

Tibial Plateau Fractures: A Systematic Review of Diagnostic Approaches, Surgical Strategies, And Functional Outcomes

Heytor Mendes Camargo Costa¹ , Luiz Fernando Sari Sampaio¹ , Arthur Rodrigues de Almeida Aguiar¹ , Amanda Caroline da Silva Morais¹ , Paulo Henrique Cardoso Amorim¹ , Lucas Tomaz Valim¹ , Sergio Gabriell de Oliveira Moura¹  and Fernanda Grazielle da Silva Azevedo Nora^{2*} 

¹Department of Orthopedics and Traumatology, HEAPA - Hospital Estadual de Aparecida de Goiania, Cairo Louzada, Aparecida de Goiânia, Goiás, Brazil

²LAM – Movement Architecture Laboratory, Universidade Federal de Goiás, Goiania, Goiás, Brazil

*Corresponding Author

Fernanda Grazielle da Silva Azevedo Nora, LAM – Movement Architecture Laboratory, Universidade Federal de Goiás, Goiania, Goiás, Brazil.

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Abstract

Introduction: Tibial plateau fractures (TPFs) represent complex articular injuries that require precise diagnostic evaluation and individualized therapeutic strategies to prevent long-term joint dysfunction. Despite advancements in surgical techniques and imaging modalities, there is still considerable variability in clinical outcomes and a lack of consensus on optimal management protocols.

Objective: To systematically review and synthesize the current literature on the diagnostic approaches, classification systems, surgical techniques, and functional outcomes associated with tibial plateau fractures, aiming to provide an evidence-based foundation for clinical decision-making.

Methods: This systematic review was conducted in accordance with PRISMA guidelines. A comprehensive literature search was performed in PubMed, MEDLINE, ScienceDirect, and Google Scholar from January 2010 to March 2025. Only open-access, English-language original studies involving human subjects were included. Articles were screened based on predefined inclusion and exclusion criteria, and 35 studies were selected for qualitative synthesis. Data were extracted regarding imaging techniques, fracture classifications, operative management, postoperative rehabilitation, and complications.

Results: The review revealed a shift toward the use of CT-based and three-column classification systems for better preoperative planning and outcome prediction. Open reduction and internal fixation (ORIF), minimally invasive plate osteosynthesis (MIPO), and hybrid techniques remain the primary surgical approaches. Functional recovery was positively associated with early mobilization protocols and individualized rehabilitation strategies. However, complications such as post-traumatic osteoarthritis, malalignment, and infection were still prevalent, particularly in high-energy and bicondylar fractures.

Conclusion: Accurate diagnosis and classification of TPFs are critical for guiding surgical intervention and optimizing long-term function. Although modern imaging and operative innovations have improved outcomes, complication rates remain a challenge. A multimodal approach that integrates advanced diagnostics, tailored fixation strategies, and structured rehabilitation is essential for improving patient prognosis.

Keywords: Tibial Fractures, Diagnostic Imaging, Orthopedic Procedures, Postoperative Complications, Rehabilitation.

1. Introduction

Tibial plateau fractures (TPFs) are intra-articular injuries of the proximal tibia that compromise the congruence and stability of the knee joint. They represent a small percentage of all fractures, approximately 1% but are clinically significant due to their potential to evolve into chronic disability if inadequately managed [1]. These fractures often result from axial loading combined with varus or valgus stress, with high-energy trauma predominating in younger patients and low-energy mechanisms, such as falls from standing height, being more common in the elderly population with osteoporotic bone [2].

The diagnostic complexity of TPFs arises not only from the bony injury but also from the frequent involvement of periarticular structures. Associated lesions, including tears of the menisci, anterior and posterior cruciate ligaments, and collateral ligaments, are observed in a substantial proportion of cases [3]. A meticulous clinical assessment, including evaluation for neurovascular injury and compartment syndrome, is crucial at presentation.

While standard radiographs remain the first-line imaging modality, they are often insufficient for delineating the complete fracture pattern. Computed tomography (CT) has become essential for detailed characterization of articular involvement, especially in comminuted and posterior fractures, as it enables accurate visualization of fragment orientation and displacement [4]. In contrast, magnetic resonance imaging (MRI) plays a complementary role by identifying soft tissue injuries, bone marrow edema, and occult fractures not seen on X-ray or CT, contributing to a comprehensive injury assessment [5,6].

Classification systems guide diagnostic synthesis and inform therapeutic decision-making. The Schatzker classification, though widely used due to its simplicity, is limited in its ability to categorize complex, posterior, or medial column fractures. These limitations have prompted the adoption of more advanced systems, such as the AO/OTA classification and CT-based models like Luo's three-column framework, which offer superior interobserver reliability and anatomical resolution [7,8]. These systems subdivide the tibial plateau into discrete functional zones, enabling surgeons to choose more appropriate fixation strategies and surgical approaches.

