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Advancements in micromotion-based fixation systems for fracture healing

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Abstract

Micromotion—defined as controlled cyclic axial movement at the fracture site—has emerged as a promising approach to enhance bone fracture healing. This review aims to evaluate micromotion-based fixation systems across biomechanical, preclinical, and clinical domains, highlighting their benefits, limitations, and technological progress. We summarize key micromotion technologies applied across various fixation systems, including far cortical locking and dynamic locking mechanisms in screws, suspension-based and shape-memory alloy-driven adjustments in plates, dynamization approaches in intramedullary nails through selective removal of interlocking components, and the evolution of external fixators from manually adjusted systems to intelligent, sensor-guided constructs such as the OrthoSpin frame.While internal fixations often rely on passive micromotion with limited controllability and potential safety concerns, external systems allow precise control but lack consensus on optimal stimulation parameters. Future advancements should focus on integrating real-time sensing and adaptive feedback to tailor micromotion based on healing stages and patient-specific needs.

Keywords

bone regeneration, delayed union, dynamization, fracture healing, micromotion

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Introduction

Fracture healing is a complex physiological process involving inflammation, cell recruitment, angiogenesis, and remodeling, all of which are influenced by systemic conditions, local biology, and mechanical stimuli.[1,2] Delayed healing and nonunion are prevalent complications, especially in long bones, with nonunion rates reaching approximately 14% in tibial and femoral fractures.[3,4] Beyond biological influences, growing evidence highlights the critical role of the mechanical environment—both insufficient and excessive interfragmentary motion can impair healing. As our understanding of the biological mechanisms of fracture healing has advanced, various therapeutic strategies have been developed to enhance bone regeneration. These include pulsed electromagnetic fields (PEMF), low-intensity pulsed ultrasound (LIPUS), extracorporeal magneto transduction therapy (EMTT), extracorporeal shock wave therapy (ESWT), vertical whole-body low-magnitude high-frequency vibration (LMHFV), and dynamization.[5–11]

Dynamization, achieved through techniques such as flexible fixation, modulating of fixation stiffness, or axial micromotion, has emerged as a key approach.[12–15]

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Micromotion, defined as dynamic cyclic axial interfragmentary motion, can be induced by patient activity or external mechanical devices. When maintained within an optimal range, it has been shown to promote bone regeneration by stimulating callus formation and accelerating fracture bridging.[16] The seminal work by Goodship and Kenwright in 1985 demonstrated that cyclic micromotion, applied via an external fixator, significantly enhanced callus formation and bone stiffness in tibial fractures.[17] Subsequent research has focused on optimizing micromotion parameters. Current evidence suggests that an amplitude of 0.2–1.0 mm at the fracture site is most beneficial, while amplitudes exceeding 2.0 mm may impede healing.[18] Axial micromotion is generally advantageous, whereas shear forces are detrimental. The timing of micromotion remains controversial, with ongoing debate over whether early or late application is more effective.[19] The concept of reverse dynamization has also been introduced, suggesting that micromotion at different healing stages may activate distinct mechanical and biological pathways.[20,21] Early micromotion may induce localized inflammation and release of inflammatory mediators, while late-stage micromotion likely operates through strain-related mechanisms.[22] Building on these findings, recent efforts have increasingly focused on the design and refinement of fixation devices capable of delivering controlled, stage-specific micromotion to maximize regenerative outcomes.

Recent advancements in micromotion research, combined with breakthroughs in materials science and smart technologies, have led to the development of a diverse range of micromotion-based fixation systems (Figure 1), which continue to evolve (Figure 2). This paper presents a comprehensive review of micromotion-enabled devices, encompassing screws, plates, intramedullary nails, and external fixators, with a particular focus on their design principles, biomechanical properties, animal studies, and clinical applications. Through this multidimensional analysis, the study aims to critically evaluate the strengths and limitations of various micromotion systems, particularly in comparison to widely used locked plating constructs, while providing insights into potential future directions for the development of micromotion fixation products.

Micromotion screws

Micromotion screws have been a focal point of research since the early 21st century. These screws can be broadly categorized into two types based on their design principles and mechanisms of action. The first type, represented by Far Cortical Locking (FCL) screws, introduces structural innovations to traditional locking screws, enabling controlled micromotion at the fracture site. The second type incorporates bioresorbable materials at specific regions of the screw, allowing micromotion to occur once the material degrades. Dynamic Locking Screws (DLS), an advanced version of FCL screws, have shown promising clinical efficacy, yet safety and durability concerns remain significant barriers to their widespread adoption. In contrast, bioresorbable screws remain largely experimental, with limited clinical validation. As a result, most micromotion screws rely on passive micromotion driven by patient activity, lacking the ability to actively or precisely control micromotion parameters.

