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Modern Methods of Connecting Bone Fragments – A Review of Techniques, Materials and Treatment Results

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ABSTRACT

The aim of this paper is to review current and emerging methods of surgical treatment of long bone fractures. Particular attention is paid to features such as fixation stability, protection of the biological environment and the impact of new technologies. Classic techniques, such as locking plates and intramedullary nails, remain the standard, offering comparable treatment results with differences in the frequency of complications. MIPO reduces blood supply destabilization and preserves post-traumatic hematoma, reducing the number of complications. Rapidly developing methods such as 3D printing and robotic surgery enable precise planning and personalization of implants, leading to increased positioning accuracy and reducing radiation exposure. At the same time, there is growing interest in biodegradable implants. Magnesium alloys show osteogenic and angiogenic potential, although their clinical effectiveness depends on controlling the rate of degradation. PLGA polymers are used especially in pediatric traumatology, eliminating the need for metal removal. However, many of the innovations described require further research. Combining classic methods with new technologies allows for individualized treatment and optimized results.

Keywords: long bone fractures, osteosynthesis, MIPO, 3D printing, robotic-assisted surgery, biodegradable, implants, magnesium alloys, PLGA, fixation stability, orthopedic trauma

Content

1. Introduction

Surgical treatment of long bone fractures has advanced significantly in recent years. A better understanding of the biology of fracture healing has led to the emergence of new stabilization techniques and higher expectations for a rapid return to fitness after injury. (1–3)

Currently, osteosynthesis is largely based on maintaining a balance between mechanical stability and protection of the biological environment of the fracture. This is particularly important given that a very high percentage of injuries occur in elderly patients with multiple comorbidities. (2,3)

The basic methods of stabilization are locking plates and intramedullary nails. These methods show comparable clinical results, but differ in their complication profile and impact on soft tissues. (2,4–8) These characteristics of traditional implants encourage the use of minimally invasive techniques, such as MIPO, which promote the preservation of fracture biology. (11–13)

Technological advances have led to the introduction of solutions based on 3D printing, personalized implants, 3D FEA analysis, navigation systems and robotic surgery. These systems increase the precision of planning and implantation. (14–23) Biodegradable materials, including magnesium alloys and resorbable polymers, are beginning to be considered as alternatives to permanent implants. Thanks to their controlled degradation and potential bioactive properties, they offer new possibilities for fracture treatment. (25–31,33)

The aim of this paper is to present a comprehensive and critical review of current and developing methods of surgical treatment of long bone fractures. Particular emphasis has been placed on the issues of fixation stability, biological aspects of healing, and innovations that may influence future clinical practice. The individual chapters of the paper provide an overview of the current state of knowledge and indicate areas requiring further research in order to optimize and further develop the management of long bone fractures.

2. Methodology

A narrative literature review was performed. Searches were conducted in PubMed, ResearchGate and Springer up to 2025 using a concise combination of keywords related to long bone fractures and contemporary osteosynthesis techniques. The search strategy included terms such as “long bone fractures”, “diaphyseal fractures”, “pelvic fractures”, “periarticular fractures”, “calcaneal fractures” and “shaft fractures”, combined with osteosynthesis-related keywords (“locking plate”, “intramedullary nail”, “MIPO”, “biodegradable”, “magnesium”, “3D printing”, “additive manufacturing”, “personalized implants” and “robot-assisted” [or “robotic surgery”]) and outcome-related terms (“clinical outcomes”, “union”, “nonunion”, “biomechanical evaluation”, “surgical accuracy” and “complications”). Eligible studies included original research and review articles on the treatment of long bone fractures, published in English within the last 10 years. Animal studies, low-quality reviews, and incomplete or non-clinical reports were excluded. The final selection of articles was based on clinical relevance and alignment with the scope of the review.

3. Results

Classic fixation methods

The aim of modern techniques for treating long bone fractures is to achieve the fastest possible and stable union of bone fragments. Complex and open fractures with concomitant soft tissue damage remain a particular challenge in traumatology, as they are associated with an increased risk of complications and delayed healing.(1,2) From an epidemiological perspective, they represent a significant clinical problem, and long-term treatment outcomes are highly dependent on both the stabilisation method used and the patient's general health, comorbidities, and social and psychological factors.(2,3)

