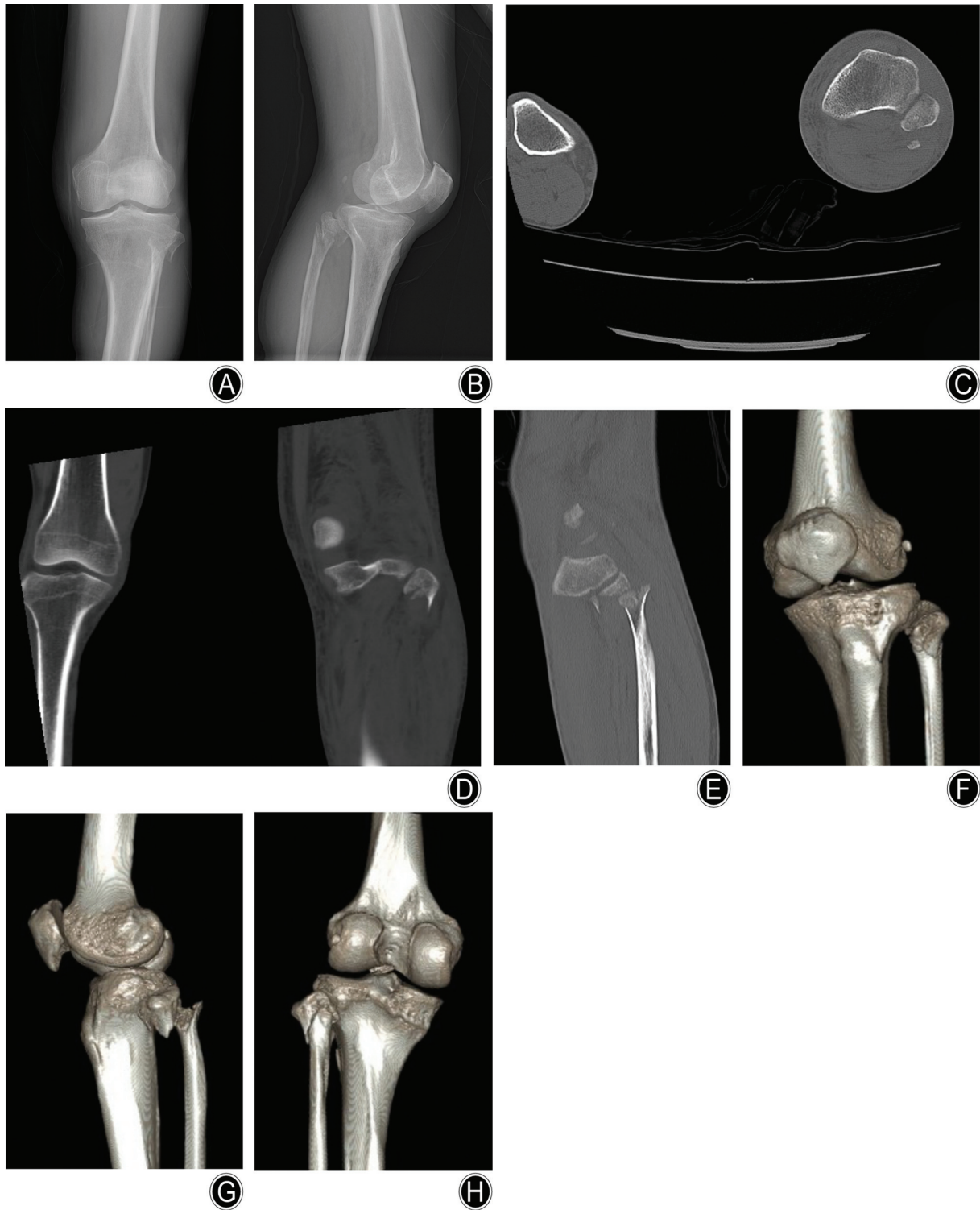


Fig. 8 Wu Classification of isolated proximal fibular fracture. A 65-year-old male patient sustained fractures of the left isolated proximal fibular fracture due to a traffic accident in January 2013. It cannot be classified using the Schatzker classification from X-ray imaging (A, B), and Luo classification from CT (C). According to the Wu classification, based on results of CT (C, D, E) and 3D reconstruction (F, G, H), the fracture was located in posterolateral column in region IV, segment 2.