Far cortical locking (FCL) screw

The Far Cortical Locking (FCL) screw, first proposed by the Orthopedic Research Association (ORA) in 2005. The design concept screw involves single cortical locking at the far cortex, with a screw shaft of reduced diameter that allows elastic bending within the proximal cortical hole. Key biomechanical advantages of FCL screws include: (1) reduced axial stiffness, promoting interfragmentary motion within the optimal range of 0.2–1.0 mm for secondary bone healing; (2) parallel micromotion at the fracture site and along the proximal and distal sides of the plate; (3) structural strength comparable to standard locking plates; (4) progressive stiffening as screws gain near cortex support under increasing loads.[23–26] Experimental studies have demonstrated the efficacy of FCL screws in promoting fracture healing. FCL constructs exhibited 88% lower initial axial stiffness compared to locked plating constructs, while achieving 54% greater torsional strength and 21% higher bending strength in non-osteoporotic diaphyseal bone.[23] In ovine models, FCL screws resulted in 36% greater callus volume, 54% higher torsional strength, and 156% more energy to failure compared to locked plating constructs at week 9.[27]

Clinical studies on FCL screws have evolved from retrospective observational studies to high-quality randomized controlled trials (RCTs), providing insights into their safety and efficacy across diverse fracture sites and patient populations.[28–37] Early studies, such as the retrospective analysis by Ries et al. in 2013, demonstrated the safety of FCL screws in distal femoral fractures, with no instances of implant failure.[28] Subsequent research expanded the application of FCL screws to periarticular fractures around the knee and tibial fractures.[31,32] While some studies reported faster healing with FCL screws, others found no significant differences in complication rates or overall healing success compared to traditional locking plates.[33,34] Notably, a 2023 RCT highlighted contrasting findings, with FCL screws showing a shorter working length but slower healing time in distal femoral fractures.[35] Studies involving Asian populations further emphasized the potential of FCL screws to accelerate healing.[37]

In summary, FCL screws have demonstrated promising biomechanical and clinical outcomes, particularly in

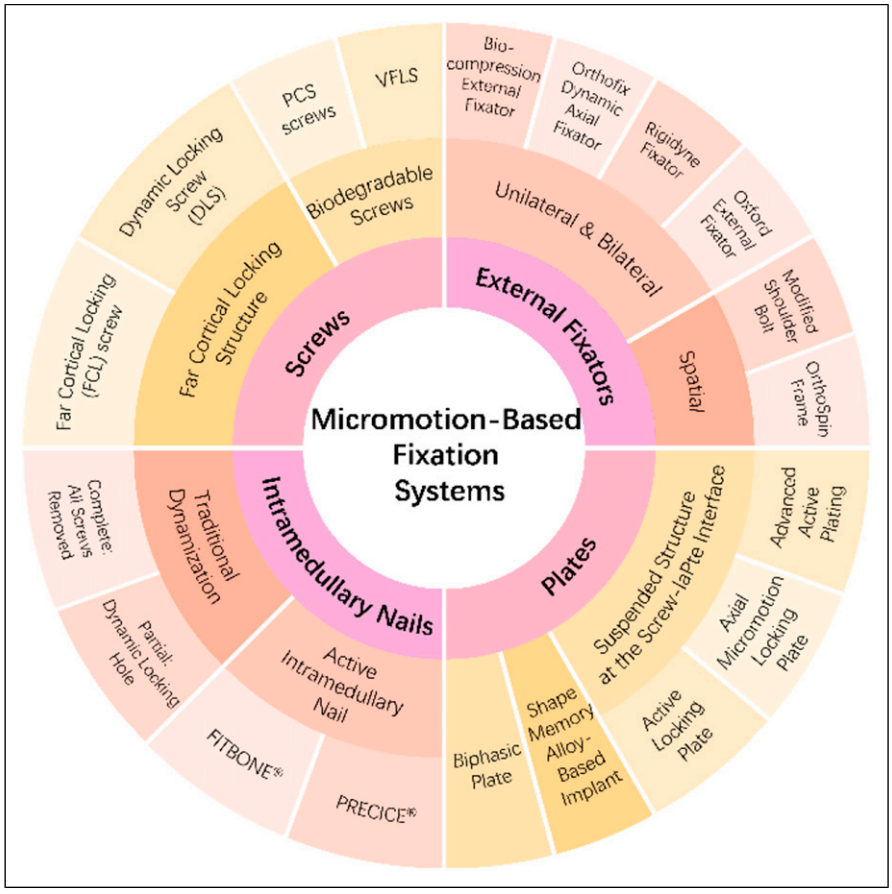

Figure 1. Classification of micromotion fixation systems by fixation type. PCS screws: Screws containing threaded degradable polymer collars; VFLS: variable fixation locking screw.