In clinical practice, the most commonly used methods of stabilising long bone fractures are locking plates and intramedullary nails. Numerous studies have shown their comparable effectiveness in terms of functional outcomes and complication rates.(2,4–6) An analysis of the differences between these two classic fixation methods indicates that locking plates provide high stability and promote faster recovery of function in the early postoperative period, including better external rotation and higher Constant–Murley scores.(4,5) Intramedullary nails, on the other hand, are characterised by shorter operating times, less blood loss and faster healing.(7,8) However, it should be emphasised that both techniques carry a risk of complications. The use of locked plates is associated with greater blood loss, longer surgery times and a higher rate of postoperative complications compared to intramedullary nails.(7,8) On the other hand, the use of intramedullary nails may be associated with an increased risk of malunion of the tibia (9) and, depending on the surgical technique, the possibility of postoperative pain in the shoulder in the case of treatment of proximal humerus fractures.(10) It should be noted that modern nail designs and improved surgical techniques reduce the risk of rotator cuff damage and thus reduce the incidence of associated pain, which limits the differences between the compared methods.(10)

The effectiveness of treatment, both with classical and modern methods, remains largely dependent on the precise reduction of fragments, the quality of soft tissues and the characteristics of the fracture itself. The choice of stabilisation method should be made on an individual basis, considering the patient's general condition and the surgeon's experience.(1–4)

Minimally invasive MIPO techniques

Minimally invasive percutaneous plate osteosynthesis (MIPO) has become an important technique in trauma surgery. While initially developed for humeral shaft fractures, it has subsequently been adapted for treatment of fractures at multiple anatomical sites. In contrast to traditional open reduction and internal fixation (ORIF), MIPO allows the surgeon to achieve adequate mechanical stability through a few small incisions, thereby minimizing soft-tissue damage and preserving the vascular integrity of the fracture zone.(11–13)

The biology of fracture healing after MIPO is based on principles that differ substantially from those of conventional direct osteosynthesis. Whereas classic ORIF relies on full exposure of the fracture site and anatomic reduction of individual fragments, MIPO is built around indirect reduction and a bridge-plate construct that spans the fracture.(12) This concept preserves the fracture haematoma – a natural milieu promoting callus formation and endochondral ossification – which in turn accelerates bone healing.(12)

A recent network meta-analysis of humeral shaft fractures (25 studies, 1908 patients) showed that MIPO was associated with a significantly lower overall complication rate (2.1%) compared with conventional ORIF (16.1%).(11) For non-union specifically, MIPO demonstrated the lowest rate (0.65%) among all investigated treatment techniques.(11) However, the overall quality of evidence remains limited and heterogeneity between studies cannot be excluded.(11)

On the other hand, MIPO requires mastery of specific technical skills and equipment. The procedure depends heavily on intraoperative fluoroscopy to guide reduction and plate insertion through small incisions, which is technically more demanding than open exposure.(13) Accurate plate positioning in relation to the mechanical axis of the bone requires experience and meticulous preoperative planning, and some reviews have emphasised that MIPO should not be employed routinely without adequate training, as improper execution can lead to complication rates comparable to or exceeding those of ORIF.(12)

3D printing in preoperative planning and patient-specific implants

While 3D printing technology offers potential advantages in fracture management, most current evidence comes from small case series and retrospective studies. The following section reviews the available evidence, with explicit attention to study limitations and quality considerations.

Three-dimensional (3D) printing, or additive manufacturing, is another disruptive technology in orthopaedic surgery, enabling the transition from standard, off-the-shelf implants towards truly patient-specific solutions.(14,15) This technology reshapes preoperative planning, intraoperative decision-making and, increasingly, the design of fixation constructs themselves.(14,15)

The workflow typically starts with high-resolution CT imaging and careful artefact reduction, followed by segmentation of the bone and fracture morphology.(14,15) Using computer-aided design (CAD) software, the surgeon (often in collaboration with an engineer) can reconstruct the fracture in a virtual environment, assess deformity, simulate reduction, and design a plate that conforms closely to the patient's individual bony contours.(14) From this virtual plan, either anatomical models and cutting/contouring guides or patient-specific implants can be manufactured.

3D printing is particularly valuable in the management of complex fractures, where traditional 2D imaging and standard implants may be insufficient.(14,15) Although a retrospective case series (n=5) of 3D printing-assisted fixation for complex limb fractures documented successful outcomes (16), the generalizability of these findings is severely limited by the retrospective design, minimal patient cohort, and lack of comparative controls.(16) Prospective multicenter studies are essential to establish whether 3D printing offers clinically meaningful advantages over conventional approaches.(16) These data suggest that the combination of precise preoperative planning and patient-specific hardware may help extend the indications for reconstructive surgery in otherwise borderline or highly challenging cases.(16) However, this conclusion requires confirmation in controlled comparative studies before broader clinical adoption can be recommended.(16)