divisions that are not based on physiology^{6, 17, 25, 26}. Besides these three columns in the horizontal plane, Wu classification also distinguishes between four regions in the frontal plane and two segments in the sagittal plane, based on the 3D morphology of the proximal tibia and fibula. The 329 (24.12%) PTFF cases could not be classified using Schatzker or Luo classification, but only using Wu classification. One great advantage of this new classification system is that it could be used to classify all PTFF and TPF patterns observed in this study.

Morphological Basis from Radiological Measurements

Prominent bony protuberance of the cortical surface of the proximal tibia and fibula were used as markers for the division of regions in the frontal plane in the Wu classification system. According to radiological measurements, region I is the smallest, and regions II to IV were progressively larger. The average heights determined using CT were 0.82 cm for region I, 1.32 cm for region II, 1.54 cm for region III, and 3.58 cm for region IV. The relevant region is determined as that containing the lowest point of the fracture line. For example, fractures in region II include those located only in region II as well as those where the fracture line extends from regions I to II. This is possibly why the most frequently affected region was region IV (663, 48.61%) and the least frequently involved was region I (14, 10.26%).

Segment classification is very simple. Segment 1 is the anterior part of the proximal tibia and fibula, with the same length (3.75 ± 0.42 cm) as the diameter of the shaft of the proximal tibia. The remaining posterior portion of the proximal tibia and the fibula comprises segment 2, with an average length of 1.68 cm. As the relevant segment is based on the most posterior point of the fracture line, fractures involving segment 2 include those where the entire fracture line is within segment 2, and those where the fracture line extends from segment 1 to 2. This is a possible reason why the number of fragments determined to involve segment 2 (1009, 73.97%) was more than that involving segment 1 (355, 26.03%) in the cohort.

Incidence and Fracture Characteristics of PTFF and the Advantage of Wu Classification

The second advantage of Wu classification is that PTFFs can be divided into enough groups to distinguish all PTFF types. The 1364 PTFF cases in this multicenter study could be divided into 45 types. Therefore, it may assist doctors and researchers to gain a better understanding of the anatomy and spatial relationships of the knee bones in various types of fractures. This original approach is also convenient for academic discussion of PTFF. The most common PTFF according to Wu classification was that involving all four columns in region IV, segment 2 (235, 17.23%), which is similar to fractures of type VI in the Schatzker classification (225, 16.50%), and those involving the lateral, medial, and posterior columns in the Luo classification (259, 18.99%).

The third advantage of Wu classification is that it allows for the classification of more nuanced fractures than is possible with other classification systems. Torn ligaments and insertion fractures are common in PTFF. In one study³¹, 77.7% (80/103) of patients with PTFF were observed to have an injury of the ACL or lateral collateral ligament during operation. In another study³², it was reported that 70.9% (73/103) of patients with PTFF had at least one torn ligament and 53.4% (55/103) had multiple ligament injuries. In this cohort, 21.48% (293/1364) of PTFFs were ACL and/or PCL avulsion fractures. Hardly any classification systems exist in which ligaments avulsion fracture of the ACL and/or PCL can be classified. Isolated avulsion fracture of the ACL was categorized as three injury types according to Wu classification in this study, most of which involved the lateral and medial columns in region II, segment 1 (40/63, 64%). As for isolated avulsion fracture of the PCL, more than 97% of cases involved the posterolateral and posteromedial columns in region II, segment 2.

