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Management of Complex Fractures: Modern Approaches, Patient Outcomes, and Evolving Strategies

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Abstract

Introduction and Purpose: Complex fractures represent a significant challenge in orthopedic trauma, requiring sophisticated surgical techniques, multidisciplinary collaboration, and innovative fixation methods to optimize patient outcomes. This comprehensive review synthesizes current evidence on the management of complex fractures, focusing on modern surgical approaches, fixation innovations, patient outcomes, complications, and evolving treatment strategies.
Description of the State of Knowledge: A narrative review was conducted across multiple databases, yielding 69 high-quality papers published primarily between 2020-2025, with selected seminal earlier studies included. Evidence was synthesized from systematic reviews, meta-analyses, randomized controlled trials, and prospective cohort studies addressing complex fracture management. Modern management emphasizes orthoplastic collaboration, minimally invasive techniques, and technological innovations including 3D printing, robotic-assisted surgery, and advanced imaging. Orthoplastic approaches demonstrate reduced infection rates (2.4-37%), with reported union rates ranging from >80% to near-complete union in selected series, and enhanced functional outcomes. Three-dimensional printing technology significantly reduces operative time, blood loss, and fluoroscopy use while improving anatomical reduction. Minimally invasive plate osteosynthesis achieves excellent functional outcomes in 65% of cases with rapid union rates. Complications remain a concern, with infection rates varying from 2.4% to 20% depending on fracture severity and management approach.
Summary (Conclusions): Contemporary complex fracture management requires integrated multidisciplinary care, selective application of innovative technologies, and individualized treatment strategies. Future directions include artificial intelligence integration, personalized implant design, and enhanced biological augmentation strategies.

Keywords: complex fractures; orthoplastic surgery; minimally invasive fixation; 3D printing; patient outcomes; multidisciplinary care

1. Introduction

Complex fractures represent a formidable challenge in orthopedic trauma care, characterized by severe bone comminution, articular involvement, soft tissue compromise, and frequently occurring in polytrauma settings [1], [2]. Recent epidemiological data indicate that the global burden of fractures has increased significantly, with over 178 million new fractures reported worldwide in 2019, highlighting the urgent need for effective management strategies [29]. These injuries demand surgical expertise, multidisciplinary collaboration, and innovative treatment strategies to achieve optimal functional restoration and minimize complications [3], [4].

The definition of “complex” encompasses multiple dimensions: fracture pattern complexity (comminution, intra-articular extension, bone loss), anatomical location (periarticular, metaphyseal), soft tissue injury severity (Gustilo-Anderson classification for open fractures), and patient-specific factors (age, comorbidities, polytrauma) [5], [6]. The increasing prevalence of fragility fractures in the aging population further exacerbates the complexity of care, placing a substantial economic burden on healthcare systems [30].

The past decade has witnessed remarkable advances in complex fracture management, driven by technological innovation, refined surgical techniques, and enhanced understanding of biological healing processes [7], [8]. Three-dimensional printing technology has revolutionized preoperative planning and enabled customized implant fabrication [9], [10]. Minimally invasive approaches have gained prominence, preserving soft tissue envelope and periosteal blood supply while achieving stable fixation [11]. Orthoplastic collaboration has emerged as a paradigm shift, recognizing that optimal outcomes require coordinated management of both skeletal and soft tissue components [3], [4], [12].

Despite these advances, complex fractures continue to pose significant challenges. Complication rates remain substantial, with infection, nonunion, malunion, and functional impairment affecting patient outcomes and healthcare costs [13], [14]. The financial impact of complications such as nonunion is profound, often doubling the cost of treatment compared to uncomplicated healing [31]. The heterogeneity of fracture patterns, variability in soft tissue injury, and diversity of patient populations necessitate individualized treatment algorithms rather than standardized protocols [15], [16]. Furthermore, the optimal timing of definitive fixation, choice of fixation method, and role of emerging technologies remain areas of active investigation and debate [17], [18].

This comprehensive review synthesizes current evidence on complex fracture management, examining modern surgical approaches, fixation innovations, patient outcomes, complications, and evolving treatment strategies. By integrating findings from systematic reviews, meta-analyses, randomized controlled trials, and prospective cohort studies, we aim to provide clinicians with evidence-based guidance for managing these challenging injuries while identifying critical knowledge gaps and future research directions.

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2. Classification and Definition of Complex Fractures

Complex fractures defy simple categorization, encompassing a spectrum of injury patterns that challenge conventional classification systems. The term “complex” refers to fractures characterized by one or more of the following features: severe comminution with multiple fragments, intra-articular involvement with joint surface disruption, significant bone loss requiring reconstruction, associated soft tissue injury compromising vascularity and healing potential, and occurrence in anatomically challenging locations such as periarticular regions [1], [5], [19].

The AO/OTA (Arbeitsgemeinschaft für Osteosynthesefragen/Orthopaedic Trauma Association) classification system provides a standardized framework for describing fracture patterns, with Type C fractures representing the most complex injuries involving complete articular disruption [20]. For tibial plateau fractures, the Schatzker classification identifies Types V and VI as complex patterns involving both condyles with metaphyseal-diaphyseal dissociation [21]. The three-column concept for tibial plateau fractures—dividing the plateau into lateral, medial, and posterior columns—has enhanced surgical planning by recognizing the importance of posterior column involvement in complex patterns [21].

Open fractures are classified using the Gustilo-Anderson system, with Grade III injuries representing severe soft tissue damage that significantly impacts treatment strategy and prognosis [13], [3]. Grade IIIA fractures have adequate soft tissue coverage despite extensive laceration, Grade IIIB injuries require flap coverage due to periosteal stripping and bone exposure, and Grade IIIC fractures involve arterial injury requiring vascular repair [3]. This classification directly influences the need for orthoplastic collaboration and timing of definitive fixation [4], [12].

Proximal humerus fractures are classified using the Neer system, with three-part and four-part fractures representing complex patterns that may require arthroplasty rather than fixation in elderly patients with poor bone quality [22]. The AO classification for proximal humerus fractures (Types 11-B and 11-C) identifies increasingly complex patterns with metaphyseal comminution and articular involvement [5]. Distal femoral fractures classified as AO/OTA 33-C represent complex intra-articular injuries requiring specialized fixation strategies [20].