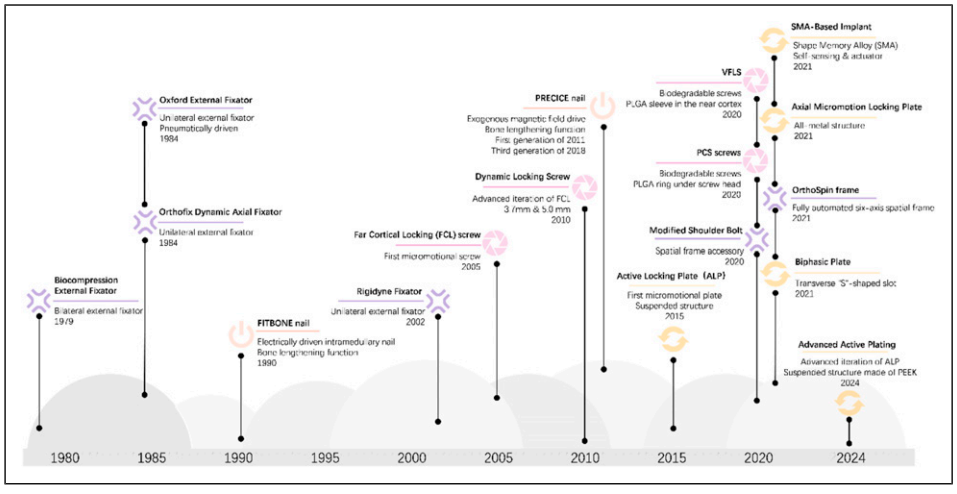

Figure 2. The evolution of micromotion internal fixation systems. VFLS: variable fixation locking screw; PCS screws: screws containing threaded degradable polymer collars; PLGA: polylactic-co-glycolic acid; SMA: shape memory alloy.

weight-bearing fractures where early mobilization is critical. However, their ability to meaningfully reduce complications and improve healing rates requires further validation through large-scale, rigorously designed clinical trials.

Dynamic locking screw (DLS)

The Dynamic Locking Screw, introduced in 2010, represents an advanced iteration of micromotion-enabled fixation, available in two specifications: 3.7 and 5.0 mm. The DLS design consists of a threaded sleeve and an elastic pin with a locking head, which collectively reduce axial stiffness while increasing interfragmentary motion.[38] This design promotes more symmetrical micromotion at the fracture site, enhancing mechanical stability and fracture healing.[39]

Biomechanical studies have demonstrated the advantages of DLS constructs. Dobele et al. reported that the 3.7 mm DLS reduced axial stiffness by 16% and increased interfragmentary motion at the near cortex from 282 μm to 423 μm compared to standard locking screws.[38] Further testing with the 5.0 mm DLS revealed a 74.4% reduction in initial axial stiffness and a significant increase in interfragmentary motion from 0.033 mm to 0.210 mm.[39] In osteoporotic bone models, DLS constructs exhibited higher screw pullout strength, highlighting their potential in challenging clinical scenarios.[40] However, outcomes varied across fracture types. For example, DLS demonstrated superior fatigue resistance in proximal humerus fractures,[41] but reduced construct stability in open wedge high tibial osteotomy models.[42] Animal studies have further supported the efficacy of DLS in promoting fracture healing. Goat models showed improved biomechanical performance and greater callus volume with DLS constructs, suggesting enhanced healing outcomes.[43,44] Despite these promising results, clinical studies on DLS remain limited, with most evidence derived from low-level observational research. By 2015, DLS research and application had largely stalled due to safety concerns, including pin perforation and breakage during implant removal.[45–47] These issues led to a manufacturer recall in some regions, further limiting its clinical adoption.[48]

In conclusion, while DLS offers significant biomechanical advantages, its clinical application is hindered by safety concerns. Advances in new metal alloys and synthetic materials may pave the way for its resurgence, particularly in specific clinical scenarios where controlled micromotion is critical.

Biodegradable screws

Biodegradable screws represent a novel approach to micromotion-enabled fixation, leveraging the dynamic mechanical requirements of different fracture healing phases. The design rationale is based on the understanding that a stable environment during the inflammatory phase promotes vascularization and osteogenic differentiation, while controlled micromotion during callus formation and remodeling enhances vascular network remodeling and stimulates bone formation.[49]

Recent innovations in biodegradable screw designs include the locking screws with threaded degradable polymer collars (PCS screws) and the Variable Fixation Locking Screw (VFLS). PCS screws incorporate a polymer collar made from 85/15 polylactic-co-glycolic acid (PLGA), which initially provides axial stiffness comparable to conventional locked plating. Upon degradation, the polymer collar allows increased interfragmentary motion, achieving the optimal range of 0.2–1.0 mm for fracture healing.[49] Similarly, VFLS utilizes a poly-(lactide-co-glycolide) sleeve in the near cortex, which degrades over time to progressively increase screw flexibility and enable dynamic fracture stabilization.[50]

Biomechanical and in vivo studies have demonstrated the potential of biodegradable screws. VFLS constructs promoted larger and more evenly distributed callus formation in animal models, although histological and biomechanical properties were comparable to those achieved with standard fixation.[51] Despite these promising results, biodegradable screws face inherent structural limitations and lack robust clinical validation, hindering their widespread adoption.