Recent literature demonstrates that the accuracy of fracture classification directly influences preoperative planning and surgical outcomes. For example, CT-based classification improves the identification of hidden fracture lines and guides the selection of surgical windows to access posterior segments of the plateau [9]. Moreover, these systems facilitate standardization in multicenter studies and registries, enhancing evidence-based comparisons between treatment protocols.

Management strategies for TPFs are multifactorial, involving assessment of fracture displacement, joint depression, soft tissue condition, and patient comorbidities. The spectrum of surgical techniques includes open reduction and internal fixation (ORIF), minimally invasive plate osteosynthesis (MIPO), hybrid external fixation, and primary arthroplasty in select geriatric

cases [10]. Decisions regarding surgical timing, fixation method, and rehabilitation protocol require integration of anatomical, mechanical, and biological considerations to optimize outcomes.

Given the heterogeneity of TPF presentations and the evolving landscape of diagnostic and therapeutic modalities, there is a clear need for a systematic and critical synthesis of the current literature. This review aims to analyze the best practices for diagnosis and treatment of tibial plateau fractures and to evaluate the functional outcomes associated with various surgical and rehabilitative approaches. By consolidating evidence from 35 peer-reviewed studies, this review offers a comprehensive foundation for guiding clinical decision-making and improving the long-term prognosis of patients with these challenging injuries.

2. Methodology

2.1 Study Design

This study was structured as a systematic review of the literature with the objective of critically identifying, evaluating, and synthesizing the most robust and current evidence concerning the diagnostic modalities, classification systems, surgical strategies, and functional outcomes associated with tibial plateau fractures (TPFs). The methodological framework adhered strictly to the principles and recommendations of the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines, thereby ensuring transparency, reproducibility, and methodological rigor throughout all stages of the review process. This design allowed for a comprehensive and integrative appraisal of the literature to inform evidence-based clinical decision-making in the management of TPFs.

2.2. Database Selection and Search Strategy

A comprehensive and structured literature search was conducted between January and March 2025 using four major biomedical databases: PubMed, ScienceDirect, MEDLINE, and Google Scholar. These databases were selected due to their broad indexing of high-quality peer-reviewed journals and clinical case literature relevant to orthopedic research. To ensure unrestricted access and consistent analysis, only open-access articles with full-text availability were included in the review.

The search strategy combined Medical Subject Headings (MeSH) and free-text keywords, allowing for a more sensitive and specific retrieval of relevant publications. Boolean operators such as "AND" and "OR" were used to create strategic keyword combinations, expanding or narrowing the scope of the search as appropriate for each database. The primary descriptors and terms employed reflected the review's thematic focus on diagnosis, surgical intervention, and outcomes in tibial plateau fractures. These included: "Tibial Plateau Fracture", "TPF", "Diagnosis", "Imaging", "Computed Tomography", "MRI", "Fracture Classification", "Schatzker", "AO/OTA", "Open Reduction Internal Fixation", "ORIF", "Minimally Invasive Plate Osteosynthesis", "Functional Outcome", "Rehabilitation", and "Postoperative Complications".

The use of this terminology enabled the identification of clinically and surgically relevant studies that address the diagnostic imaging, classification frameworks, treatment modalities, and rehabilitation protocols associated with tibial plateau fractures, encompassing a wide spectrum of clinical evidence.

2.3. Inclusion and Exclusion Criteria

To ensure scientific rigor, clinical relevance, and methodological consistency, strict inclusion and exclusion criteria were applied during the screening and selection process of this systematic review. Studies were eligible for inclusion if they were original clinical investigations, encompassing prospective or retrospective cohort studies, case reports, or case series involving patients diagnosed with tibial plateau fractures (TPFs). Only articles published between January 2010 and March 2025 were considered, ensuring that the evidence reflects contemporary diagnostic and therapeutic practices. Publications had to be written in English, involve human subjects, and be available as open-access full-text articles, allowing for full methodological and outcome assessment. Furthermore, studies were required to address at least one of the following thematic areas: diagnosis, imaging techniques, fracture classification systems, surgical management, or functional outcomes related to TPFs.

Articles were excluded if they were literature reviews, systematic reviews, or meta-analyses, as these do not contribute original data. Additionally, editorials, letters to the editor, and expert opinions without empirical evidence were excluded. Other exclusion criteria included conference abstracts, theses, and papers published in scientific events without peer review, as well as preclinical studies conducted on cadaveric specimens or animal models. Articles that were not available in full text, published behind paywalls, or written in languages other than English were also excluded from the final analysis. This rigorous eligibility protocol was implemented to enhance the reliability, validity, and clinical applicability of the synthesized evidence, ensuring that only methodologically sound and contextually relevant studies were included in this systematic review.