Pelvic fractures in polytrauma patients, particularly those involving sacral disruption and multiple ring injuries, represent some of the most complex fractures encountered in trauma care [2]. The Young-Burgess classification (lateral compression, anteroposterior compression, vertical shear, combined mechanism) and the Tile/AO classification (Types A, B, C based on pelvic ring stability) guide treatment decisions [2]. Fragility fractures of the pelvis (FFP) in elderly patients, classified by the Rommens system (Types I-IV), represent an increasingly recognized complex fracture pattern requiring specialized management approaches [23].

The concept of “complex” also encompasses fractures occurring in specific patient populations that complicate management: polytrauma patients requiring damage control orthopedics [1], [2], elderly patients with osteoporotic bone and multiple comorbidities [24], and high-performance athletes requiring rapid return to competition.

Additionally, fractures with significant bone loss (>2 cm segmental defects), those requiring bone grafting or bone transport techniques, and fractures with associated neurovascular injury all fall within the complex fracture spectrum [1].

Understanding these classification systems and recognizing the multidimensional nature of fracture complexity is essential for treatment planning, prognostication, and communication among multidisciplinary team members involved in complex fracture care [5], [15].

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3. Modern Surgical Approaches and Techniques

3.1 Orthoplastic Collaboration

The orthoplastic approach represents a paradigm shift in managing complex fractures with significant soft tissue injury, emphasizing coordinated care between orthopedic and plastic surgeons from initial assessment through definitive reconstruction [3], [4], [12]. This collaborative model recognizes that optimal outcomes require simultaneous attention to skeletal stability and soft tissue coverage, rather than sequential management [13].

A landmark prospective multicenter cohort study of 160 patients with severe open tibial fractures demonstrated that orthoplastic collaboration significantly improved all outcome measures compared to traditional exclusively orthopedic treatment [4]. The study found that 70% of patients managed with an orthoplastic approach achieved superior fracture healing, soft tissue reconstruction, and functional recovery across different socioeconomic settings. This coordinated pathway successfully delivered better patient outcomes by integrating expertise in skeletal fixation and soft tissue reconstruction from the initial surgical intervention [4].

For Gustilo-Anderson Grade III upper limb injuries, a systematic review of five studies encompassing 196 patients demonstrated that combined ortho-plastic approaches achieved limb salvage rates up to 100%, reduced deep infection rates to as low as 2.4%, and achieved union rates up to 84.3% [3]. Early intervention within 72 hours was identified as a critical factor, with both single-stage and staged procedures yielding positive results when vascularized flap coverage was employed [3]. The review emphasized that early multidisciplinary care optimizes outcomes by preventing infection, maintaining tissue viability, and promoting bone healing through stable soft tissue coverage [3].

A systematic review and meta-analysis comparing orthoplastic to nonorthoplastic management of lower extremity trauma (1663 orthoplastic patients versus 692 nonorthoplastic patients) found that orthoplastic management significantly decreased time to bone fixation (standard mean difference: -0.35), reduced use of negative pressure wound therapy (risk ratio: 0.03), decreased reliance on healing by secondary intention (risk ratio: 0.02), and reduced risk of wound and osteomyelitis infections (risk ratio: 0.37) [13]. Notably, orthoplastic management resulted in increased use of free flaps (risk ratio: 3.46), reflecting the emphasis on definitive soft tissue coverage rather than temporizing measures [13].

For distal tibia high-energy fractures, a systematic review of 14 studies (283 patients) demonstrated that combining circular external fixators with reconstructive flap procedures achieved excellent outcomes [1]. The orthoplastic team approach resulted in low rates of complete flap loss (3/283 patients), low nonunion rates with successful salvage after reintervention, and minimal major complications despite bone loss ranging from 0.7 to 18.2 cm and soft tissue defects between 3×3 cm and 16×21 cm [1]. The Ilizarov external fixator proved particularly advantageous as it does not damage the flap pedicle and helps stabilize both soft tissues and bone around the reconstruction [1].

The orthoplastic approach extends beyond technical surgical coordination to encompass shared decision-making, joint preoperative planning, simultaneous operative intervention when appropriate, and integrated postoperative care [12]. This model has been successfully implemented across diverse healthcare settings, demonstrating feasibility and effectiveness in both resource-rich and resource-limited environments [4]. The key principles include early combined assessment, realistic goal-setting regarding limb salvage versus amputation, coordinated timing of skeletal fixation and soft tissue coverage, and ongoing collaborative management of complications [3], [4], [13].

3.2 Minimally Invasive Techniques

Minimally invasive plate osteosynthesis (MIPO) has emerged as a preferred technique for managing comminuted fractures of long bones, preserving soft tissue envelope and periosteal blood supply while achieving stable fixation [11]. A prospective study of 24 patients with severely comminuted fractures of the femur, tibia, and humerus demonstrated that MIPO achieved rapid union in 15 cases, with only two cases requiring secondary bone grafting for delayed consolidation [11]. Functional outcomes were excellent in 65% of cases and good in 30% using the Neer-Grantham-Shelton Criteria [11]. Complication rates included infection (5%), wound gaping (5%), joint stiffness (25%), and limb length discrepancy (20%), demonstrating the technique's safety profile [11].

The fundamental principle of MIPO involves shifting from anatomic reduction to achieving optimal stability through biological fixation [11]. By preserving the soft tissue envelope and avoiding extensive periosteal stripping, MIPO maintains the biological environment necessary for fracture healing while providing sufficient mechanical stability [12]. This approach is particularly advantageous in complex fractures where extensive soft tissue dissection would further compromise already tenuous vascularity [11].

A systematic review examining innovations in surgical techniques and advanced imaging for long bone fractures found that minimally invasive procedures lead to fewer postoperative complications and quicker convalescence compared to traditional open approaches [15]. The review highlighted that computer-assisted surgery and augmented reality serve as useful adjuncts for preoperative planning and intraoperative navigation in minimally invasive procedures, though widespread adoption remains limited by costs and initial technical difficulties [15].

For distal femoral fractures, minimally invasive techniques using lateral locking plates have demonstrated comparable outcomes to more invasive dual-plating approaches [20]. A retrospective analysis of 78 patients comparing retrograde intramedullary nailing combined with lateral locking plate versus dual plating found no significant differences in blood loss, operative time, time to weight-bearing, bone healing time, pain scores, functional scores, or complication rates [20]. Both approaches provided stable constructs and satisfactory functional outcomes, suggesting that less invasive single-plate techniques may be sufficient for many complex distal femoral fractures [20].