The integration of 3D printing with MIPO further illustrates the synergy of modern techniques. In complex middle-proximal humeral shaft fractures, 3D-printing-assisted MIPO resulted in a significantly lower complication rate than conventional open plating, with comparable functional outcomes (no significant differences in range of shoulder motion, QuickDASH, and Constant scores), while maintaining the biological benefits of minimally invasive fixation.(12) Virtual templating allowed appropriate plate selection, contouring and screw trajectory planning before surgery, which translated into more efficient intraoperative execution.(12)

Patient-specific pure titanium plates produced by 3D printing have also shown promising results in distal tibial fractures. In a small clinical study of nine patients with predominantly minimal comorbidities, eight achieved reliable bone union, with nine of ten implanted plates remaining stable and undamaged, no screw loosening, and no surgical wound complications.(17) However, one patient with neurofibromatosis required revision surgery due to implant fracture, highlighting the importance of preoperative risk stratification.(17) Importantly, the authors demonstrated that 3D-printed titanium plates can be machined to include a functional locking screw mechanism, overcoming earlier concerns about the brittleness and machinability of additively manufactured titanium.(17) These findings support the feasibility and future prospects of broader clinical use.

Biomechanical investigations using three-dimensional finite element analysis (3D FEA) based on micro-CT data compared intramedullary and plate-based fixation for Sanders II and III calcaneal fractures.(18) For Sanders II fractures under axial compression, bone stress was highest in the locking plate group and lowest in the intramedullary nail group; however, locking plate fixation demonstrated superior maximum load-bearing capacity, with approximately 1.5 times higher load capacity before failure compared to intramedullary fixation.(18) These findings require confirmation in prospective clinical studies before definitive clinical recommendations can be made.(18) Beyond mechanical considerations, 3D printing-based planning can reduce operative time and the need for intraoperative fluoroscopy. With a pre-planned implant and a precise understanding of fragment positions, surgeons can limit trial-and-error manoeuvres and the number of radiographic checks, thus decreasing radiation exposure for both patient and staff.(16) This aspect is particularly relevant when 3D planning is combined with other advanced technologies such as navigation or robotics.

However, the overall evidence base for 3D printing in fracture fixation remains primarily case-series and retrospective in nature, with limited prospective comparative trials. High-quality randomized controlled trials are necessary before definitive recommendations can be made for routine clinical practice.

Robot-assisted fixation: precision, reduced radiation exposure and clinical outcomes

Robot-assisted surgery has the potential to provide more reproducible precision and to mitigate surgeon fatigue.(19,20) Most current orthopaedic robots follow a master–slave paradigm, where the surgeon defines the plan and controls the system, while the robot executes highly accurate movements based on integrated navigation data.(20,21)

The principal advantage of robot-assisted fixation lies in the highly accurate placement of screws and the precise execution of planned reductions. Comparative studies have demonstrated high-precision screw placement with robot-assisted systems. Systematic reviews report deviations typically below 3 mm.(20) For pediatric femoral neck fractures, robotic-guided fixation achieved superior screw parallelism (1.15° vs. 1.86°, $P = 0.036$) and screw distribution (73.8% vs. 60.0%, $P < 0.001$) compared to conventional techniques.(22) Similar improvements in placement accuracy have been reported for pelvic fracture fixation.(21,23) In clinical practice this translates into high first-pass accuracy of guidewire and screw placement, reducing the need for repeated drilling attempts and thereby limiting iatrogenic bone damage.(22)

A key benefit of robotic systems is the potential for substantial reduction in fluoroscopic imaging burden. In children with Delbet II femoral neck fractures, robotic-guided closed reduction and internal fixation resulted in significantly fewer fluoroscopic images (median 6.09 vs 10.42 exposures) compared with conventional fluoroscopy-guided techniques, without compromising reduction quality or union rates.(22) However, total operative time was longer in the robotic group (mean 80.3 ± 23.86 minutes) compared to the conventional group (66.8 ± 26.80 minutes), and while this difference approached but did not reach statistical significance ($P = 0.061$) (22), it suggests that robot planning and setup time did not translate into a net reduction in total procedure duration in this population. However, this longer operative time was accompanied by significantly improved technical metrics: the robotic group demonstrated superior screw parallelism (1.15° vs. 1.86°, $P = 0.036$) and screw distribution (73.8% vs. 60.0%, $P < 0.001$). Whether these technical improvements translate into clinically meaningful patient outcomes requires investigation in larger prospective trials. Similar findings have been reported for pelvic and acetabular fractures, where percutaneous robot-assisted screw fixation allows complex trajectories to be executed with fewer fluoroscopic checks.(21,23) Since cumulative radiation dose is directly proportional to the number of exposures, this reduction in imaging frequency translates into lower radiation burden for both patients and the operating team over a lifetime of practice.(21,22)

These clinical advantages are enabled by sophisticated registration and navigation technologies. Modern navigation systems use 2D–3D registration algorithms combining fluoroscopic and preoperative CT data to provide real-time surgical guidance. Wu Z et al.(24) reported very good treatment results of unstable pelvic fractures treated by an intelligent robot-assisted fracture reduction system - 20 patients were included. 10 of them achieved excellent results and 7 good results according to Matta's criteria.