Interestingly, we observed only four cases (0.29%) of isolated tibial tubercle fracture, which lacked classification for adults^{6, 32}. In contrast, Molenaars *et al.*³³ reported that 15.7% (20/127) of patients with TPF had a tibial tubercle fragment; Maroto *et al.*³⁴ identified 85 such cases out of 392 bicondylar cases of TPF (21.7%); Chakraverty *et al.*³⁵ observed 16 similar cases; and Yao *et al.*⁶ reported 85 (12.1%) such cases. The possible reason for this difference is that those cohort studies were carried out in different regions. According to Wu classification, 3/4 isolated tibial tubercle fractures involved the lateral column in region III, segment 1.

There were 274 (20.09%) knees with combined TPF and proximal fibular fracture, and 26 (1.91%) knees with isolated proximal fibular fracture in this cohort. Yao *et al.*⁶ observed that 31.0% (218/704) of patients with TPF had a combined proximal fibular fracture. The proximal fibula is an important part of the knee joint, and is firmly connected to the tibial plateau by the tibiofibular syndesmosis, which affects TPF displacement and the necessary surgical approach⁶. Understanding the injury to the proximal fibula helps uncover the nature of the TPF, allowing the adequate restoration of the stability of the posterolateral corner^{36, 37}. In the OTA/AO classification system of 2007, proximal fibula fracture is classified as 41-A1.1. This fracture is coded independently as 4F1A/4F1B in the 2018 edition of this classification system, with the added qualifications of extra- or intra-articular³⁸. Luo classification does not consider proximal fibula fracture; it merely uses the anterior point of the fibular head¹⁵. Using Wu classification, two types of isolated proximal fibular fracture could be identified; the most common type involved the posterolateral column in region III, segment 2 (23/26, 88%); the other involved the posterolateral column in region IV, segment 2 (3/26, 12%).

The fourth advantage of Wu classification is that it allows for the classification of complicated fractures. There were different types of combined TPF and proximal fibular

fracture in this study, the most frequent of which involved all four columns in region IV, segment 2 (107/274, 39.05%). Such a fracture was a severe traumatic marker for neurovascular injury and compartment syndrome. More than 60% of cases of combined TPF and proximal fibular fracture included region IV in segment 2, which represents one of the most serious injuries according to Wu classification.

Another interesting complicated PTFF observed in this study was combined avulsion fracture of the ACL and the PCL, including serious injury of the ligament and insertion fracture. Former classification systems scarcely identify any avulsion fractures of the ACL and PCL. However, three types of avulsion fractures of the ACL and PCL were identified using Wu classification in this study, the most frequent of which included all four columns in region II, segment 2 (18/24, 75%). The other two types also included region II, segment 2. All of the isolated avulsion fractures of the ACL were located in segment 1, and all those of the PCL were located in segment 2.

Its assistance during selection of the correct internal fixation and during clinical diagnosis and treatment are the fifth advantage of Wu classification. To our knowledge, this study is the first to define PTFFs according to region on the frontal plane, allowing for different treatment strategies. For example, all fractures of region I were avulsion fractures of ligaments, which require conservative treatment or arthroscopically assisted ligament reconstruction. PTFFs involving the lateral and/or medial column in region II, segment 1, need anterolateral and/or anteromedial screw fixation with or without bone grafting. Moreover, fractures involving the lateral and/or medial columns in region III, segment 1, need anterolateral and/or anteromedial fixation using a relatively short plate and screw fixation with or without bone grafting. PTFFs involving the lateral and/or medial

columns in region IV, segment 1, need anterolateral and/or anteromedial fixation using a long plate and screws with bone grafting. And other types of fracture treatment strategies warrant further study and improvement.

Limitations

(i) Although this classification system appears complicated, it is actually quite simple. One need not remember each possible type; one only needs to understand how to classify the columns, regions, and segments. (ii) Bias and errors may exist in the results of the radiological measurement. (iii) The reliability, reproducibility, and clinical relevance of this classification including standardized treatment regimens need further study and should be improved in subsequent research.

Conclusion

In summary, an updated definition of the proximal tibia and fibula, and PTFF was proposed. All cases of PTFF could be classified using Wu classification in this study. The most common PTFF involves all four columns in region IV, segment 2. We have developed a novel, 3D-structure-based classification, including classification by column in the horizontal plane, by region in the frontal plane, and by segment in the sagittal plane. This updated system for classifying PTFF should be beneficial for clinical diagnosis, guidance of treatment, statistical analysis, academic communication, and prognosis.

