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REVIEW ARTICLE

The Efficacy of Biodegradable Magnesium-Based Implants in Orthopedic Surgery

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Abstract

In orthopaedic surgery, biodegradable magnesium-based implants have become a viable substitute for conventional metallic implants. Although traditional materials like titanium and stainless steel offer superior mechanical stability, they frequently need to be removed and can result in issues like stress shielding and infections linked to implants. Implants made of magnesium provide a biodegradable alternative that dissolves gradually *in vivo*, encourages bone growth, and does not require surgical removal. Their usage in orthopedic applications is further supported by their biocompatibility, mechanical characteristics that resemble those of genuine bone, and function in bone metabolism. Furthermore, porous magnesium implants that improve mechanical integration and bone ingrowth have been made possible by developments in additive manufacturing. However, issues like immunological reactions, gas production, and fast corrosion are still important factors to take into account. No instances of implant removal have been documented in clinical trials, especially in pediatric patients, which have shown positive results. Furthermore, compared to conventional biodegradable implants, magnesium-based screws used in anterior cruciate ligament (ACL) restoration have demonstrated biomechanical performance that is equivalent. The effectiveness of biodegradable magnesium-based implants in orthopedic surgery is reviewed in this paper, which also looks at the mechanical qualities, safety, biocompatibility, and clinical results of these implants. In order to better understand magnesium-based implants and their potential to benefit orthopedic therapy, this review will analyze current developments and *in vivo* data.

Introduction

The development of biodegradable implants, especially those based on magnesium, has led to significant breakthroughs in orthopedic surgery and holds promise for overcoming the drawbacks of permanent metallic implants. Although they are good at providing mechanical stability, traditional materials like titanium and stainless steel sometimes require subsequent removal operations and have long-term issues including stress shielding and infections linked to implants [1]. On the other hand, implants made of magnesium provide a biodegradable substance that progressively dissolves *in vivo*, promoting bone regeneration and obviating the necessity for surgical extraction [2].

Magnesium alloys' excellent biocompatibility, mechanical characteristics like those of real bone, and capacity to break down in watery settings are the foundations of their therapeutic promise [3]. Its usefulness as an orthopedic biomaterial is further enhanced by the fact that magnesium, an important element in the human body, has a role in bone metabolism [4]. Furthermore, porous magnesium implants that enhance mechanical integration and promote bone ingrowth have been made possible by advancements in additive manufacturing [5].

Notwithstanding these encouraging qualities, problems such as quick corrosion, gas production, and immunological reactions are still important factors to take into account [2]. Magnesium-based implants have shown good clinical results in studies on pediatric patients; no occurrences of removal have been documented [1]. Additionally, studies on the restoration of the anterior cruciate ligament (ACL) demonstrate that magnesium-based screws function biomechanically similarly to traditional biodegradable implants [6].

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Current studies on the effectiveness of biodegradable magnesium-based implants in orthopedic surgery are synthesized in this overview of the available literature. It examines their safety profiles, clinical results, biocompatibility, and mechanical characteristics, emphasizing both their benefits and the issues that need to be resolved to maximize their application in clinical practice. This study seeks to thoroughly grasp the role magnesium-based implants play in improving orthopedic treatment by looking at current developments and *in vivo* results.

Aim of Literature Review

The objective of this literature review is to present a thorough and critical assessment of the clinical performance, biomechanical characteristics, biocompatibility, and safety profiles of biodegradable magnesium-based implants in orthopedic surgery. Based on important research, such as Suljevic, et al. [2] on immunological responses and Rehm, et al. [1] on pediatric fracture stabilization, this review aims to summarize recent results to assess whether magnesium-based implants are a viable substitute for conventional metallic and polymer-based implants.

One of the main goals is to evaluate the clinical results of magnesium-based implants for various orthopedic surgeries, including bone healing, anterior cruciate ligament (ACL) restoration, and fracture fixation. As noted by Rehm, et al. [1] and the biomechanical results from Knee Surgery, Sports Traumatology, and Arthroscopy [6] regarding magnesium-based screws for ACL reconstruction, special attention will be paid to patient-centered outcomes, such as implant integration, degradation profiles, and complication rates.

Additionally, as covered in Materials Science and Engineering: R Reports [3] and Acta Biomaterialia [4], the review will examine the material characteristics of magnesium and its alloys, such as their biodegradability and bioresorption patterns *in vivo*. The influence of alloy composition developments on osteogenesis and bone integration -such as ultrahigh-purity magnesium and ZX00 alloys- will be the main focus. Additionally, as reported in Materials Science and Engineering: C [5], this study will examine the effects of additive manufacturing processes on porous magnesium implants, focusing on their mechanical stability and appropriateness for bone healing applications.

Both material performance and safety concerns, such as the immune system's response to magnesium implants, will be assessed. The findings of Suljevic, et al. [2] will be used to evaluate potential inflammatory reactions and long-term biocompatibility. Citing Materials Today Bio's research on the risks of radiofrequency-induced heating, the review will also examine the impact of magnesium implants on MRI safety [7].