Several comparative studies reported varying effects on operative times with robot assistance.(20,21,23) A systematic review of robot-assisted trauma surgery found mixed results, with some studies showing significant reductions in operating time (for example, pelvic fracture fixation: median 33.25 minutes robotic vs. 63.55 minutes conventional), while others reported no significant differences or even longer operative times when robot setup and planning time were included.(20) In minimally invasive treatment of pelvic fractures, robotic percutaneous screw fixation has been associated with shorter operating times, fewer fluoroscopic images and higher accuracy of screw placement compared with conventional freehand techniques.(21,23) The time saved stems mainly from avoidance of repeated adjustments and the high reliability of the guided trajectories. Improvement seems small relative to cost, and overall evidence quality is low.(20)

The available evidence suggests that robot-assisted fixation achieves at least comparable long-term functional outcomes to standard methods, with some single-centre series reporting modest advantages in specific indications; however, these differences are generally small and the overall quality of evidence is low.(20–22)

The combined use of 3D printing and robotic assistance is particularly promising. In a retrospective series of patients with unstable pelvic fractures,(23) those treated with preoperative 3D printing-based planning plus robot-assisted screw fixation demonstrated significantly shorter screw positioning times (median 3.0 vs. 4.0 minutes) and more accurate screw placement compared with robot-assisted fixation alone.(23) Importantly, combining 3D printing planning with robot-assisted fixation did not significantly increase the number of fluoroscopic exposures or total operative time compared to robot assistance alone, suggesting that 3D printing planning enhances efficiency and accuracy without requiring additional radiation exposure in this finding.(23) However, the modest clinical improvements must be weighed against the additional planning time and cost associated with 3D printing technology .(23) Additional prospective multicenter studies across diverse anatomical locations are required to fully characterize the clinical and economic value of these integrated technology combinations.

Summary of MIPO, 3D printing and robot-assisted fixation

Modern technologies such as MIPO, 3D printing and robot-assisted systems have the potential to enhance contemporary fracture fixation. MIPO appears to minimize soft-tissue trauma while supporting biologically favorable healing; 3D printing enables personalized preoperative planning and implant design, though prospective comparative data on patient outcomes remain limited. Robotics enables high-precision screw placement while reducing radiation exposure in multiple fracture types. The most promising early results are seen when these modalities are combined,(23) though current evidence is based primarily on retrospective series and requires validation in prospective multicenter trials. The key mechanical, biological and clinical characteristics of the osteosynthesis methods discussed above are summarized in Table 1.

Table 1. Comparison of contemporary osteosynthesis methods for long bone fractures

FIXATION METHOD	**MECHANICAL STABILITY**	**PRESERVATION OF FRACTURE BIOLOGY**	**COMPLICATION PROFILE**	**LEVEL OF CLINICAL EVIDENCE**
LOCKING PLATES (ORIF)	High	Low to moderate	Higher blood loss, longer surgery, soft-tissue complications	High
INTRAMEDULLARY NAILS	High	Moderate	Risk of malunion; technique-dependent shoulder pain	High
MIPO	Sufficient	High	Lowest overall complication and nonunion rates	Moderate
3D PRINTING (PLANNING / PSI)	Implant-dependent	Neutral	Limited data; mainly small case series	Low

ROBOT-ASSISTED FIXATION	Very high	Neutral	Comparable to conventional techniques	Low
BIODEGRADABLE IMPLANTS (MG, PLGA)	Variable	Very high	Strongly location- and degradation-dependent	Low to moderate

Abbreviations: ORIF – open reduction and internal fixation; MIPO – minimally invasive percutaneous plate osteosynthesis; Mg – magnesium; PLGA – poly(L-lactide-co-glycolide).

Biodegradable implants.