The success of minimally invasive techniques depends on adequate preoperative planning, appropriate patient selection, and surgeon experience with indirect reduction techniques [11], [15]. Advanced imaging including computed tomography and intraoperative fluoroscopy plays a critical role in achieving and confirming adequate reduction without direct visualization [15]. The learning curve for MIPO techniques is significant, requiring proficiency in indirect reduction maneuvers and fluoroscopic interpretation [11].

3.3 Arthroscopic-Assisted Reduction

Arthroscopic-assisted reduction internal fixation (ARIF) has gained prominence in managing complex intra-articular fractures, particularly tibial plateau fractures, by providing superior visualization of articular surfaces and enabling more accurate reduction compared to open techniques [19]. A systematic review of four case-control studies including 261 patients consistently found that ARIF yielded higher functional scores compared to open reduction internal fixation (ORIF) [19]. The review demonstrated superior IKDC, Lysholm, and KSS scores with ARIF, suggesting enhanced visualization and more accurate reduction lead to better functional outcomes and potentially faster postoperative recovery [19].

The advantages of arthroscopic assistance include direct visualization of articular surface reduction, identification and treatment of associated meniscal and ligamentous injuries, thorough joint lavage to remove debris and hematoma, and minimized soft tissue disruption compared to extensile open approaches [19]. These benefits are particularly relevant in complex tibial plateau fractures where articular congruity is critical for long-term joint function and prevention of post-traumatic arthritis [21], [19].

However, arthroscopic-assisted techniques require specialized equipment, surgeon expertise in both arthroscopy and fracture fixation, and may increase operative time compared to standard open techniques [19]. Patient selection is important, as severely comminuted fractures with extensive metaphyseal involvement may not be amenable to arthroscopic reduction [21]. The technique is most applicable to Schatzker Types I-IV fractures and selected Type V fractures where articular visualization is critical [19].

The integration of arthroscopic assistance with minimally invasive fixation techniques represents an evolution toward less invasive management of complex intra-articular fractures [19]. By combining superior articular visualization with preservation of extra-articular soft tissues, this approach optimizes both anatomical reduction and biological healing environment [11], [19].

4. Fixation Methods and Innovations

4.1 Three-Dimensional Printing Technology

Three-dimensional printing has revolutionized complex fracture management through enhanced preoperative planning, customized implant fabrication, and improved surgical precision [9], [10]. A meta-analysis of 13 randomized controlled trials including 673 patients demonstrated that 3D printing yielded significantly better perioperative results compared to conventional techniques [10]. The weighted effect sizes favored 3D printing for operative duration (effect size: -1.47), intraoperative blood loss (effect size: -1.41), and fluoroscopy use (effect size: -1.25) [10]. Additionally, 3D printing achieved superior odds ratios for overall good or excellent results (OR: 2.05) and anatomic fracture reduction (OR: 2.64) [10].

For complex tibial plateau fractures, a study evaluating 3D printing combined with customized plates demonstrated significant advantages [9]. The technology enables creation of patient-specific anatomical models for preoperative planning, allowing surgeons to understand complex three-dimensional fracture patterns, plan optimal surgical approaches, and pre-contour plates to match individual anatomy [9]. This preparation translates to reduced operative time, decreased radiation exposure, and improved reduction quality [9], [10].

A randomized controlled trial of 48 patients with complex distal intra-articular trimalleolar ankle fractures compared personalized custom-made steel plates created using 3D printing to conventional steel plates [10]. The personalized plate group exhibited significantly shorter surgical duration, reduced fracture reduction and internal fixation time, decreased intraoperative fluoroscopy frequency, and shorter surgical incision length (all $p < 0.001$) [10]. The personalized group showed higher rates of successful fracture reduction (87.5% versus 79.2%) and lower complication incidence (8.3% versus 20.8%), though these differences did not reach statistical significance [10]. Importantly, the personalized plate group demonstrated superior ankle joint function scores during follow-up ($p < 0.05$) [10].

Three-dimensional-printed pure titanium fracture plates with integrated locking screw systems represent an advanced application of this technology [9]. A case series of nine patients with distal tibia fractures treated with customized 3D-printed pure titanium plates demonstrated successful outcomes, with nine of ten plates remaining stable and undamaged [9]. Only one patient experienced plate fracture requiring revision surgery, and no screw loosening or surgical wound complications occurred [9]. The plates were produced using pure titanium powder spread to 30 μm thickness and partially sintered with a 500 W laser, with locking screws fabricated via milling process [9].

The applications of 3D printing in complex fracture management extend beyond implant fabrication to include patient-specific instrumentation, surgical guides for screw placement, and educational models for patient counseling and surgical training [9], [10]. However, widespread adoption faces barriers including cost, time required for model production, and need for specialized expertise in digital planning [15], [10]. Future developments may include bioprinting of bone scaffolds and integration with artificial intelligence for automated surgical planning [10].

4.2 Locking Compression Plates

Locking compression plates (LCPs) have become a cornerstone of complex fracture fixation, providing angular stability through the fixed-angle relationship between screws and plate, which is particularly advantageous in osteoporotic bone and periarticular fractures [24]. A case series evaluating LCPs for distal femoral fractures in 50 elderly patients demonstrated radiological union in all cases within an average of 12.7 weeks [24]. Functional recovery assessed by Knee Society Score was excellent for Type A fractures (KSS: 93), satisfactory for Type B (KSS: 88), and moderate for Type C (KSS: 80) [24]. Complication rates were low at 10%, with no cases of nonunion or deep infection [24].

The biomechanical advantages of locking plates include creation of a fixed-angle construct that functions as an internal fixator, reduced reliance on plate-bone friction and thus decreased need for precise plate contouring, preservation of periosteal blood supply through limited bone-plate contact, and enhanced stability in osteoporotic bone where conventional screw purchase is compromised [24]. These properties make LCPs particularly suitable for complex periarticular fractures in elderly patients where bone quality is poor and anatomic reduction may be difficult to achieve [24].

For complex tibial plateau fractures, three-column plate internal fixation using locking plates through antero-midline and postero-medial approaches achieved excellent outcomes in a case series of 28 patients [21]. All incisions healed primarily without complications, bone union occurred in 5 to 10 months (mean: 7.8 months), and mean HSS score was 89.35 ± 3.19, with 71.4% achieving excellent results [21]. The technique effectively achieved anatomic reduction, rigid internal fixation, and facilitated early functional exercise [21].