Future research on biodegradable screws should focus on their potential for personalized treatment, particularly in patients with compromised bone healing capacity, such as those with osteoporosis or diabetes. The rapid advancement of orthopedic implant materials, however, offers exciting opportunities for the future development of biodegradable screws. Beyond their biodegradability, these materials can be engineered to promote vascularization, neurogenesis, and osteogenesis, potentially revolutionizing micromotion-enabled orthopedic devices.

Summary of micromotion screws

Micromotion screws, including FCL, DLS, and biodegradable designs, represent significant advancements in fracture fixation technology. FCL screws have demonstrated clinical efficacy in promoting faster healing, particularly in weight-bearing fractures, although their ability to reduce complications remains uncertain. DLS offers superior biomechanical performance but faces challenges related to safety and durability. Biodegradable screws, while still in the experimental stage, hold promise for dynamic regulation of micromotion across different healing phases. Future research should focus on optimizing screw designs, enhancing safety profiles, and conducting large-scale clinical

trials to validate their efficacy. The integration of advanced materials and smart technologies may further enhance the functionality and clinical applicability of micromotion screws, paving the way for more personalized and effective fracture management strategies.

Micromotion plates

Micromotion plates have emerged as a prominent area of research over the past decade. These plates are designed to introduce micromotion at the fracture site, typically through innovative structural modifications or advanced materials. The most common approach involves creating a suspended structure at the screw-plate interface, often using silicone-based materials or unique geometric designs. Recent developments, such as the Biphasic Plate (BP) and Shape Memory Alloy (SMA)-based plates, represent bold advancements in this field. Like micromotion screws, most micromotion plates rely on passive micromotion generated by patient activity, limiting the ability to precisely control micromotion parameters post-implantation. However, the integration of advanced materials like SMA, with their self-sensing and actuation capabilities, holds promise for delivering precisely controlled micromotion stimuli, potentially revolutionizing fracture management.

Active locking plate

The Active Locking Plate, pioneered in 2015, marks a significant milestone in the evolution of micromotion-enabled plating systems. Its design features locking screw holes elastically suspended within silicone envelopes housed in lateral plate pockets. This flexible fixation construct not only reduces axial stiffness and dampens impact loads but also facilitates controlled interfragmentary motion, promoting fracture healing.[52]

Biomechanical studies have demonstrated the advantages of active locking plates. Capanni et al. reported that these constructs exhibit 58% less stiffness and reduce impact load transmission by up to 48% compared to standard locked plating constructs.[52] Tsai et al. further confirmed that active locking plate enhanced interfragmentary motion by 0.32 mm at the near cortex and 0.33 mm at the far cortex, with a 77% reduction in axial stiffness, while maintaining strength comparable to standard locked constructs.[53] Henschel et al. compared four micromotion-capable fixation devices and found that active locking plate reduced stiffness by 75%, significantly increasing axial motion without affecting shear motion.[54]

In vivo studies have supported these findings. Bottlang et al. conducted sheep model experiments, revealing that active locking plates promote faster, stronger, and more symmetric fracture healing compared to standard locking and compression plates.[55,56] Torsion tests after plate removal showed that specimens in the active locking plate group recovered 81% of their native strength and were 399% stronger than those in the standard locking plate group.[56] Despite these promising results, clinical translation remains cautious. To date, only one prospective observational study involving 11 patients has been reported, with 10 achieving successful healing and 1 experiencing atrophic delayed union.[57]

The Active Locking Plate, pioneered by Professor Bottlang, represents a significant advancement in micromotion-enabled plating systems. Its innovative design, featuring elastically suspended screw holes, has demonstrated reduced axial stiffness and enhanced interfragmentary motion, promoting faster and stronger fracture healing. While the design shows great promise, further optimization may be needed to address potential challenges related to structural complexity.

Axial micromotion locking plate (AMLP)

The axial micromotion locking plates (AMLP) , introduced by Han et al. in 2021, offers a simpler yet effective approach to achieving controlled micromotion.[58] Constructed entirely from titanium alloy (Ti−6Al−4V), the AMLP features a threaded gliding wedge integrated into pentagon-shaped slots. This design allows controlled axial interfragmentary micromotion of 0.3 or 0.6 mm, with slots strategically placed in opposite orientations to maintain stability. In an in vivo sheep study, AMLP constructs demonstrated faster and stronger bone healing compared to rigid locking plate (LP) constructs, particularly with 0.6 mm micromotion group. The stiffness of the 0.6-mm AMLP was 86% and 41% lower than that of the LP, enabling improved healing dynamics. Specimens in this group also endured 27% greater torque to failure than those with LP constructs.[58] Despite these promising results, no clinical studies have been reported to date. The AMLP's simple structure and material composition make it easy to assemble, but potential issues such as tissue ingrowth into micromotion gaps require further investigation. The AMLP represents a significant step forward in micromotion plating systems, offering a balance between simplicity and efficacy. Future research should focus on clinical validation and addressing potential complications to ensure its widespread adoption.