The development of biodegradable materials for internal fracture stabilization is due to the increased demand for reducing the number of reoperations to remove metal, reducing the stress shielding effect, and improving bone tissue regeneration conditions. Unlike traditional titanium or steel implants, materials such as magnesium alloys and resorbable polymers (PLGA) undergo gradual degradation in the body environment, and their products can further affect the bone microenvironment, being beneficial for osteogenesis and angiogenesis. (25–27) Within biodegradable metals, the most important group is magnesium alloys. Its mechanical properties (density, elastic modulus) are similar to those of cortical bone. This effect significantly reduces the stress shielding effect observedin titanium implants. As for resorbable materials, poly(L-lactide-co-glycolide) (PLGA) is used in pediatric traumatology. It is used as a material for intramedullary nails and other fixation elements. (25,28–31)

Magnesium alloys - mechanism of action and biological basis of healing

Magnesium implants undergo a gradual electrochemical corrosion process in the body. The rate of degradation depends on the alloy, microstructure, mechanical loading, and local environmental conditions (pH, blood flow, presence of proteins and cells). This degradation product positively affects osteogenic and angiogenic cells, as well as the immune system. (25–27,32,33) One of the key issues is controlling the degradation time, as excessively rapid prosthesis degradation can result in premature loss of stability and gas accumulation, while excessively slow degradation can result in the material persisting beyond the biomechanical requirements of the fracture. (25–27)

Osteogenic, Angiogenic, and Immunomodulatory Effects

Magnesium ions act as cofactors for numerous enzymes and influence numerous signaling pathways involved in osteogenesis. Experimental data indicate that magnesium ions stimulate osteoblast proliferation and differentiation by activating their pathways and modulating the expression of transcription factors. Animal studies have shown that degradation products of magnesium alloys increase the expression of genes associated with bone formation and periosteal remodeling, which translates into accelerated neosteogenesis. Angiogenesis, a crucial aspect of bone healing, should not be overlooked. It is supported by the alkalization of the peri-implant environment by these ions. They increase the expression of VEGF and other vasogenic mediators, leading to increased formation of new vascular connections within the bone union. From an immunological perspective, magnesium implants modulate the macrophage phenotype to promote regeneration and reduce osteoclast activity, thereby limiting bone resorption. (25,32,33)

Bone-Implant Interface and Degradation Control

A modern approach to magnesium alloy design involves optimizing the chemical composition, but also engineering the bone-implant interface. Studies on alloys based on magnesium, calcium, and silicon have shown that rapid but controlled biocorrosion can initiate the formation of a protective, multilayered mineral-organic surface on the implant. This stabilizes the rate of degradation and simultaneously promotes bone integration. Furthermore, this layer acts as a bridge between the implant and the bone, enabling the decrease in the implant's mechanical strength to be synchronized with the increase in the strength of maturing bone tissue. (34) Reviews of material properties emphasize that both the selection of alloying elements and their processing techniques are crucial. These can reduce the corrosion rate, limit gas release, and improve the surface's bioactivity. (26–28,33)

Clinical Applications of Magnesium Alloys - Biomechanical Data and Treatment Outcomes

Biomechanical Analysis - Radial Head.

A biomechanical study compared biodegradable pins made of magnesium, zinc, and polylactide in a radial head fracture model. Magnesium pins demonstrated the highest primary fixation stability, significantly exceeding polylactide in terms of transverse and axial stiffness. Zinc pins exhibited intermediate properties while maintaining good biocompatibility. After 1,000 axial loading cycles, fracture gap displacement was lowest in the magnesium group. This indicates the favorable mechanical profile of this material under repeated loading conditions. (35) The literature suggests that in locations exposed to high shear and bending forces, magnesium implants may provide better stability than traditional bioresorbable polymers. At the same time, they retain the ability to gradually disintegrate after the union process is complete. (28,35)

Navicular Fractures – Limitations of Current Solutions

The situation is somewhat different in analyses of the treatment outcomes of navicular fractures using bioresorbable magnesium screws. In a retrospective study of 20 patients, the bone nonunion rate reached 40%, and screw fracture was noted in 25% of the patients. Cystic lesions around the implant were also common. Although no infections were observed, and functional results were within acceptable limits, the high radiographic failure rate calls into question the safety of routine use of this system in this specific location. (36) These studies clearly demonstrate that the clinical effectiveness of magnesium alloys is significantly dependent on the specific fracture location, implant geometry, the biochemical conditions prevailing in the fracture environment, and implant degradation parameters. The use of this technique in carpal fractures requires further refinement and further research. (26,28,36)

Fractures of the mandibular condyle head – long-term results of magnesium screws.