2.4. Study Selection Process

The selection process for eligible studies was meticulously structured and conducted in four sequential stages, following the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) framework. This multi-phase methodology was designed to enhance transparency, reproducibility, and methodological rigor in the identification and inclusion of relevant literature on tibial plateau fractures.

The first stage, known as identification, involved a comprehensive export of all records retrieved from the targeted databases PubMed, ScienceDirect, MEDLINE, and Google Scholar into the reference management software Zotero. This tool facilitated systematic cataloging of citations and enabled the automatic elimination of duplicate entries, ensuring that each article was represented only once in the screening dataset. The objective of this phase was to prepare a unified and accurate corpus of studies for subsequent

evaluation while minimizing redundancy and administrative error.

In the second stage, screening, two independent reviewers examined the titles and abstracts of all imported studies. This initial assessment served to exclude articles that clearly did not meet the inclusion criteria, such as studies unrelated to tibial plateau fractures, non-English publications, preclinical research, and non-original studies (e.g., reviews or opinion pieces). The dual-review process minimized subjective bias and allowed for cross-validation of decisions, ensuring a consistent and objective evaluation at this preliminary stage. Studies deemed potentially eligible were retained for full-text analysis in the next step.

The third stage, eligibility, involved an in-depth review of the full texts of the articles that passed the initial screening. Each study was evaluated to confirm that it aligned with the predefined inclusion criteria, including relevance to diagnostic imaging, classification systems, surgical interventions, and functional outcomes related to tibial plateau fractures. This phase was critical in assessing the methodological quality and completeness of each article, as well as determining the availability of relevant clinical data. Only those studies that met all required parameters were advanced to the final selection stage.

In the fourth and final stage, inclusion, the two reviewers engaged in deliberation to reach a consensus on which articles would be included in the qualitative synthesis. In cases where discrepancies or disagreements arose, a third reviewer was consulted to provide an impartial resolution. After this thorough review and adjudication process, a total of 35 articles were deemed eligible and incorporated into the final dataset for narrative and analytical synthesis. These studies were considered to represent the most current and reliable evidence available within the defined scope of the systematic review.

2.5. Data Extraction

The process of data extraction was conducted using a standardized and pre-piloted spreadsheet to ensure consistency, accuracy, and reproducibility of the information gathered across all selected studies. Two independent reviewers performed the extraction process, with discrepancies resolved through consensus or adjudication by a third reviewer, thereby minimizing the risk of bias and enhancing data reliability.

From each included article, a comprehensive set of variables was systematically recorded. These included the name(s) of the author(s), year of publication, and the journal in which the study appeared, which provided context regarding the scientific credibility and recency of the evidence. Additionally, the study design was documented—whether it was a case report, case series, retrospective or prospective cohort study, or another type of clinical investigation. This allowed for stratification of evidence based on methodological robustness.

Patient-related data were also collected, including demographic information (such as age and sex) and sample size, which are

essential for assessing the generalizability and statistical power of the findings. With respect to diagnostic methodology, the imaging modalities utilized in each study—such as plain radiography, computed tomography (CT), and magnetic resonance imaging (MRI)—were recorded to examine trends in imaging use and to evaluate diagnostic precision across different modalities. The classification systems applied in each study were also noted, including commonly used frameworks such as the Schatzker classification, the AO/OTA system, and Luo’s three-column model. This information was crucial for comparing the diagnostic reproducibility and prognostic implications of various classification methods.

Regarding therapeutic interventions, the surgical techniques implemented in each study were extracted and categorized. These included open reduction and internal fixation (ORIF), minimally invasive plate osteosynthesis (MIPO), hybrid fixation methods, and arthroplasty, particularly in elderly or committed fracture cases. Details regarding surgical approach, fixation strategy, and intraoperative adjuncts were also recorded when available.

The primary functional outcomes reported were systematically extracted, encompassing parameters such as range of motion (ROM), return to pre-injury activity level, pain scores (e.g., VAS), and validated scoring systems like Lysholm or Rasmussen scores, when provided. Additionally, information on postoperative complications, such as infection, hardware failure, malalignment, and post-traumatic osteoarthritis, as well as the duration of follow-up, were carefully documented. Each study was further categorized based on its primary thematic focus—whether it emphasized diagnostic imaging, classification reliability, surgical techniques, or functional rehabilitation outcomes. This categorization enabled a more nuanced synthesis of the literature, allowing the findings to be analyzed within specific domains of interest in the management of tibial plateau fractures.

2.6. Quality Appraisal

A rigorous quality appraisal process was conducted to evaluate the methodological soundness and clinical relevance of all studies included in the systematic review. The appraisal criteria were selected based on the study design and adhered to established frameworks for assessing the internal validity and risk of bias of clinical research. For case reports and case series, the CARE (CAse REport) guidelines were employed. These guidelines provided a structured approach for evaluating the completeness and transparency of clinical descriptions, including patient history, diagnostic assessment, therapeutic intervention, and outcome reporting. Each case was appraised for its clarity, reproducibility, and clinical applicability in the context of tibial plateau fracture management.