Advanced active plating (AAP)

The Advanced Active Plating (AAP) system, introduced by Bottlang in 2024, represents a cutting-edge innovation in micromotion-enabled fracture fixation. Constructed from Ti6Al4V titanium alloy with polyether-ether ketone (PEEK) components, the AAP system utilizes PEEK anvils suspended within rectangular plate pockets by implant-grade silicone bumpers. This design enables up to 3 mm of axial

motion across the osteotomy gap while providing stable fixation under bending and torsional loading.[48]

In an in vivo sheep study, AAP constructs recovered 54% of their native strength by week 9, significantly outperforming standard locking plates, which regained only 17%.[48] The use of PEEK, with its exceptional fatigue strength and flexibility, offers a better modulus match with bone compared to traditional materials like titanium or stainless steel. PEEK's modulus of elasticity (approximately 3.5 GPa) closely aligns with cortical bone (12–20 GPa) and is highly compatible with cancellous bone (~1 GPa).[59] Additionally, the integration of passive real-time strain sensors made of PEEK allows for direct laser writing on the fixation surface, providing potential applications for micromotion strain detection in the future.[60]

Despite concerns about plate thickness and the practical efficacy of micromotion in vivo, the AAP system represents a promising direction in micromotion-based fracture treatment. Its advantages, including excellent biocompatibility, reduced stress shielding, radiolucency, and corrosion resistance, make it a strong candidate for future clinical applications.

Biphasic plate (BP)

The Biphasic Plate (BP), introduced by Epari in 2021, features a unique transverse "S"-shaped slot in a region of increased cross-sectional thickness. This design prevents twisting and ensures stability under reverse bending and torsional forces, while optimizing stiffness and strength.[18] The plate gradually tapers from an 11 mm thick central section to thinner ends, enhancing its mechanical performance.

In an in vivo sheep study, BP constructs demonstrated 45% greater strength and 48% higher stiffness compared to standard locking plates, without compromising implant durability.[61] Biomechanical tests revealed that at low loads, BP construct was 55% more compliant, allowing greater interfragmentary motion (0.18 mm vs 0.04 mm). At high loads, BP constructs were 476% stiffer than locking compression plates (LCP), with peak stress reduced by 63%.[18] This combination of enhanced flexibility at low loads and robust stiffness at high loads highlights the BP's potential to optimize fracture healing without sacrificing implant strength.

The BP's design not only promotes controlled micromotion but also ensures safety for early weight-bearing. However, further validation and optimization of the plate's thickness and slot placement are needed to address the demands of complex clinical fracture scenarios.

Shape memory alloy (SMA)-based implant

The Shape Memory Alloy (SMA)-based implant, introduced by Zimmer in 2021, represents a groundbreaking innovation in micromotion-enabled fixation. This smart implant integrates two key mechanisms: one for dynamically altering implant stiffness and another for active stimulation. Both mechanisms rely on Nitinol SMA actuator wires, which are highly biocompatible and suitable for medical applications.[62] The actuator systems feature a spring configuration with SMA wires, enabling precise control of micromotion with up to 0.5 mm of axial displacement.

While no reports on its application in large animal models or clinical settings have been published, SMA-based implants show great promise due to their super elasticity and shape memory properties. These properties facilitate rebound after micromotion-induced compression, making SMA an ideal material for micromotion plates. Shape memory alloys (SMAs), with their unique properties of super elasticity and shape memory, hold great promise for the development of next generation micromotion plates capable of delivering precise and adaptive mechanical stimuli. Future research should focus on preclinical validation and clinical trials to fully realize the potential of SMA-based implants in enhancing bone healing through controlled dynamic stimuli.

Summary of micromotion plates

Micromotion plates, including Active Locking Plates, AMLP, AAP, BP, and SMA-based implants, represent significant advancements in fracture fixation technology. These plates leverage innovative designs and advanced materials to achieve controlled micromotion, promoting faster and stronger bone healing. Active Locking Plates and AMLP have demonstrated promising biomechanical and in vivo results, although clinical validation remains limited. The AAP system, with its use of PEEK, offers a unique combination of flexibility and strength, while BP's biphasic design optimizes stiffness. SMA-based implants, though still in the experimental stage, hold immense potential for precise micromotion control.