Acknowledgment

In radiographic measurement, data collection, and analysis, this work was supported by the Science and Technology Project of Guangdong province, China (2014359).

References

- Liu YW, Li YH, Yu T, Yang T, Li Y, Tan L. Popliteal artery transection associated with a minimally displaced tibial plateau fracture: a case report and review of the literature. *BMC Musculoskelet Disord*, 2020, 21: 59.
- Bernholt DL, DePhillipo NN, Crawford MD, Aman ZS, Grantham WJ, LaPrade RF. Incidence of displaced posterolateral tibial plateau and lateral femoral condyle impaction fractures in the setting of primary anterior cruciate ligament tear. *Am J Sports Med*, 2020, 48: 545–553.
- Yi Z, Hui S, Binbin Z, et al. A new strategy to fix posterolateral depression in tibial plateau fractures: introduction of a new modified Frosch approach and a "barrel hoop plate" technique. *Injury*, 2020, 51: 723–734.
- Xie X, Zhan Y, Wang Y, 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.
- Zheng ZL, Yu YY, Chang HR, Liu H, Zhou HL, Zhang YZ. Establishment of classification of tibial plateau fracture associated with proximal fibular fracture. *Orthop Surg*, 2019, 11: 97–101.
- Yao X, Xu Y, Yuan J, et al. Classification of tibia plateau fracture according to the "four-column and nine-segment". *Injury*, 2018, 49: 2275–2283.
- Zhu Y, Meili S, Dong MJ, 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.
- Hall RF Jr, Gonzales M. Fracture of the proximal part of the tibia and fibula associated with an entrapped popliteal artery. A case report. *J Bone Joint Surg Am*, 1986, 68: 941–944.
- Mendelson D, Kates S, Pacos J, Clark N, Wu J. Proximal tibia and fibula fragility fracture complicated by anticoagulation and demand-mediated myocardial infarction. *Geriatr Orthop Surg Rehabil*, 2011, 2: 110–116.
- Sakamoto A, Okamoto T, Matsuda S. Insufficiency fracture at an osteochondroma bridging the proximal fibula and the tibia: case report. *J Orthop*, 2018, 15: 384–387.
- Schatzker J, McBroom R, Bruce D. The tibial plateau fracture. The Toronto experience 1968–1975. *Clin Orthop Relat Res*, 1979, 138:94–104.
- Hohl M. Tibial condylar fractures. *J Bone Joint Surg Am*, 1967, 49: 1455–1467.
- Moore TM. Fracture-dislocation of the knee. *Clin Orthop Relat Res*, 1981, 156: 128–140.
- Marsh JL, Slongo TF, Agel J, et al. Fracture and dislocation classification compendium - 2007: Orthopaedic Trauma Association classification, database and outcomes committee. *J Orthop Trauma*, 2007, 21: S1–S133.
- Luo CF, Sun H, Zhang B, Zeng BF. Three-column fixation for complex tibial plateau fractures. *J Orthop Trauma*, 2010, 24: 683–692.
- 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.
- Yang G, Zhai Q, Zhu Y, Sun H, Putnis S, Luo C. The incidence of posterior tibial plateau fracture: an investigation of 525 fractures by using a CT-based classification system. *Arch Orthop Trauma Surg*, 2013, 133: 929–934.
- Wahlquist M, Iagulli N, Ebraheim N, Levine J. Medial tibial plateau fractures: a new classification system. *J Trauma*, 2007, 63: 1418–1421.