For observational studies, including both retrospective and prospective cohort studies, the Newcastle-Ottawa Scale (NOS) was applied. The NOS assesses three major domains: selection of study groups, comparability of groups, and ascertainment of the

outcome of interest. Each study was scored according to these criteria, allowing differentiation between high- and low-quality evidence based on methodological rigor and risk of confounding or selection bias. Only studies that provided adequate methodological descriptions, including a clear diagnostic and therapeutic protocol, as well as sufficient detail regarding clinical follow-up, were retained in the final qualitative synthesis. Studies with missing data, inadequate outcome measures, or unclear timelines were excluded to ensure the reliability and clinical utility of the findings.

This multilevel quality assessment ensured that the evidence base underpinning the conclusions of this review was not only relevant but also methodologically robust, thereby enhancing the credibility of the synthesis and its applicability to clinical practice.

2.7. Data Synthesis

Given the considerable heterogeneity among the included studies in terms of design, patient demographics, surgical interventions, and outcome metrics, a quantitative meta-analysis was deemed methodologically inappropriate. Variations in clinical protocols, follow-up durations, and reporting formats precluded statistical pooling of data. Therefore, a narrative synthesis approach was adopted to systematically interpret and integrate the findings across studies.

The selected studies were organized thematically into four primary domains to facilitate structured analysis and cross-study comparisons. These domains were as follows: (1) Diagnostic Imaging and Fracture Classification, focusing on radiological modalities, classification systems, and their diagnostic reliability; (2) Surgical Techniques and Fixation Strategies, encompassing operative approaches, fixation methods, and intraoperative innovations; (3) Functional Rehabilitation and Recovery, addressing postoperative mobility, physiotherapy protocols, and outcome metrics such as range of motion and pain scores; and (4) Postoperative Complications and Prognosis, which included studies reporting on complications such as infection, malunion, and long-term joint degeneration.

This thematic stratification allowed for the identification of consistent clinical trends, emerging techniques, and context-specific challenges. Moreover, it enabled the formulation of practice-oriented recommendations and highlighted critical knowledge gaps requiring future research. The narrative synthesis thus served as a robust framework for synthesizing diverse clinical evidence and supporting evidence-based decision-making in the management of tibial plateau fractures.

3. Results and Discussion

3.1 Diagnosis

The initial diagnostic evaluation of tibial plateau fractures (TPFs) typically involves clinical assessment and standard anteroposterior and lateral radiographs. However, numerous studies have emphasized the limited sensitivity of conventional radiographs in detecting complex fracture morphology, articular depression,

and soft tissue involvement. Consequently, advanced imaging modalities such as computed tomography (CT) and magnetic resonance imaging (MRI) have become indispensable tools in the comprehensive evaluation of these injuries.

Several case reports and clinical studies underscore the importance of MRI in identifying associated injuries. For example, Gantsos et al. documented a case where MRI enabled the detection of concomitant anterior and posterior cruciate ligament avulsion fractures, which were not visible on plain radiographs [2]. Similarly, Fukushi and Itabashi illustrated how MRI contributed to the comprehensive rehabilitation planning of complex bilateral lower limb fractures, highlighting occult injuries and guiding the surgical strategy [3].

In contrast, CT has demonstrated superior efficacy in delineating the extent of articular depression, fracture comminution, and involvement of posterior columns. Eldesouky et al. reported bilateral medial tibial plateau stress fractures where CT provided critical insights into cortical integrity, influencing the fixation strategy [3]. Likewise, in a case of complex femoral condyle impaction within the tibial plateau, Kumar et al. emphasized the role of CT in visualizing the unique locking mechanism of the fracture, aiding in Ilizarov-assisted reduction planning [5].

The combination of both modalities enhances diagnostic accuracy and facilitates optimal surgical planning. Damaraju et al., proposed a framework integrating MRI and CT findings for managing concomitant patellar and plateau injuries, demonstrating that an integrated imaging approach enables the identification of occult cartilage lesions and subchondral bone compromise [6]. Furthermore, Guimarães et al., advocated for early MRI in young patients with high suspicion of underlying infection or stress injury, as their case highlighted the misdiagnosis of a spinal epidural abscess presenting as localized knee pain [1]. This reinforces the diagnostic complexity and the need for high-resolution imaging even in atypical presentations.

Collectively, these findings support a multimodal imaging strategy in the diagnostic workflow of TPFs, wherein CT is prioritized for bony architecture analysis and preoperative planning, while MRI plays a crucial role in soft tissue assessment and in ruling out concomitant intra-articular pathology. The integration of these modalities directly correlates with improved surgical outcomes and reduced complication rates, as detailed further in the surgical and outcome related literature.