Despite these advancements, challenges remain, including concerns about structural integrity, clinical efficacy, and the need for large-scale trials. Future research should focus on optimizing plate designs, integrating smart technologies, and conducting rigorous clinical validation to ensure the safe and effective application of micromotion plates in fracture management. The continued development of advanced materials and sensing technologies will likely play a pivotal role in the evolution of micromotion-enabled plating systems.

Moreover, the development of internal micromotion systems should consider the potential synergy between micromotion screws and plates, allowing for tailored combinations suited to specific fracture types and patient needs. Computational tools such as finite element analysis

may aid in evaluating interfragmentary stress and strain patterns, as well as in assessing the mechanical stability of various micromotion configurations.[63–66]

Traditional dynamization of intramedullary nails

Dynamization has proven to be an effective strategy for addressing delayed union and nonunion in tibial and femoral fractures.[67] This technique is typically achieved through two primary methods: (1) Complete Dynamization, where all locking screws at one end are removed to allow axial micromotion between fracture fragments, and (2) Partial Dynamization, where screws within dynamic locking holes are retained, enabling limited axial micromotion and rotational movement.[68] Currently, dynamization is applied passively as a remedial measure for delayed union and nonunion, rather than proactively during normal fracture healing. Despite the absence of intramedullary nails specifically designed to leverage micromotion for osteogenesis, advancements in smart intramedullary nails, such as the FITBONE® and PRECICE® series, offer promising insights into the potential integration of micromotion functionality into fixation systems.

FITBONE nail and PRECICE nail

Intramedullary nails, compared to screws and plates, offer greater potential for integrating advanced functionalities and material innovations. The FITBONE® and PRECICE® nails, both automated intramedullary lengthening devices, represent significant advancements in this field. The FITBONE nail, introduced in the 1990s, is an electrically driven, fully implantable lengthening nail.[69] It employs two mechanisms—telescopic and sliding—with the telescopic mechanism holding potential for adaptation to micromotion functionality.[70] The PRECICE series, introduced in 2011, utilizes a magnetic drive system to achieve controlled limb lengthening, allowing surgeons to maintain precise control over distraction rates and rhythms.[71]

Despite their success in limb lengthening, these devices currently lack dedicated micromotion capabilities. However, the technical barriers to incorporating micromotion functionality are relatively low. Once adapted, these systems could enable precise control over parameters such as frequency, duration, and strain, significantly enhancing their therapeutic potential.

The PRECICE series has evolved through multiple iterations to overcome initial design challenges, particularly those related to implant durability and patient comfort. The first generation faced issues with implant fractures, which were resolved in the second generation.[72] The third-generation PRECICE® STRYDE, launched in 2018, was made of Biodur108 stainless steel alloy and allowed immediate post-operative weight-bearing of up to 68 kg.[71,73] However, the Stryde nail was recalled in 2021 due to concerns over pain, radiographic abnormalities at the telescoping interface, and nail corrosion.[72] These challenges highlight the importance of rigorous preclinical validation and material optimization in the development of advanced intramedullary nails.

In summary, while current intramedullary nails lack dedicated micromotion functionality, the FITBONE and PRECICE systems demonstrate the potential for integrating such capabilities. Future research should focus on adapting these devices to deliver controlled micromotion, optimizing material properties, and conducting rigorous clinical trials to validate their efficacy in promoting fracture healing.

Micromotion external fixators

Micromotion external fixators have been a significant area of research since the late 20th century. Achieving micromotion in external fixators was relatively straightforward, and early research focused on optimizing micromotion parameters rather than developing new devices. Most early micromotion external fixators were unilateral systems, incorporating telescopic mechanisms in the connecting rods to enable controlled axial movement. In recent years, the design of micromotion external fixators has shifted toward spatial configurations, driven by the increasing use of circular and hexapod frames. A notable example is the OrthoSpin system, a smart, sensor-controlled, self-adjusting external fixator designed for limb lengthening and deformity correction. This system represents a significant advancement, nearly achieving the ultimate goal of micromotion external fixators and highlighting a promising direction for future applications of micromotion technologies.

Biocompression external fixator

The Biocompression External Fixator, introduced by Lazo in 1979, is a bilateral external fixator based on a modified Hoffmann-Vidal frame. The original four rods of the Vidal frame were replaced with telescopic sliding rods, enabling controlled micromotion at the fracture site. This micromotion is driven by the patient's own activity, facilitating natural healing.[74] In 1984, Lazo further reported the successful application of this device in treating tibial fractures in 127 patients, all of whom achieved healing with callus formation.

The Biocompression External Fixator represents an early attempt to incorporate micromotion into external fixation, demonstrating the potential of controlled axial movement in promoting bone healing. However, its design limitations, such as the reliance on patient activity for micromotion,

highlight the need for more advanced systems capable of precise control over micromotion parameters.