19. Yang G, Zhu Y, Luo C, Putnis S. Morphological characteristics of Schatzker type IV tibial plateau fractures: a computer tomography based study. *Int Orthop*, 2012, 36: 2355–2360.
20. Chen HW, Liu GD, Ou S, Zhao GS, Pan J, Wu LJ. Open reduction and internal fixation of posterolateral tibial plateau fractures through fibula osteotomy-free posterolateral approach. *J Orthop Trauma*, 2014, 28: 513–517.
21. Gicquel T, Najihi N, Vendeuvre T, Teysseidou S, Gayet LE, Hutten D. Tibial plateau fractures: reproducibility of three classifications (Schatzker, AO, Duparc) and a revised Duparc classification. *Orthop Traumatol Surg Res*, 2013, 99: 805–816.
22. Chang SM, Zhang YQ, Yao MW, Du SC, Li Q, Guo Z. Schatzker type IV medial tibial plateau fractures: a computed tomography-based morphological subclassification. *Orthopedics*, 2014, 37: e699–e706.
23. Hoekstra H. Are there four tibia plateau columns. *Int Orthop*, 2017, 41: 2631–2632.
24. Gebel PJ, Tryzna M, Beck T, Wilhelm B. Tibial plateau fractures: fracture patterns and computed tomography evaluation of tibial plateau fractures in winter sports. *Orthop Rev (Pavia)*, 2018, 10: 7517.
25. Krause M, Preiss A, Meenen NM, Madert J, Frosch KH. "Fracturoscopy" is superior to fluoroscopy in the articular reconstruction of complex tibial plateau fractures-an arthroscopy assisted fracture reduction technique. *J Orthop Trauma*, 2016, 30: 437–444.
26. Krause M, Preiss A, Müller G, et al. Intra-articular tibial plateau fracture characteristics according to the "ten segment classification". *Injury*, 2016, 47: 2551–2557.
27. 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.
28. Rossmann M, Fensky F, Ozga AK, et al. Tibial plateau fracture: does fracture classification influence the choice of surgical approach? A retrospective multicenter analysis. *Eur J Trauma Emerg Surg*, 2020. <https://doi.org/10.1007/s00068-020-01388-z>
29. Millar SC, Arnold JB, Thewlis D, Fraysse F, Solomon LB. A systematic literature review of tibial plateau fractures: what classifications are used and how reliable and useful are they. *Injury*, 2018, 49: 473–490.
30. Yao X, Zhou K, Lv B, et al. 3D mapping and classification of tibial plateau fractures. *Bone Joint Res*, 2020, 9: 258–267.
31. Stannard JP, Lopez R, Volgas D. Soft tissue injury of the knee after tibial plateau fractures. *J Knee Surg*, 2010, 23: 187–192.
32. Pretell-Mazzini J, Kelly DM, Sawyer JR, et al. Outcomes and complications of Tibial tubercle fractures in pediatric patients: a systematic review of the literature. *J Pediatr Orthop*, 2016, 36: 440–446.
33. Molenaars RJ, Mellema JJ, Doornberg JN, Kloen P. Tibial plateau fracture characteristics: computed tomography mapping of lateral, medial, and Bicondylar fractures. *J Bone Joint Surg Am*, 2015, 97: 1512–1520.
34. Maroto MD, Scolaro JA, Henley MB, Dunbar RP. Management and incidence of tibial tubercle fractures in bicondylar fractures of the tibial plateau. *Bone Joint J*, 2013, 95: 1697–1702.
35. Chakraverty JK, Weaver MJ, Smith RM, Vrahas MS. Surgical management of tibial tubercle fractures in association with tibial plateau fractures fixed by direct wiring to a locking plate. *J Orthop Trauma*, 2009, 23: 221–225.
36. Vojdani S, Fernandez L, Jiao J, et al. Novel spiked-washer repair is biomechanically superior to suture and bone tunnels for Arcuate fracture repair. *J Orthop Trauma*, 2017, 31: e81–e85.
37. Cohen AP, King D, Gibbon AJ. Impingement fracture of the anteromedial tibial margin: a radiographic sign of combined posterolateral complex and posterior cruciate ligament disruption. *Skeletal Radiol*, 2001, 30: 114–116.
38. Meinberg EG, Agel J, Roberts CS, Karam MD, Kellam JF. Fracture and dislocation classification compendium-2018. *J Orthop Trauma*, 2018, 32: S1–S170.