The evolution of locking plate technology includes development of polyaxial locking screws allowing variable screw angulation within the locking mechanism, far cortical locking screws that provide controlled interfragmentary motion to stimulate healing, and anatomically pre-contoured plates designed for specific fracture locations [24]. These refinements enhance the versatility and biological performance of locking plate constructs [24].

4.3 Intramedullary Fixation

Intramedullary fixation remains a fundamental technique for diaphyseal and selected metaphyseal fractures, providing load-sharing biomechanics and preserving soft tissue envelope

[11]. For distal femoral fractures, retrograde intramedullary nailing combined with lateral locking plate demonstrated outcomes equivalent to dual plating in a retrospective analysis of 78 patients [20]. The nail-plate combination provided stable constructs with no significant differences in blood loss, operative time, healing time, functional scores, or complication rates compared to dual plating [20]. No implant failures occurred in either group, demonstrating the reliability of combined nail-plate fixation for complex distal femoral fractures [20].

A systematic review of open fracture management identified early stabilization with intramedullary rods as improving functional outcomes [13]. The review emphasized that intramedullary fixation provides immediate stability while minimizing additional soft tissue trauma, which is particularly important in open fractures where soft tissue injury is already significant [13]. Early stabilization within 6 hours combined with broad-spectrum antibiotics significantly reduces infection risk [13].

For pediatric polytrauma patients with diaphyseal femur fractures, various fixation methods including flexible intramedullary nails, rigid intramedullary nails, plates, and external fixators have been employed [25]. The choice depends on patient age, fracture pattern, and associated injuries, with flexible nails preferred for younger children (5-10 years) and rigid nails or plates for older children (>11 years) [25]. Functional outcomes were satisfactory in 97.6% of cases, with full consolidation achieved in 95.2% [25].

The advantages of intramedullary fixation include load-sharing biomechanics that allow early weight-bearing, preservation of fracture hematoma and soft tissue envelope, and suitability for minimally invasive insertion [11], [13]. However, intramedullary devices may be less suitable for very proximal or distal metaphyseal fractures where adequate fixation length is difficult to achieve, necessitating supplemental plate fixation in some cases [20].

4.4 External Fixation Systems

External fixation plays multiple roles in complex fracture management, serving as definitive treatment in selected cases, temporary stabilization in damage control orthopedics, and adjunct to internal fixation in severe soft tissue injury [1], [28]. Circular external fixators, particularly the Ilizarov system, have proven effective for complex fractures with significant bone loss and soft tissue compromise [1].

A systematic review of 14 studies (283 patients) examining orthoplastic reconstruction of distal tibia high-energy fractures using circular external fixators demonstrated excellent outcomes [1]. The fixation period ranged from 4 to 22.74 months, with bone loss between 0.7 and 18.2 cm successfully managed [1]. The circular fixator combined with flap coverage (80 free flaps and 73 pedicled flaps) achieved low rates of complete flap loss (3/283 patients) and nonunion, with all nonunions successfully treated with reintervention [1]. The Ilizarov fixator proved advantageous as it does not damage the flap pedicle and helps stabilize soft tissues and bone around the reconstruction [1].

For complex proximal tibial fractures, a randomized controlled trial compared Ilizarov external fixation to open reduction internal fixation [28]. Both techniques achieved satisfactory outcomes, though specific comparative results were not detailed in the available metadata [28]. External fixation offers advantages in severely contaminated open fractures where internal hardware placement risks infection, and in polytrauma patients where rapid stabilization is needed before definitive fixation [1], [28].

The principles of external fixation include achieving stability through pins or wires connected to an external frame, allowing access to soft tissues for wound care and reconstruction, and enabling gradual correction of deformity or bone transport for segmental defects [1]. Modern external fixation systems include monolateral frames for temporary stabilization, circular frames for definitive treatment and bone transport, and hybrid constructs combining both approaches [1], [28].

4.5 Robotic-Assisted Reduction

Robotic-assisted fracture reduction represents an emerging technology with potential to enhance precision and reproducibility in complex fracture management [23]. A single-center case series of 15 patients with displaced fragility fractures of the pelvis (Rommens FFP Type III) evaluated a robot-assisted fracture reduction system comprising tracking device, path planning software, and robotic arms [23].

The robot-assisted reduction and internal fixation (RARIF) achieved a 100% success rate, with all 15 patients showing excellent or good reductions per Matta criteria [23]. Operative times averaged 165 ± 44 minutes with median blood loss of 50 mL [23]. All fractures healed without complications, and 6-month follow-up revealed an average modified Majeed score of 81.4, with 85.7% of patients rated excellent or good [23]. The system optimizes force and direction during reduction, potentially reducing radiation exposure and surgeon fatigue while improving reduction accuracy [23].

The advantages of robotic assistance include precise control of reduction forces, reproducible reduction maneuvers, potential reduction in radiation exposure through decreased fluoroscopy time, and decreased physical demands on surgeons [23]. However, the technology requires significant capital investment, specialized training, and may increase operative time during the learning curve [23]. Current applications are limited to specific fracture patterns and anatomical locations, with pelvic fractures representing an ideal application due to complex three-dimensional anatomy and difficulty of manual reduction [23].

Future developments in robotic-assisted fracture surgery may include integration with preoperative 3D planning, real-time navigation systems, and artificial intelligence algorithms for optimal reduction strategies [23]. As the technology matures and costs decrease, broader applications across various fracture types may become feasible [23].

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5. Patient Outcomes and Prognostic Factors

5.1 Union Rates and Healing Times

Union rates represent a fundamental outcome measure in complex fracture management, with contemporary techniques achieving high success rates across diverse fracture patterns [1], [22], [24]. For distal femoral fractures in elderly patients treated with locking compression plates, radiological union was achieved in 100% of cases within an average of 12.7 weeks [24]. Complex tibial plateau fractures managed with three-column plate fixation achieved bone union in 5 to 10 months (mean: 7.8 months) with no cases of nonunion [21].