Orthofix dynamic axial fixator

The Orthofix dynamic axial fixator, first reported in 1984, is a unilateral fixation system that leverages axial micromotion through a telescopic mechanism. The device consists of a single bar with articulating ends that clamp self-tapping screws, allowing it to transition from rigid to dynamic fixation once periosteal callus formation begins. Controlled distraction or compression is achieved via a detachable compressor unit.[75]

Biomechanical studies have demonstrated the efficacy of the Orthofix system. Aro et al. confirmed that axial dynamization minimally affected the rigidity of the Orthofix fixator under rotational and flexion forces.[76] Comparative studies by Jaskulka et al. demonstrated that the Orthofix system provided excellent stiffness, stability, and torsional resistance in both dynamic and static phases.[77] Clinical outcomes further validate its effectiveness, with Bastiani et al. reported a 94% success rate in 288 fresh fractures and an average healing time of 4.4 months.[75] Similarly, Meléndez et al. achieved a mean healing time of 22.6 weeks in 45 open tibial fractures, with staged dynamization enhancing fracture consolidation.[78–80]

The Orthofix Dynamic Axial Fixator represents a significant advancement in unilateral external fixation, offering controlled micromotion and excellent clinical outcomes. However, its reliance on patient activity for micromotion limits its ability to deliver precise and consistent mechanical stimuli.

Rigidyne fixator

The Rigidyne fixator, initially described by Anthony in 2002, is a purpose-built unilateral external fixator designed to provide axial micromotion during walking. Its sliding mechanism allows for controlled interfragmentary movement, while its six degrees of freedom offer versatility for managing complex cases.[22] The Rigidyne Fixator has been used in a variety of clinical and military applications, including hybrid external fixation, simultaneous management of ipsilateral limb fractures, compression arthrodesis, leg lengthening, and bone transport.

The Rigidyne Fixator's ability to provide reliable axial micromotion makes it a valuable tool for promoting fracture healing. However, its clinical adoption has been limited by the complexity of its design and the need for specialized training. Future research should focus on simplifying the device and optimizing its mechanical performance to enhance its clinical applicability.

Oxford external fixator

The Oxford external fixator, introduced by Kenwright in 1984, represents a significant advancement in micromotion technology. Unlike earlier devices that relied on patient-driven motion, the Oxford external fixator employs a pneumatically driven pump to generate controlled axial micromotion through two sliding clamps.[81] This design allows precise control over multiple parameters, including frequency (0.5 Hz), strain rate (30×10^{-3} με/sec), cycle count (500 cycles), and maximum axial micromotion (1 mm).[81,82]

Animal studies using the Oxford External Fixator demonstrated superior radiographic outcomes and stiffness in goats.[81] Clinical trials in 1986 revealed that daily micromotion interventions (30 min for 1 week post-surgery) resulted in larger callus formation and shorter healing times.[83] Subsequent RCTs further confirmed these findings, showing faster healing, improved mechanical properties, and no significant differences in complication rates for the micromotion group compared to controls.[84]

The Oxford External Fixator's capability to deliver controlled micromotion underscores its potential to enhance fracture healing outcomes. However, its reliance on external pneumatic actuators limits its practicality for long-term use. Future research should focus on developing more compact and user-friendly systems to enhance clinical adoption.

Experimental micromotion external fixators

Various experimental external fixators capable of producing micromotion have been developed to investigate the effects of different micromotion parameters on bone healing. These devices, though not commercially available, offer valuable insights into the potential clinical applications of micromotion.

In 1998, Wolf designed a custom unilateral external fixator for sheep tibias, incorporating a telescoping shaft to allow controlled axial micromotion. An electromechanically driven stimulation module, controlled by a microprocessor, was used to generate active micromotion.[85] Similarly, Claes introduced a spring-based external fixator in 1995, which allowed interfragmentary movement proportional to the applied load.[86–88] Hente developed an actuator-driven fixator in 2004, which alternated between compressive and distractive forces to promote healing.[89] Noordeen modified the Orthofix external fixator in 1995 to allow dynamic micromotion, with an option to lock the mechanism for rigid fixation when needed.[90] Glatt reported a dynamic fixator with flexible fixation and custom nylon dynamizers, enabling 2 mm of controlled axial micromotion.[20,21]

These experimental devices highlight the potential of micromotion in promoting bone healing. However, their

complexity and lack of commercialization limit their clinical applicability. Future research should focus on simplifying these designs and integrating them into commercially available systems.