A retrospective study evaluated the results of open reduction and internal fixation of mandibular condyle head fractures with magnesium alloy canal screws. Most patients achieved encouraging functional results with a relatively low complication rate. No patients required removal of the fixation. The condyle head remodeling process proceeded normally despite the observed changes in volume and shape on imaging studies. These results suggest that in joints with relatively favorable biomechanical conditions, magnesium canal screws may be a safe and effective alternative to conventional implants. An additional benefit is the absence of the need for subsequent reoperation. (29)

Biodegradable Polymer Implants (PLGA) - Pediatric Traumatology

In pediatric traumatology, the most clinical data concerns biodegradable PLGA intramedullary nails used in the treatment of forearm shaft fractures. In a study of 38 children treated with PLGA nails, 100% union was achieved. There were no significant limitations in mobility, but this treatment was characterized by very good aesthetic results with scars. There were minor differences in elbow flexion, but these differences had no significant functional impact. All patients and their caregivers reported high treatment satisfaction. (29)

Another study comparing titanium ESIN (Elastic Stable Intramedullary Nailing) nails with biodegradable PLGA nails in children found a significantly lower complication rate in the PLGA group. Functional outcomes were similar in both groups. The key clinical difference was the need for secondary implant removal in the titanium group. This results in increased anesthetic risk, psychological burden, and treatment costs. A randomized trial with a minimum four-year follow-up confirmed that PLGA nails biodegrade within a predictable timeframe. Functional outcomes were no worse than those achieved with conventional nails. (31)

Comparison of clinical results and properties – magnesium alloys vs. conventional and other biodegradable implants.

The mechanical properties of magnesium alloys place them between titanium and polymers. The tensile strength of magnesium alloys is lower than that of titanium but higher than that of typical polymer implants. Magnesium alloys and polymers exhibit favorable imaging profiles, unlike titanium, which hinders precise assessment of fusion. (25,27,28) From a biological perspective, magnesium is distinguished by its ability to support osteogenesis and angiogenesis. PLGA polymers do not exhibit such a pronounced antimicrobial effect, but offer a more predictable resorption profile and good biocompatibility – particularly in children. (25,28–31,37)

4. Conclusions

Modern methods of osteosynthesis for long bone fractures constitute a rapidly developing field of orthopedic traumatology. They combine traditional surgical techniques with new technologies. The literature review shows that the selection of the ideal method for eyelid stabilization must be individualized, considering the fracture characteristics and the patient's biological predispositions.

Locking plates and intramedullary nails remain the gold standard for the treatment of long bone fractures. They demonstrate similar effectiveness in achieving satisfactory results. Each method has its own advantages and challenges. Plates provide greater stability and faster early functional recovery, while nails enable faster operative times and reduced blood loss.

The MIPO technique, three-dimensional printing, and robotic-assisted systems have opened up new possibilities for osteosynthesis treatment, particularly in highly complex cases. MIPO has demonstrated promising results by minimizing soft tissue damage and improving the biological conditions for healing. This technique also achieves lower complication rates compared to traditional approaches. 3D printing of materials allows for detailed preoperative planning and design of implants tailored to the individual patient's anatomy, although current data is primarily based on retrospective studies and small case series. Robotic-assisted systems demonstrate high precision in screw placement and a significant reduction in radiation exposure. Particularly promising results are observed when combining these technologies. Integrating 3D printing with robotic assistance leads to shorter operating times and higher accuracy without increasing radiation exposure.

The development of biodegradable materials offers a promising complement to traditional osteosynthesis methods. Magnesium alloys, due to their mechanical properties similar to bone tissue, and resorbable polymers (PLGA) have demonstrated the ability to support osteogenesis and angiogenesis through biological mechanisms. Controlling the degradation time remains a key challenge to avoid both premature loss of stability and undesirably prolonged implant fixation times. Another issue is the variable effectiveness of biodegradable implants depending on the anatomical location. Data suggest that the sensitivity of biodegradable implants to parameters of the local biochemical environment and implant geometry requires further research aimed at precisely tailoring material characteristics to specific anatomical locations.

Despite growing interest in modern osteosynthesis methods, the available scientific evidence for many of them is based primarily on retrospective studies, case series, and small patient cohorts. Multicenter, prospective, randomized controlled trials are essential to implement these technologies into widespread clinical practice.

A modern approach to the treatment of long bone fractures should combine traditional knowledge with the capabilities offered by advanced technologies, always considering the individual clinical context of the patient. Although many modern techniques have shown promising preliminary results, their routine use in practice will require rigorous validation of their effectiveness through high-quality scientific research.

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Supplementary materials

Not applicable.