Minimally invasive plate osteosynthesis for comminuted long bone fractures demonstrated rapid union in 62.5% of cases (15/24 patients), with only 8.3% (2/24) requiring secondary bone grafting for delayed consolidation [11]. This high union rate despite severe comminution reflects the biological advantages of preserving soft tissue envelope and periosteal blood supply [11]. The study reinforces MIPO as a promising approach with excellent union rates, highlighting advantages in preserving soft tissue and periosteal circulation [11].

Orthoplastic management of severe open tibial fractures using circular external fixators achieved low nonunion rates, with all cases of nonunion successfully salvaged through reintervention [1]. Despite bone loss ranging from 0.7 to 18.2 cm, the combination of stable fixation and adequate soft tissue coverage promoted bone healing [1]. This demonstrates that even severe bone loss can achieve union when biological principles are respected and soft tissue coverage is adequate [1].

For complex proximal humerus fractures, union rates vary significantly based on treatment modality [22]. Open reduction and internal fixation achieved better clinical outcomes compared to hemiarthroplasty and reverse shoulder arthroplasty, though tuberosity nonunion remains a concern with arthroplasty procedures [24]. A comprehensive meta-analysis questioned whether arthroplasty procedures are truly superior for complex proximal humerus fractures, highlighting the importance of patient selection and fracture pattern in determining optimal treatment [22].

Factors influencing union rates include fracture pattern and comminution severity, soft tissue injury extent, fixation stability, patient age and comorbidities, smoking status, and timing of definitive fixation [1], [11], [24], [13]. Early stabilization combined with adequate soft tissue coverage optimizes the biological environment for healing [3], [4], [13]. Conversely, delayed fixation, inadequate soft tissue coverage, and unstable fixation increase nonunion risk [1], [13].

5.2 Functional Outcomes

Functional outcomes represent the ultimate measure of treatment success, reflecting patients' ability to return to activities of daily living, work, and recreation [11], [22], [24], [19]. For complex tibial plateau fractures treated with three-column plate fixation, mean HSS score was 89.35 ± 3.19, with 71.4% achieving excellent results, 17.9% good, 7.1% fair, and 3.6% poor [21]. No significant differences were found in tibial plateau angle, posterior slope angle, and femorotibial angle between immediate postoperation and one-year follow-up, indicating maintenance of anatomical alignment [21].

Minimally invasive plate osteosynthesis achieved excellent functional outcomes in 65% of cases, good in 30%, and fair in 5% using the Neer-Grantham-Shelton Criteria [11]. These results demonstrate that MIPO can achieve satisfactory function despite severe comminution, likely due to preservation of soft tissue envelope and early mobilization [11]. However, complications including joint stiffness (25%) and limb length discrepancy (20%) affected some patients, highlighting the importance of postoperative rehabilitation [11].

For distal femoral fractures in elderly patients treated with locking compression plates, functional recovery varied by fracture complexity [24]. Type A fractures achieved excellent KSS scores (93), Type B fractures satisfactory scores (88), and Type C fractures moderate scores (80) [24].

This gradient reflects the increasing difficulty of achieving anatomical reduction and stable fixation in more complex fracture patterns [24]. The study demonstrated that LCPs provide biomechanical stability and promote early mobilization, which is crucial for functional recovery in elderly patients [24].

Arthroscopic-assisted reduction internal fixation for tibial plateau fractures consistently yielded superior functional scores compared to open reduction internal fixation [19]. The systematic review demonstrated better IKDC, Lysholm, and KSS scores with ARIF, suggesting that enhanced visualization and more accurate articular reduction translate to improved long-term joint function [19]. This finding emphasizes the importance of anatomical articular reduction in achieving optimal functional outcomes [19].

For sacral fractures, a comparative study of open versus closed reduction found no significant differences in functional outcomes including sitting ability, standing ability, and sexual function between ORIF and CRIF techniques [17]. Both approaches achieved comparable functional recovery with low complication incidence, suggesting that technique selection should be based on fracture pattern and surgeon expertise rather than presumed functional superiority [17].

Prognostic factors for functional outcomes include quality of articular reduction, restoration of mechanical alignment, achievement of stable fixation allowing early mobilization, patient age and pre-injury functional status, presence of associated injuries, and compliance with rehabilitation protocols [22], [24], [19]. Elderly patients and those with multiple comorbidities generally achieve lower functional scores, reflecting both physiological limitations and reduced healing capacity [24].

5.3 Quality of Life Measures

Quality of life outcomes extend beyond traditional functional scores to encompass pain, psychological well-being, social participation, and patient satisfaction [23], [17]. For geriatric pelvic fractures managed with robot-assisted reduction, the modified Majeed score averaged 81.4 at 6-month follow-up, with 85.7% of patients rated excellent or good [23]. This outcome measure captures multiple dimensions including pain, work capacity, sitting ability, sexual function, and gait, providing a comprehensive assessment of recovery [23].

The orthoplastic approach to severe limb injuries has demonstrated improvements in all outcome measures including fracture healing, soft tissue reconstruction, and limb function recovery [4]. The prospective multicenter cohort study found that coordinated orthoplastic care delivered better patient outcomes across different socioeconomic settings, suggesting that the collaborative model enhances not only technical outcomes but also overall patient experience and satisfaction [4].

Pain management represents a critical component of quality of life after complex fractures [11], [17]. Studies evaluating various fixation techniques have reported pain using visual analog scales (VAS) and numerical rating scales, with most modern techniques achieving satisfactory pain control [11], [26], [17]. However, chronic pain remains a concern in some patients, particularly those with articular involvement or post-traumatic arthritis [19].

Return to work and recreational activities represents an important quality of life outcome, particularly in younger patients and athletes [26]. Functional treatment protocols for athletes with metatarsal fractures have demonstrated successful return to sports within three weeks, with no complaints after 13 months [26]. This rapid return reflects both the effectiveness of functional treatment and the importance of individualized rehabilitation protocols for high-performance athletes [26].

Psychological outcomes including depression, anxiety, and post-traumatic stress disorder are increasingly recognized as important components of recovery from severe trauma [4]. The multidisciplinary approach to complex fracture management should include psychological support and screening for mental health complications, particularly in patients with severe injuries, prolonged hospitalization, or multiple surgical procedures [4].

6. Complications and Their Management

6.1 Infection

Infection represents one of the most serious complications of complex fracture management, with rates varying from 2.4% to 20% depending on fracture severity, soft tissue injury, and management approach [3], [11], [13]. For Gustilo-Anderson Grade III upper limb injuries managed with combined ortho-plastic approaches, deep infection rates as low as 2.4% were achieved with early intervention within 72 hours [3]. This dramatic reduction compared to historical rates reflects the importance of early multidisciplinary care, adequate debridement, and prompt soft tissue coverage [3].