Dynamized spatial frame

The spatial frame, a circular external fixator composed of rings connected by six angled struts, has been widely used for limb lengthening and deformity correction. Conventional methods of dynamization involve replacing struts with Ilizarov rods and loosening nuts to allow controlled axial micromotion. In 2020, Christopher introduced a dynamized spatial frame incorporating a modified shoulder bolt with an extended 2 mm shank, designed to achieve controlled axial micromotion of approximately 2 mm.[91]

The OrthoSpin fully automated six-axis spatial frame represents a significant advancement in this field. Preliminary results from 10 patients in 2021 demonstrated that the frame achieved all planned correction goals, with all patients successfully completing treatment.[92] The second-generation OrthoSpin frame, approved by the FDA in the same year, features automated software-controlled threaded adjustments, eliminating the need for manual adjustments by the patient. This system allows daily adjustment volumes to be divided into 2–20 smaller increments, significantly reducing patient discomfort.

The OrthoSpin system's ability to deliver precise and controlled micromotion highlights its potential to optimize fracture healing and deformity correction. Future research should focus on validating its efficacy in larger clinical trials and exploring its integration with other advanced technologies. The OrthoSpin system, with its automated software-controlled adjustments, has demonstrated significant potential in clinical settings, particularly for complex fractures and deformity correction.

Summary of micromotion external fixators

Micromotion external fixators, from early unilateral systems to advanced spatial frames like the OrthoSpin, have demonstrated the potential of controlled axial movement in promoting bone healing. Devices such as the Biocompression External Fixator, Orthofix Dynamic Axial Fixator, and Oxford External Fixator have provided valuable insights into the biomechanical and clinical benefits of micromotion. Experimental devices, though not commercially available, have further expanded our understanding of optimal micromotion parameters.

The OrthoSpin system, with its automated software-controlled adjustments, represents the future of micromotion external fixators. Its ability to deliver precise and controlled micromotion, combined with its user-friendly design, makes it a promising tool for fracture healing and deformity correction. However, challenges remain, including the need for larger clinical trials and further optimization of mechanical performance. The integration of advanced materials and smart technologies into external fixators holds great promise for revolutionizing fracture management, offering more personalized and effective treatment options.

Conclusions

Micromotion fixation systems have evolved significantly since their inception, with external fixation devices pioneering the field through two primary mechanisms: self-driven micromotion, generated by patient activity, and externally powered micromotion, facilitated by mechanical actuators. Early clinical trials with external fixators, such as the Oxford External Fixator and Orthofix Dynamic Axial Fixator, demonstrated the efficacy of micromotion in promoting bone healing. Over time, technological advancements have transformed externally powered systems from simple pneumatic actuators to sophisticated, intelligent devices like the OrthoSpin system, which integrates sensor-controlled, self-adjusting capabilities for precise micromotion delivery.

In contrast, internal fixation systems, such as Far Cortical Locking screws and Dynamic Locking Screws, rely on passive micromotion generated by patient activity. While these devices have shown faster bone formation in some clinical studies, their superiority over standard locking screws remains unclear, and their clinical application has been limited. Similarly, micromotion-enabled plating systems, such as the Active Locking Plate and Biphasic Plate, have emerged as a research hotspot, offering innovative designs to promote fracture healing. However, despite encouraging preclinical results, micromotion devices have yet to achieve widespread clinical adoption due to unresolved safety concerns and limited demonstrated clinical advantage over conventional fixation.

Several challenges remain in translating micromotion fixation systems into clinical practice. The primary hurdle is the lack of consensus on optimal micromotion parameters, including amplitude, frequency, and timing. Bone healing is a complex, dynamic process involving distinct biological mechanisms at different stages, necessitating a tailored micromotion strategy that adapts to each phase of healing. For example, early healing may benefit from minimal micromotion to stabilize the fracture site, while later stages may require controlled dynamic stimuli to enhance callus formation and remodeling. In addition, the integration of novel structures and materials into fixation systems requires rigorous biomechanical validation and clinical testing to ensure long-term stability, safety, and reliability.

The future of micromotion fixation systems lies in the creation of intelligent devices capable of real-time sensing,

precise control, and adaptive adjustment of mechanical stimuli. For external fixators, this vision is already becoming a reality with systems like OrthoSpin, which offer automated, software-controlled adjustments. However, achieving similar functionality in internal fixation systems, such as plates and screws, poses significant challenges, particularly in ensuring safety and durability. Advances in materials science, such as the use of shape memory alloys and bioresorbable polymers, along with the integration of real-time strain sensors, hold great promise for overcoming these barriers. Future research should prioritize the development of intelligent devices that integrate sensing, control, and adjustment capabilities, particularly for internal fixation systems such as plates and screws.

In conclusion, while micromotion fixation systems have made significant strides in both external and internal fixation, further research is needed to optimize their design, validate their clinical efficacy, and address safety concerns. The integration of advanced materials, smart technologies, and adaptive control mechanisms will be critical for advancing micromotion technology and achieving its full potential in clinical applications. By addressing these challenges, micromotion fixation systems can revolutionize fracture management, offering more personalized and effective treatment options for patients.

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