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References

1. Balbachevsky D, Gomes PS, Credídio MV, Cruz BAP, Fernandes HJA, Baldy Dos Reis F, et al. Intramedullary nail versus bridge plate in open tibial fractures - randomized clinical trial. Injury. 2021 Jul;52 Suppl 3:S77–83.
2. Vallier HA. Current Evidence: Plate Versus Intramedullary Nail for Fixation of Distal Tibia Fractures in 2016. J Orthop Trauma. 2016 Nov;30 Suppl 4:S2–6.
3. Chen BK, Tai TH, Lin SH, Chen KH, Huang YM, Chen CY. Intramedullary Nail vs. Plate Fixation for Pathological Humeral Shaft Fracture: An Updated Narrative Review and Meta-Analysis of Surgery-Related Factors. J Clin Med. 2024 Jan 28;13(3):755.
4. D'Ameida SS, Cannon R, Vu NT, Ponce BA, Redden D. Comparing Intramedullary Nails and Locking Plates in Displaced Proximal Humerus Fracture Management: A Systematic Review and Meta-Analysis. Cureus [Internet]. 2024 Feb 15 [cited 2025 Dec 2]; Available from: https://www.cureus.com/articles/189074-comparing-intramedullary-nails-and-locking-plates-in-displaced-proximal-humerus-fracture-management-a-systematic-review-and-meta-analysis
5. Sun Q, Ge W, Li G, Wu J, Lu G, Cai M, et al. Locking plates versus intramedullary nails in the management of displaced proximal humeral fractures: a systematic review and meta-analysis. Int Orthop. 2018 Mar 1;42(3):641–50.
6. Wang G, Mao Z, Zhang L, Zhang L, Zhao Y, Yin P, et al. Meta-analysis of locking plate versus intramedullary nail for treatment of proximal humeral fractures. J Orthop Surg. 2015 Sep 15;10:122.
7. Bu G, Sun W, Li J, Yang T, Li M, Wei W. MutiLoc Nail Versus Philos Plate in Treating

Proximal Humeral Fractures: A Retrospective Study Among the Alderly. Geriatr Orthop Surg Rehabil. 2021 Jan;12:21514593211043961.

8. Shi X, Liu H, Xing R, Mei W, Zhang L, Ding L, et al. Effect of intramedullary nail and locking plate in the treatment of proximal humerus fracture: an update systematic review and meta-analysis. J Orthop Surg. 2019 Aug 30;14(1):285.
9. Yu J, Li L, Wang T, Sheng L, Huo Y, Yin Z, et al. Intramedullary nail versus plate treatments for distal tibial fractures: A meta-analysis. Int J Surg. 2015 Apr 1;16:60–8.
10. Boadi PJ, Da Silva A, Mizels J, Joyce CD, Anakwenze OA, Klifto CS, et al. Intramedullary versus locking plate fixation for proximal humerus fractures: indications and technical considerations. JSES Rev Rep Tech. 2024 Aug 1;4(3):615–24.
11. Colasanti CA, Anil U, Cerasani MN, Li ZI, Morgan AM, Simovitch RW, et al. Management of Humeral Shaft Fracture: A Network Meta-Analysis of Individual Treatment Modalities. J Orthop Trauma. 2024 Jul 1;38(7):e257–66.
12. Hu C, Qiu B, Cen C, Luo Q, Cao Y. 3D printing assisted MIPO for treatment of complex middle-proximal humeral shaft fractures. BMC Musculoskelet Disord. 2024 Jan 24;25(1):93.
13. Jiamton C, Rungchamrussopa P, Taweekitikul P, Leelasestaporn T, Anantasinkul P, Apivatthakakul T. Lateral minimally invasive plate osteosynthesis (MIPO) with long PHILOS for proximal metaphyseal-diaphyseal humeral fracture: surgical techniques and a clinical series. Eur J Orthop Surg Traumatol Orthop Traumatol. 2024 Jan;34(1):689–97.
14. Marinescu R, Popescu D, Laptoiu D. A Review on 3D-Printed Templates for Precontouring Fixation Plates in Orthopedic Surgery. J Clin Med. 2020 Sep 9;9(9):2908.
15. Meng M, Wang J, Huang H, Liu X, Zhang J, Li Z. 3D printing metal implants in orthopedic surgery: Methods, applications and future prospects. J Orthop Transl. 2023 Sep 1;42:94–112.
16. Liang H, Chen B, Duan S, Yang L, Xu R, Zhang H, et al. Treatment of complex limb fractures with 3D printing technology combined with personalized plates: a retrospective study of case series and literature review. Front Surg. 2024;11:1383401.
17. Clinical Efficacy of Three-Dimensional-Printed Pure Titanium Fracture Plates with Locking Screw Systems in Distal Tibia Fractures - PubMed [Internet]. [cited 2025 Dec 8]. Available from: https://pubmed.ncbi.nlm.nih.gov/39859118/
18. Wu J, Zhang L, Shen C, Wang X, Zhou X. Comparative 3D finite element analysis of intramedullary fixation versus locking plate fixation in calcaneal fractures using micro-CT image technology. BMC Musculoskelet Disord. 2024 Dec 19;25(1):1044.
19. Ram PR, Jeyaraman M, Jeyaraman N, Yadav S, Venkatasalam R. Revolutionizing Orthopedic Healthcare: The Role of Robotics. Cureus. 2023 Sep;15(9):e44820.