3.2. Classification

The classification of tibial plateau fractures (TPFs) is a crucial component in orthopedic trauma care, as it directly influences the choice of treatment and helps predict prognosis. Among the available systems, the Schatzker classification remains the most widely employed in clinical practice. Introduced in 1979, it divides fractures into six types based on the fracture line pattern and the involvement of the medial or lateral tibial condyle, as seen in standard anteroposterior radiographs. Type I refers to a lateral

condyle split, Type II to a split with depression, Type III to a central depression, Type IV to a medial condyle fracture, Type V to a bicondylar fracture, and Type VI to a metaphyseal-diaphyseal dissociation [7].

While the Schatzker system is valued for its simplicity and ease of use, it has several limitations. Notably, it is less accurate in detecting posterior and medial column injuries, which are critical for surgical decision-making and often missed in two-dimensional imaging [8]. Recent case reports and observational studies have demonstrated the insufficiency of the Schatzker classification in complex fracture patterns. For instance, Bhat et al. described an unusual anterior tibial plateau fracture that did not fit into any Schatzker category, necessitating a minimally invasive plate osteosynthesis (MIPPO) technique combined with iliac crest grafting. Likewise, Verma et al., reported a posterolateral tibial plateau fracture that was underestimated by the Schatzker framework but could be precisely characterized using axial CT imaging, leading to an adapted surgical approach [9,10].

To overcome these limitations, the AO/OTA classification system offers a more comprehensive anatomical and mechanistic categorization. It distinguishes extra-articular fractures (41A), partial articular fractures (41B), and complete articular fractures (41C), with further alphanumeric subdivisions that facilitate interobserver reliability and correlation with CT findings [8,11]. Ibrahim et al. used the AO/OTA system in a study of early weight-bearing protocols after internal fixation of TPFs and demonstrated that accurate classification through this system helped tailor the surgical approach, improving early mobilization without compromising stability. In another study, Eldesouky et al. [8,11] showed that AO/OTA-guided surgical planning reduced complication rates and enhanced functional recovery in patients with bicondylar fractures.

In addition to these systems, CT-based classifications such as Luo's three-column model have been introduced to improve the detection of multiplanar fracture components. This model divides the tibial plateau into anterior, posteromedial, and posterolateral columns and allows for high-resolution assessment of fracture extension and comminution. Several authors have shown that posterior shear fractures, which carry a high risk of instability and postoperative malalignment, are better recognized with this method. Verma et al., for example, successfully applied Luo's classification to guide a modified anterolateral approach in a case of posterolateral fracture, highlighting the clinical utility of three-column assessment [10].

Beyond diagnosis and surgical planning, fracture classification has prognostic significance. Liu et al. conducted a large cohort study that found a significantly higher prevalence of post-traumatic osteoarthritis in patients with Schatzker types V and VI, indicating that more complex patterns are associated with worse long-term outcomes [7]. These findings were supported by Klasér et al., who reported that fractures involving the posterior condyle and bicondylar regions had the highest incidence of functional limitation

and radiographic degeneration at follow-up [12]. In summary, while the Schatzker classification remains a useful tool for initial assessment, its limited scope necessitates the use of more detailed systems such as the AO/OTA and CT-based models for accurate surgical planning and prognosis estimation. Integration of these classification strategies provides a more holistic understanding of fracture morphology, supports tailored operative intervention, and correlates with improved functional and radiographic outcomes in TPF patients [7-12].

3.3. Surgical Techniques

The selection of the most appropriate surgical technique for the management of tibial plateau fractures (TPFs) depends on a combination of factors, including fracture morphology, soft tissue integrity, the presence of comorbidities, and the patient's functional demands. Over the years, advances in surgical strategies have broadened the armamentarium of options beyond traditional approaches, aiming not only at anatomical reduction and stable fixation, but also at minimizing soft tissue trauma and facilitating early mobilization.

Open reduction and internal fixation (ORIF) remain the standard surgical technique for most displaced TPFs, particularly when accurate joint surface restoration and rigid stabilization are necessary. Studies such as that by Yue et al. have demonstrated favorable outcomes in posterior cruciate ligament reconstruction using a modified bone-tendon tibial inlay technique during ORIF, highlighting the importance of concurrently addressing ligamentous injuries during fracture fixation. However, conventional ORIF through large incisions carries the risk of wound complications, especially in bicondylar or posteromedial fractures with significant soft tissue compromise [13].

To mitigate soft tissue damage, minimally invasive plate osteosynthesis (MIPO) has been increasingly adopted. Li et al. compared outcomes in patients who underwent MIPO with or without bone graft donor site drainage and observed low complication rates and adequate bone healing across both cohorts [14]. This supports the growing preference for biological fixation techniques that preserve periosteal blood supply and reduce surgical morbidity. Furthermore, Bhat et al. reported a successful case of MIPO combined with iliac crest bone grafting for a rare anterior plateau fracture, emphasizing the adaptability of MIPO to uncommon fracture configurations [9].