A systematic review of open fracture management found that early debridement within 6 hours combined with broad-spectrum antibiotics significantly reduces infection risk [13]. The review emphasized that prompt tissue coverage is crucial for preventing complications in high-grade fractures, with multidisciplinary management and personalized interventions essential for optimizing results [13]. Early stabilization, particularly with intramedullary rods, improves functional outcomes while minimizing infection risk [13].

Orthoplastic management of lower extremity trauma demonstrated significant reduction in wound and osteomyelitis infections (risk ratio: 0.37) compared to nonorthoplastic management [13]. This benefit likely reflects multiple factors including coordinated timing of skeletal fixation and soft tissue coverage, appropriate use of free flaps for definitive coverage rather than temporizing measures, and integrated postoperative care [13].

Minimally invasive plate osteosynthesis achieved low infection rates (5%) despite managing severely comminuted fractures [11]. The preservation of soft tissue envelope and periosteal blood supply likely contributes to this favorable infection profile by maintaining local immune function and vascularity [11]. However, when infection does occur in the setting of internal fixation, management is challenging and may require hardware removal, prolonged antibiotics, and staged reconstruction [11].

Prevention strategies for infection include meticulous surgical technique with gentle soft tissue handling, appropriate antibiotic prophylaxis and treatment, early definitive soft tissue coverage for open fractures, avoidance of excessive hardware and dead space, and careful patient selection for internal fixation in contaminated wounds [3], [13]. When infection occurs, management requires aggressive debridement, culture-directed antibiotics, assessment of fixation stability (stable hardware may be retained while unstable hardware should be removed), and consideration of staged reconstruction with temporary external fixation [13].

6.2 Nonunion and Malunion

Nonunion and malunion represent mechanical complications that compromise functional outcomes and may require revision surgery [1], [22], [24], [25]. For complex tibial plateau fractures managed with three-column plate fixation, no cases of nonunion were reported, though one case (2.4%) of malunion occurred [21]. The high union rate reflects the importance of achieving stable fixation and anatomical reduction [22].

In pediatric polytrauma patients with diaphyseal femur fractures, one case (2.4%) of nonunion and one case (2.4%) of malunion were observed, while 95.2% achieved full consolidation [25]. These low rates demonstrate that appropriate fixation selection based on patient age and fracture pattern can achieve excellent healing [25].

For orthoplastic reconstruction of distal tibia high-energy fractures using circular external fixators, the percentage of nonunion was low, and in all cases union was achieved after reintervention [1]. This finding demonstrates that even when initial healing is delayed, persistent treatment with appropriate biological and mechanical interventions can achieve union [1]. The combination of stable fixation and adequate soft tissue coverage creates an environment conducive to healing even in severe injuries [1].

Tuberosity nonunion remains a specific concern in proximal humerus fractures treated with hemiarthroplasty [24]. The systematic review of 92 studies including 4500 patients found that while arthroplasty may be necessary for unreconstructable fractures, tuberosity healing is unpredictable and significantly impacts functional outcomes [5]. This complication highlights the importance of secure tuberosity fixation and consideration of alternative treatments when possible [24].

Risk factors for nonunion include inadequate fixation stability, poor soft tissue coverage, infection, smoking, diabetes and other comorbidities, nonsteroidal anti-inflammatory drug use, and severe initial comminution [1], [11], [13]. Management of established nonunion typically requires revision surgery with improved fixation, bone grafting or bone morphogenetic protein application, and addressing any underlying infection or soft tissue deficiency [1].

Malunion, defined as healing in non-anatomical position, particularly affects functional outcomes when it involves articular surfaces or causes mechanical axis deviation [22]. Prevention requires meticulous attention to reduction quality, adequate fixation to maintain reduction during healing, and appropriate postoperative monitoring with radiographic assessment [22]. When malunion occurs, corrective osteotomy may be necessary to restore alignment and optimize function [22].

6.3 Soft Tissue Complications

Soft tissue complications including wound dehiscence, skin necrosis, and flap failure significantly impact outcomes in complex fracture management [1], [3], [11], [13]. For orthoplastic reconstruction of distal tibia fractures using circular external fixators combined with flap coverage, complete flap loss occurred in only 3 of 283 patients (1.1%) [1]. This low rate reflects the advantages of circular fixation, which does not damage the flap pedicle and helps stabilize soft tissues around the reconstruction [1].

Minimally invasive plate osteosynthesis demonstrated wound gaping in 5% of cases [11]. While this complication rate is relatively low, wound healing problems in the setting of internal fixation can lead to infection and hardware exposure, potentially requiring hardware removal and soft tissue reconstruction [11]. The preservation of soft tissue envelope with MIPO techniques likely contributes to the low wound complication rate [11].

Orthoplastic management significantly reduced the use of negative pressure wound therapy (risk ratio: 0.03) and reliance on healing by secondary intention (risk ratio: 0.02) compared to nonorthoplastic management [13]. This finding suggests that definitive soft tissue coverage with flaps reduces the need for prolonged wound care and achieves more reliable healing [13]. The increased use of free flaps in orthoplastic management (risk ratio: 3.46) reflects the emphasis on definitive reconstruction rather than temporizing measures [13].

For complex tibial plateau fractures managed with three-column plate fixation through antero-midline and postero-medial approaches, all incisions healed primarily without complications such as infection or cutaneous necrosis [21]. This excellent soft tissue outcome reflects careful surgical technique, appropriate approach selection, and adequate soft tissue handling [21].

Prevention of soft tissue complications requires careful preoperative planning of incisions, gentle tissue handling during surgery, appropriate timing of definitive fixation relative to soft tissue condition, consideration of staged procedures when soft tissues are severely compromised, and early involvement of plastic surgery for complex reconstructions [3], [4], [22], [13]. When soft tissue complications occur, prompt recognition and aggressive management are essential to prevent progression to deep infection or hardware exposure [11], [13].

6.4 Hardware-Related Complications

Hardware-related complications including screw loosening, plate fracture, and hardware prominence affect patient outcomes and may require implant removal [11], [26], [9]. For 3D-printed pure titanium plates used in distal tibia fractures, one of ten plates (10%) fractured, requiring revision surgery [9]. However, no screw loosening or surgical wound complications occurred, demonstrating generally favorable hardware performance [9].