20. Schuijt HJ, Hundersmarck D, Smeeing DPJ, van der Velde D, Weaver MJ. Robot-assisted fracture fixation in orthopaedic trauma surgery: a systematic review. OTA Int. 2021 Oct 5;4(4):e153.
21. Wang M, Zheng S, Zhang Y, Lu J. Analysis of the therapeutic efficacy of robot-assisted percutaneous screw fixation in the minimally invasive treatment of pelvic fractures. Front Surg. 2024;11:1392719.
22. Shen Z, Liu Z, Shen C, Mo Z, Chen Y, Guo Y, et al. Long-term outcome of robotic-guided closed reduction internal fixation for Delbet II femoral neck fractures in children. J Orthop Surg. 2024 Sep 6;19:543.
23. Jing Y, Chang L, Cong B, Wang J, Chen M, Tang Z, et al. Preoperative 3D printing planning technology combined with orthopedic surgical robot-assisted minimally invasive screw fixation for the treatment of pelvic fractures: a retrospective study. PeerJ. 2024;12:e18632.
24. Wu Z, Dai Y, Zeng Y. Intelligent robot-assisted fracture reduction system for the treatment of unstable pelvic fractures. J Orthop Surg. 2024 Apr 30;19(1):271.
25. Taghipour S, Vakili-Tahami F, Allahverdizadeh A. Optimum design of a biodegradable implant for femoral shaft fracture fixation using finite element method. Phys Eng Sci Med. 2025 Sep;48(3):999–1014.
26. Ma TL, Zhou C, Qi GB, Jiang C, Jiang ZX, Wang X, et al. Ability of magnesium implants to remodel the osteoporotic immune microenvironment in a murine femoral fracture model. Rare Met. 2025;44(8):5672–88.
27. Montufar EB. Bone Response to Biodegradable Metals and In Vitro Evaluation of the Cytocompatibility. JOM. 2025 Jun 1;77(6):4473–92.
28. Jin B, Zhang C, Zhong Z, Liu Z, Zhang Z, Li D, et al. A novel degradable PCL/PLLA strapping band for internal fixation of fracture. J Mater Sci Mater Med. 2023;34(11):57.
29. Leonhardt H, Matschke JB, Sembdner P, Seidler A, McLeod NMH, Bräuer C, et al. Functional and three-dimensional radiographic outcomes after open reduction and internal fixation of condylar head fractures using magnesium alloy cannulated screws - a retrospective long-term follow-up. Clin Oral Investig. 2025 Sep 29;29(10):479.
30. Szwed-Georgiou A, Płociński P, Kupikowska-Stobba B, Urbaniak MM, Rusek-Wala P, Szustakiewicz K, et al. Bioactive Materials for Bone Regeneration: Biomolecules and Delivery Systems. ACS Biomater Sci Eng. 2023 Sep 11;9(9):5222–54.
31. Liu Y, Du T, Qiao A, Mu Y, Yang H. Zinc-Based Biodegradable Materials for Orthopaedic Internal Fixation. J Funct Biomater. 2022 Sep 26;13(4):164.
32. Gailani G, Moumni R, Brahimi M. Contact Analysis for Coupling of Plates and Screws in

Fracture Fixation of Cortical Bone. Adv Res. 2015 Jan 10;4:94–101.

33. Fu R, Zhao X, Liu Y, Qiao A, Yang H. An In Silico Model to Examine the Interaction Between Implant Degradation and Fracture Healing Under Mechanical Loading. Ann Biomed Eng. 2025 Aug;53(8):1919–30.
34. Egerci OF, Dogruoz F, Cetin H, Ertan MB, Yapar A, Kose O. High rate of failure after magnesium bioabsorbable compression screw fixation for scaphoid fractures. J Orthop Surg. 2025 Mar 19;20(1):296.
35. Yang Y, Ma X. Clinical efficacy analysis of one-stage posterior debridement, bone graft fusion, and internal fixation for the treatment of lumbar brucellosis spondylitis. BMC Surg. 2025 Aug 25;25(1):391.
36. Bhatti M, Malik J, Suleman H, Hussain S, Habib M, Nazir I, et al. Comparison of Volar Plating and Percutaneous K-Wire Fixation in Distal Radius Fractures. Indus J Biosci Res. 2025 Sep 15;3:5–9.
37. Wang P, Gong Y, Zhou G, Ren W, Wang X. Biodegradable Implants for Internal Fixation of Fractures and Accelerated Bone Regeneration. ACS Omega. 2023 Jul 26;8(31):27920–31.