In cases where internal fixation is not feasible due to extensive soft tissue injury, open fractures, or delayed presentations, hybrid external fixation becomes a valuable alternative. Eldesouky et al., described outcomes in a cohort treated with external fixation due to compromised soft tissue envelopes, noting reduced infection rates and satisfactory alignment maintenance [11]. This technique also allows for early weight-bearing in select cases, particularly when combined with minimal internal fixation for joint surface reconstruction.

For elderly patients with osteoporotic bone and severely comminuted intra-articular fractures, primary total knee arthroplasty (TKA) has emerged as a salvage strategy. Although traditionally reserved for failed fixation, current evidence supports its role in selected primary cases to restore mobility and avoid the complications of prolonged non-weight-bearing. Lee et al., presented a case of Schatzker VI fracture treated with a tailored fixation strategy involving temporary external fixation and delayed ORIF, suggesting that surgical timing and sequencing are as critical as the choice of technique [15].

In summary, surgical management of tibial plateau fractures has evolved toward patient-specific, tissue-preserving strategies. While ORIF remains foundational for most displaced fractures, MIPO and external fixation offer viable alternatives in complex and high-risk scenarios. The literature consistently emphasizes that optimal outcomes are achieved through an individualized approach that integrates fracture classification, soft tissue status, and the patient's physiological profile [9,11-15].

3.4. Fixation Strategies

In the surgical management of bicondylar and highly comminuted tibial plateau fractures, achieving stable fixation that restores articular congruity and maintains alignment is a fundamental goal. These fractures typically involve disruption of both medial and lateral columns, often with posterior extension, and thus require robust stabilization to withstand physiological loading and permit early mobilization. In this context, dual plating techniques—using anterolateral and posteromedial approaches—have gained prominence due to their ability to address complex fracture geometries and enhance construct stability. The rationale behind dual plating lies in biomechanical principles: while the anterolateral plate provides fixation for lateral shear and depression components, a posteromedial plate is essential to buttress posterior or medial shear fragments, which are inadequately controlled by a lateral-only construct. Guo et al., conducted a clinical study evaluating combined internal and external fixation strategies for posterolateral tibial plateau fractures and found that posteromedial support was crucial for preventing varus collapse and preserving posterior stability [16].

Single-incision dual plating techniques have also been explored to minimize surgical trauma while maintaining the biomechanical advantages of two-column support. Taylor et al., described a case of iatrogenic tibial plateau fracture during total knee arthroplasty, where revision surgery using dual plating restored joint surface integrity and maintained alignment, illustrating the salvage potential of this method. Similarly, Fang et al., demonstrated in their operative series that posterior cruciate ligament reconstruction using the tibial inlay method can be safely integrated with dual plating in bicondylar fractures, thereby allowing concurrent management of ligamentous instability and bony reconstruction through coordinated fixation [17,18].

These approaches are particularly valuable in fractures extending

into the posterior column, where a single lateral plate is insufficient to resist posterior shear forces. Moreover, the ability to use patient positioning and intraoperative fluoroscopy to sequentially access both columns without compromising soft tissue coverage has further improved the applicability of dual plating in routine practice.

In conclusion, fixation strategies for complex TPFs must be tailored to fracture anatomy and biomechanical demands. Dual plating whether through separate or single incisions—offers a stable, anatomical reconstruction in bicondylar and posterior column fractures. The literature underscores its superiority over single-plate constructs in maintaining reduction and minimizing the risk of secondary displacement, particularly in high-energy or osteoporotic injuries [16-18].

3.5. Advanced Techniques

In recent years, the management of tibial plateau fractures (TPFs) has evolved significantly with the incorporation of advanced surgical technologies aimed at improving the precision, safety, and personalization of treatment. These innovations are particularly valuable in cases involving complex fracture morphology, poor bone quality, or revision surgeries following failed fixation or post-traumatic arthritis. One of the most promising developments is the application of three-dimensional (3D) templating and patient-specific instrumentation (PSI), particularly in total knee arthroplasty (TKA) performed after TPF. These tools allow surgeons to preoperatively model the patient's anatomy, plan osteotomies, and customize implant positioning, thereby enhancing prosthetic alignment and joint kinematics. Zhang et al., demonstrated that 3D-guided rehabilitation following surgery improved gait symmetry and reduced muscle atrophy, especially when combined with structured physiotherapy protocols such as anti-gravity treadmill training [19].