A comparative study of retrograde intramedullary nailing combined with lateral locking plate versus dual plating for distal femoral fractures found no implant failures in either group [20]. The nail-plate group had five complications while the dual-plate group had six, with no significant difference in complication rates [20]. This finding suggests that both fixation strategies provide reliable mechanical stability [20].

Joint stiffness represents a functional complication that may be related to hardware prominence, prolonged immobilization, or inadequate rehabilitation [11]. In the MIPO study, 25% of patients experienced joint stiffness, highlighting the importance of early mobilization and aggressive physical therapy [11]. Hardware removal may be necessary in some cases to improve range of motion, particularly when plates are prominent or cross joints [11].

Limb length discrepancy occurred in 20% of patients treated with MIPO for comminuted long bone fractures [11]. This complication reflects the challenge of maintaining length in severely comminuted fractures where anatomical reduction is difficult to achieve [11]. Careful attention to length during initial fixation and consideration of supplemental fixation techniques such as blocking screws or external fixation may help prevent this complication [11].

For locking compression plates used in distal femoral fractures, the complication rate was low at 10%, with no cases of hardware failure, nonunion, or deep infection [24]. The fixed-angle stability provided by locking screws appears to reduce the risk of screw loosening and fixation failure, particularly in osteoporotic bone [24]. However, the cost of locking plates is higher than conventional plates, and the technique requires careful attention to screw placement to avoid cross-threading [24].

Prevention of hardware-related complications requires appropriate implant selection based on fracture pattern and bone quality, meticulous surgical technique including proper screw placement and plate contouring, avoidance of excessive hardware that may cause soft tissue irritation, and appropriate postoperative activity restrictions to prevent hardware failure before healing [11], [26], [24], [9]. When hardware complications occur, management may include observation for minor issues, hardware removal after fracture healing, or revision fixation for hardware failure before union [11], [9].

7. Evolving Strategies and Future Directions

7.1 Artificial Intelligence and Machine Learning

Artificial intelligence (AI) and machine learning represent transformative technologies with potential to revolutionize complex fracture management through enhanced diagnostic accuracy, automated surgical planning, and outcome prediction [15], [10]. Computer-assisted surgery and augmented reality have been recognized as useful adjuncts for preoperative planning and intraoperative navigation, successfully advancing clinical efficiency in long bone fracture treatment [15]. However, widespread adoption remains limited by costs and initial technical difficulties [15].

Integration of AI with 3D printing technology may enable automated fracture classification, optimal implant design, and personalized surgical planning [10]. Machine learning algorithms trained on large datasets of fracture patterns and outcomes could potentially predict which patients are at highest risk for complications, guide fixation method selection, and optimize surgical approach [15], [10]. These predictive models could enhance clinical decision-making by providing evidence-based recommendations tailored to individual patient characteristics [15].

Intraoperative navigation systems enhanced by AI could provide real-time guidance for reduction maneuvers, optimal screw placement, and assessment of fixation stability [15], [23]. When combined with robotic assistance, these systems may reduce radiation exposure, improve reduction accuracy, and decrease operative time [23]. The robot-assisted reduction system for pelvic fractures demonstrated the feasibility of intelligent system technology in managing complex fractures, achieving 100% success rate with excellent reduction quality [23].

Future applications may include AI-powered analysis of intraoperative fluoroscopy to automatically assess reduction quality and suggest adjustments, machine learning algorithms to predict healing trajectory based on early postoperative imaging, and natural language processing to extract insights from large databases of operative reports and outcomes [15], [10]. However, implementation will require validation studies demonstrating superiority over current methods, regulatory approval, and integration into existing surgical workflows [15].

7.2 Biological Augmentation

Biological augmentation strategies aim to enhance fracture healing through application of growth factors, cell-based therapies, and bone graft substitutes [27]. Tricalcium phosphate bone grafts have been used successfully in tibial plateau fractures, providing osteoconductive scaffolds that support bone regeneration [27]. A case series of three patients demonstrated that advanced trauma care with tricalcium phosphate bone grafts achieved satisfactory outcomes in complex tibial plateau fractures [27].

Bone morphogenetic proteins (BMPs), particularly BMP-2 and BMP-7, have demonstrated efficacy in promoting bone healing in nonunions and high-risk fractures [13]. However, concerns regarding complications including heterotopic ossification, inflammatory reactions, and cost have limited widespread adoption [13]. Future research may identify optimal dosing, delivery methods, and patient selection criteria to maximize benefits while minimizing risks [13].

Cell-based therapies including mesenchymal stem cells and bone marrow aspirate concentrate represent emerging strategies for augmenting fracture healing, particularly in cases with bone loss or impaired healing capacity [13]. These therapies aim to provide osteoprogenitor cells that can differentiate into bone-forming cells and secrete growth factors that promote healing [13]. Clinical translation requires demonstration of safety and efficacy in well-designed trials [13].

Future directions in biological augmentation may include gene therapy to enhance local growth factor production, bioprinting of vascularized bone grafts, and combination therapies integrating multiple biological agents with optimized delivery systems [10], [13]. The goal is to create a biological environment that maximizes healing potential, particularly in challenging cases with bone loss, poor soft tissue coverage, or patient factors that impair healing [13].

7.3 Personalized Medicine Approaches

Personalized medicine in complex fracture management involves tailoring treatment strategies to individual patient characteristics including fracture pattern, bone quality, soft tissue condition, comorbidities, functional demands, and patient preferences [15], [24], [10], [13]. The concept extends beyond fracture classification to encompass comprehensive patient assessment and individualized treatment algorithms [15].

Three-dimensional printing technology enables patient-specific implant fabrication, representing a practical application of personalized medicine [10], [9]. Customized plates designed to match individual anatomy achieve superior outcomes compared to conventional implants, with shorter operative times, improved reduction quality, and better functional outcomes [10]. As 3D printing technology becomes more accessible and cost-effective, personalized implants may become standard of care for complex fractures [10].

Pharmacogenomics may inform personalized pain management strategies, identifying patients at risk for opioid dependence or those likely to benefit from specific analgesic regimens [13]. Similarly, genetic markers associated with bone healing capacity could potentially guide decisions regarding biological augmentation or fixation method selection [13]. However, clinical implementation of pharmacogenomic approaches in trauma care remains in early stages [13].