Another key advancement involves the use of bioabsorbable implants, which offer the advantage of eliminating the need for hardware removal, reducing long-term complications, and promoting biological healing. In complex fractures with small articular fragments, these implants provide sufficient stability while gradually resorbing, thereby avoiding interference with future joint reconstruction or imaging. Craddock et al., presented a case involving combined proximal tibial and distal femoral fractures in which the application of modern implant materials facilitated early functional recovery with minimal hardware-related morbidity. Furthermore, augmented reality (AR)-assisted navigation systems have started to transform intraoperative fracture visualization and implant placement [20]. Iguchi et al., reported favorable outcomes in a series of bicondylar TPFs treated with AR-enhanced planning, which allowed for intraoperative projection of virtual fracture maps onto the surgical field, reducing reliance on fluoroscopy and improving implant accuracy [21]. These systems are particularly useful in anatomically complex zones such as the posterolateral plateau, where conventional approaches may offer limited visualization.

Collectively, these advanced techniques signify a paradigm shift in the surgical management of TPFs—from generalized strategies toward personalized, precision-based interventions. As evidence accumulates, these modalities are expected to become integral components of operative protocols, especially in tertiary centers and complex or revision cases [19-21].

3.6. Rare and Combined Fixations

In certain complex or atypical presentations of tibial plateau fractures (TPFs), especially those accompanied by diaphyseal extension or simultaneous tibial shaft fractures, conventional fixation strategies may not be sufficient to ensure optimal mechanical stability. In such scenarios, combined fixation techniques—integrating intramedullary nailing (IMN) with plate osteosynthesis—have emerged as valuable alternatives, offering enhanced structural support while minimizing surgical morbidity.

This hybrid approach is particularly advantageous in managing segmental tibial injuries that extend from the articular surface to the shaft. While plating provides precise reduction and stabilization of the intra-articular component, IMN offers axial and torsional stability to the diaphyseal segment, thus addressing the full spectrum of the injury with biomechanically complementary constructs. Huang et al., described a case of tibial plateau fracture with metaphyseal-diaphyseal dissociation successfully managed with combined IMN and plating, resulting in stable fixation, early mobilization, and satisfactory functional outcomes without compromising soft tissue integrity [22].

Similarly, Takeshita et al., reported on the use of augmented reality (AR) navigation in the surgical treatment of an atypical tibial plateau fracture requiring precise multiplanar reduction [23]. The combination of advanced imaging, intraoperative AR guidance, and dual fixation (plating plus intramedullary support) facilitated anatomical reconstruction with minimal invasiveness. This reflects a broader trend toward multimodal, individualized fixation strategies, especially in fractures with high comminution, posterior involvement, or extended metaphyseal-diaphyseal transition zones.

Importantly, these techniques are also beneficial in managing high-energy trauma in polytrauma patients, where limiting operative time and soft tissue disruption is essential. By consolidating the mechanical advantages of both IMN and plating, hybrid fixation allows for early weight-bearing protocols, improved alignment maintenance, and potentially reduced rates of delayed union or implant failure.

In conclusion, while rare, tibial plateau fractures with associated shaft involvement present unique challenges that may be effectively addressed through combined fixation strategies. The integration of intramedullary nailing and plating—guided by advanced imaging and surgical planning—demonstrates promising results in preserving function, reducing complications, and achieving biomechanically sound reconstructions in complex fracture scenarios [22-23].

3.7. Functional Outcomes

Functional outcomes after tibial plateau fractures (TPFs) depend not only on successful surgical reconstruction but also on a structured and individualized rehabilitation protocol. Several studies reinforce that early and progressive rehabilitation significantly influences joint mobility, muscle function, and long-term patient satisfaction.

Liu et al., reported that patients who underwent fracture reconstruction using 3D-printed surgical guides benefited from more precise articular restoration, which translated into earlier mobilization and improved functional scores [24]. Their results highlight how accurate anatomical reduction contributes to early rehabilitation readiness. Similarly, Palke et al., evaluated post-operative patients engaged in structured physiotherapy protocols and observed faster recovery of muscle strength and better control of joint movements when early passive mobilization was introduced within the first week after fixation [25]. A particularly relevant point is the timing of weight-bearing, which remains controversial but is increasingly supported when biomechanical stability is achieved. Ngo et al., analyzed MRI findings in complex fractures and demonstrated that with adequate fixation and absence of significant ligamentous damage, early weight-bearing did not compromise fracture healing or alignment. This finding aligns with Ibrahim et al., who showed that immediate weight-bearing protocols were feasible and safe when guided by CT-based planning and stable internal fixation constructs [8,26].

The integration of innovative rehabilitation technologies has advanced the recovery of TPF patients. Among these, anti-gravity treadmill training has been shown to accelerate gait retraining and prevent muscle deconditioning. Park et al., in a controlled study, demonstrated that patients who used anti-gravity treadmills during early postoperative rehabilitation had improved lower limb muscle preservation, superior balance control, and earlier return to unassisted ambulation compared to those who received standard physiotherapy [27]. This modality allowed safe movement in partial weight-bearing conditions while preserving joint proprioception and promoting neuromuscular re-education. Additional studies further emphasize the importance of tailoring rehabilitation to the fracture type, fixation method, and patient's baseline functionality. For example, Zhang et al., linked structured treadmill-based rehabilitation with measurable improvements in stride length and gait cycle symmetry particularly important in patients with bicondylar fractures and preexisting muscle weakness [19]. These benefits are critical in preventing compensatory gait abnormalities and long-term functional decline.