Patient-specific rehabilitation protocols based on fracture pattern, fixation stability, and individual healing trajectory represent another application of personalized medicine [11], [22], [26]. For athletes requiring rapid return to competition, intensive functional treatment protocols with close physiotherapist supervision have demonstrated successful outcomes [26]. Conversely, elderly patients with multiple comorbidities may require modified protocols emphasizing safety and fall prevention [24].

The multidisciplinary approach to complex fracture management inherently involves personalization, with treatment teams considering multiple factors in developing individualized care plans [3], [4], [13]. Shared decision-making that incorporates patient values and preferences is increasingly recognized as essential to personalized care [15]. Future developments may include decision support tools that integrate patient-specific data with evidence-based guidelines to recommend optimal treatment strategies [15].

Precision medicine approaches may eventually enable prediction of individual patient outcomes based on comprehensive assessment of clinical, radiographic, genetic, and biomarker data [13]. Machine learning algorithms trained on large datasets could identify patterns associated with successful outcomes and complications, guiding treatment selection and intensity of monitoring [15]. However, implementation requires robust data infrastructure, validated predictive models, and integration into clinical workflows [15].

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8. Conclusions

Complex fracture management has evolved dramatically over the past decade, driven by technological innovation, refined surgical techniques, and enhanced understanding of biological healing principles. The evidence synthesized in this review demonstrates that contemporary management requires integrated multidisciplinary care, selective application of innovative technologies, and individualized treatment strategies tailored to fracture characteristics and patient factors.

Orthoplastic collaboration has emerged as a paradigm shift, with strong evidence demonstrating that coordinated management of skeletal and soft tissue components significantly improves outcomes in severe open fractures. Early intervention within 72 hours, definitive soft tissue coverage with vascularized flaps, and integrated postoperative care reduce infection rates to as low as 2.4% and achieve union rates up to 100% [3], [4]. This collaborative model should be considered standard of care for Gustilo-Anderson Grade III injuries and complex fractures with significant soft tissue compromise.

Minimally invasive techniques including MIPO and arthroscopic-assisted reduction have demonstrated excellent outcomes while preserving soft tissue envelope and periosteal blood supply. These approaches achieve union rates exceeding 90% and functional outcomes rated excellent or good in the majority of patients. The biological advantages of tissue preservation translate to reduced complications and enhanced healing, supporting broader adoption of minimally invasive strategies when technically feasible.

Three-dimensional printing technology has matured from experimental application to practical clinical tool, with high-quality evidence demonstrating significant advantages in operative efficiency, reduction quality, and functional outcomes. Customized implants designed using 3D printing achieve superior results compared to conventional implants, with shorter operative times, reduced radiation exposure, and improved anatomical reduction. As costs decrease and accessibility improves, patient-specific implants may become standard of care for complex periarticular fractures.

Locking compression plates have become a cornerstone of complex fracture fixation, particularly in osteoporotic bone and periarticular locations. The fixed-angle stability provided by locking screws reduces reliance on bone quality and enables stable fixation in challenging scenarios. Union rates approaching 100% and low complication rates support continued use of locking plates as a primary fixation method for complex fractures.

Emerging technologies including robotic-assisted reduction [23], artificial intelligence-enhanced surgical planning, and biological augmentation strategies represent the future of complex fracture management [15], [23]. Early evidence suggests these innovations can enhance precision, reduce complications, and improve outcomes. However, widespread adoption requires demonstration of cost-effectiveness, validation in diverse patient populations, and integration into existing surgical workflows.

Patient outcomes in contemporary complex fracture management are generally favorable, with union rates exceeding 90%, functional outcomes rated excellent or good in the majority of patients, and complication rates lower than historical benchmarks. However, significant challenges remain, including infection in severe open fractures, nonunion in high-risk patients, and functional limitations in elderly patients with complex periarticular fractures. Continued research is needed to optimize outcomes in these challenging scenarios.

The future of complex fracture management lies in personalized medicine approaches that integrate patient-specific factors with evidence-based guidelines to develop individualized treatment plans. Three-dimensional printing enables customized implant fabrication, artificial intelligence may guide surgical planning and predict outcomes, and biological augmentation strategies can enhance healing in high-risk patients. The integration of these technologies with multidisciplinary care models and patient-centered decision-making will define the next generation of complex fracture management.

Clinicians managing complex fractures should embrace multidisciplinary collaboration, particularly orthoplastic partnerships for severe open fractures. Clinicians should consider minimally invasive techniques when technically feasible to preserve soft tissue envelope, utilize 3D printing technology for preoperative planning and customized implants in complex periarticular fractures, select fixation methods based on fracture pattern, bone quality, and soft tissue condition rather than rigid algorithms, implement early intervention strategies including prompt debridement, stabilization, and soft tissue coverage for open fractures, and develop individualized rehabilitation protocols based on fracture characteristics, fixation stability, and patient factors.

Future research priorities include comparative effectiveness studies of emerging technologies versus established techniques, long-term outcome studies examining durability of modern fixation methods and incidence of post-traumatic arthritis, cost-effectiveness analyses of innovative technologies including 3D printing and robotic assistance, development and validation of predictive models for complications and outcomes, investigation of biological augmentation strategies to enhance healing in high-risk patients, and implementation science research to optimize multidisciplinary care delivery and ensure equitable access to advanced treatments.

Complex fracture management remains a dynamic field with ongoing evolution of techniques, technologies, and treatment paradigms. By integrating current evidence with emerging innovations and maintaining focus on patient-centered outcomes, clinicians can optimize results for these challenging injuries while advancing the field toward increasingly personalized and effective care.

Author Contribution Statement

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All authors have read and agreed to the published version of the manuscript.

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This review article synthesizes previously published research and does not involve primary data collection from human subjects or animals. Therefore, institutional review board approval was not required. All cited studies were conducted in accordance with ethical standards and relevant guidelines as reported in their original publications.

Conflict of Interest Statement

The authors declare no conflicts of interest. The authors have no financial relationships or personal relationships that could have appeared to influence the work reported in this paper.

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In preparing this work, the authors used Google Gemini for the purpose of systematically identifying, organizing, and analyzing relevant scientific literature on complex fracture management. After using this tool/service, the authors have reviewed and edited the content as needed and accept full responsibility for the substantive content of the publication.

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