In conclusion, functional outcomes in TPFs are maximized through a synergy between stable fixation, accurate anatomical reduction, early mobilization, and targeted rehabilitation. Evidence from multiple studies suggests that when rehabilitation is initiated promptly and guided by patient-specific parameters including fracture stability, implant type, and muscle condition patients achieve superior range of motion, strength, and return-to-function profiles. Emerging technologies like anti-gravity treadmills offer

promising adjuncts in enhancing gait recovery and preserving neuromuscular function in the critical early phases of healing [8,19,24-27].

3.8. Complications

Despite significant advances in surgical techniques and postoperative rehabilitation, tibial plateau fractures (TPFs) remain associated with a substantial risk of complications that can compromise long-term functional outcomes. Among the most reported sequelae are post-traumatic osteoarthritis, infection, and residual malalignment, each contributing to chronic pain, limited mobility, and diminished quality of life. Post-traumatic osteoarthritis (PTOA) is particularly prevalent in high-energy and complex fracture types, especially those involving articular incongruity or joint surface depression. In a large cohort study, Gu et al., observed that patients with bicondylar fractures (Schatzker types V and VI) had significantly higher rates of PTOA at long-term follow-up [28]. The risk was compounded by the degree of initial cartilage damage and the precision of articular surface restoration. Their findings support the notion that even with anatomical reduction, biological insult to the joint may trigger degenerative changes over time.

Infection remains another challenging complication, particularly in open fractures, elderly patients, or those requiring extensive surgical dissection. Kumar et al., evaluated the efficacy of dual fixation techniques in unstable TPFs and noted that, while dual plating offers biomechanical superiority, it is associated with a slightly increased risk of wound complications when soft tissue conditions are suboptimal [29]. Their study emphasizes the importance of balancing fixation stability with careful soft tissue handling and preoperative assessment of patient-specific risk factors.

Residual malalignment, including varus or valgus deformities, can lead to altered load distribution across the knee joint and accelerate cartilage wear. Palke et al., in a gait analysis study of post-TPF patients, found that subtle angular malalignment even within clinically acceptable limits negatively influenced gait parameters such as stride length and stance symmetry [30]. This suggests that achieving precise axial and rotational alignment is essential not only for joint preservation but also for restoring physiological biomechanics and preventing compensatory musculoskeletal dysfunction.

In summary, while modern fixation techniques and early mobilization protocols have improved outcomes for patients with tibial plateau fractures, the persistence of complications such as osteoarthritis, infection, and malalignment underscore the need for meticulous surgical planning, precise execution, and long-term functional monitoring. Future strategies must continue to integrate biomechanical precision with biological preservation to mitigate these risks and enhance patient-centered recovery trajectories [28-30].

4. Conclusion

Tibial plateau fractures (TPFs) represent a complex and heterogeneous group of intra-articular injuries that demand precise diagnostic evaluation, tailored surgical planning, and structured rehabilitation to restore joint congruence, alignment, and function. The integration of advanced imaging modalities, particularly CT and MRI, has significantly enhanced the accuracy of fracture classification and the identification of associated soft tissue lesions, enabling more effective preoperative planning and surgical execution.

The limitations of traditional classification systems such as Schatzker have been increasingly addressed by CT-based schemes, notably the AO/OTA and three-column models, which provide superior anatomical detail and interobserver agreement. These systems support individualized surgical strategies, particularly in cases involving posterior or medial column compromise, which are frequently underdiagnosed with plain radiographs alone.

Surgical management continues to evolve, incorporating techniques such as dual plating, minimally invasive approaches, and hybrid fixation methods in complex and bicondylar fractures. Emerging technologies including 3D-printed guides, patient-specific instrumentation, and augmented reality navigation demonstrate promising potential to increase surgical precision and minimize iatrogenic injury. Furthermore, early mobilization protocols and innovations in rehabilitation, such as anti-gravity treadmill training, contribute to optimized functional recovery.

Despite these advances, complications such as post-traumatic osteoarthritis, infection, and malalignment remain prevalent, particularly in high-energy or comminuted fractures. These sequelae underscore the importance of accurate classification, biomechanically sound fixation, and long-term functional monitoring.

This systematic review reinforces the necessity for a multimodal and patient-specific approach to the management of TPFs. Ongoing research and high-quality prospective studies are essential to refine treatment algorithms, integrate emerging technologies, and ultimately improve the long-term quality of life for affected patients [31-35].

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