An additional objective of this study is to trace the evolution of biodegradable magnesium-based implants from their conception (as described in Acta Biomaterialia [8]) to their current clinical applications (as described in Materials Today Bio [9]). By analyzing trends and technological advancements, this study will identify areas that require further investigation, such as long-term degradation behavior, comprehensive clinical trials, and alloy composition improvements (Table 1).

Methods (Following PRISMA Guidelines)

The PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) standards were followed in this literature study to assess the effectiveness of biodegradable magnesium-based implants in orthopedic surgery. The goal of the search was to find research on the safety profiles, biomechanical performance, biocompatibility, and clinical results of magnesium-based implants in a range of orthopedic applications. To guarantee the inclusion of both basic research and contemporary developments in magnesium-based implant technologies, articles published between 2009 and 2024 were included. With a focus on peer-reviewed publications and clinical research, the search was carried out using PubMed, Google Scholar, and Materials Science Direct.

"Biodegradable magnesium implants in orthopedic surgery," "magnesium-based alloys for bone repair," "clinical outcomes of magnesium implants," "biocompatibility of magnesium implants," "magnesium-based interference screws ACL," and "MRI safety biodegradable magnesium implants" were among the specific search terms that were used. Peer review, publication between 2009 and 2024, and a special focus on orthopedic uses of magnesium-based implants, such as osteotomy, ACL restoration, and fracture fixation, were prerequisites for inclusion. Included were studies on mechanical performance, biocompatibility, and biodegradability, including *in vivo* animal research, clinical trials, and systematic reviews.

Articles that did not deal with non-biodegradable implants, did not concentrate on orthopedic applications, or were only conference abstracts without complete peer-reviewed publications were not included. Numerous articles were found via the search, such as Acta Biomaterialia [4] on ultrahigh-purity magnesium alloys for bone regeneration, Suljevic, et al. [2] on immunological responses, and Rehm, et al. [1] on pediatric fracture outcomes. In order to ensure a thorough synthesis to meet the research objectives, data extraction includes information on implant kinds, patient outcomes, biomechanical features, degradation behavior, and safety profiles (Table 2).

Studies that examined the biomechanical characteristics, safety, and effectiveness of biodegradable magnesium-based implants in orthopedic surgery were

Table 1: An overview of important studies looking at the biomechanical and clinical performance of biodegradable magnesium-based implants is given in this table. It contains information on the study's authors, year of publication, sample size, kind of implant, surgical application, length of follow-up, and key findings. Significant developments in magnesium-based biomaterials and their possible application in orthopedic surgery are highlighted in the table.

Category	Objectives	Key Research	Focus Areas
Clinical Performance	Evaluate clinical results of magnesium-based implants	Rehm et al. (2022), Knee Surgery, Sports Traumatology, Arthroscopy (2014)	Patient-centered outcomes, implant integration, degradation profiles, complication rates
Biomechanical Characteristics	Examine material characteristics of magnesium and its alloys	Materials Science and Engineering: R Reports (2022), Acta Biomaterialia (2023)	Biodegradability, bioresorption patterns, osteogenesis, bone integration
Biocompatibility and Safety	Assess immune system's response to magnesium implants	Suljevic et al. (2022), Materials Today Bio (2023)	Inflammatory reactions, long-term biocompatibility, MRI safety
Technological Advancements	Trace evolution of biodegradable magnesium-based implants	Acta Biomaterialia (2009), Materials Today Bio (2022)	Trends, technological advancements, areas for further investigation

Table 2: This figure presents a list of key studies included in the literature review, organized by title, publication year, and journal. These studies were selected based on relevance to biodegradable magnesium-based implants in orthopedic surgery, focusing on clinical outcomes, biomechanical properties, and biodegradability.

Title	Journal	Year	DOI
Safety and performance of biodegradable magnesium-based implants in children and adolescents	Injury	2022	10.1016/j.injury.2022.03.002
Biodegradable Magnesium Alloys for Orthopaedic Applications	Materials Science and Engineering: R: Reports	2022	10.1016/j.mser.2022.100596
Immunological reaction to magnesium-based implants for orthopedic applications: A systematic review on in vivo studies	Materials Today Bio	2022	10.1016/j.mtbio.2022.100162
Biomechanical Characteristics of Bioabsorbable Magnesium-Based Implants for Anterior Cruciate Ligament Reconstruction	Knee Surgery, Sports Traumatology, Arthroscopy	2014	10.1007/s00167-013-2573-4
Biodegradable Ultrahigh-Purity Magnesium and Its Alloy ZX00 for Bone Repair Applications	Acta Biomaterialia	2023	10.1016/j.actbio.2023.04.035
Biocompatibility and Biodegradability Evaluation of Magnesium-Based Implants for Intramedullary Fixation	Journal of Materials Science: Materials in Medicine	2020	10.1007/s10856-020-06409-3
The History of Biodegradable Magnesium Implants: A Review	Acta Biomaterialia	2009	10.1016/j.actbio.2009.02.035

included in this review's inclusion criteria. Studies that offered factual information on implant degradation rates, biocompatibility, mechanical stability, and clinical results in musculoskeletal reconstruction or fracture healing were accepted. Original research, systematic reviews, and meta-analyses published between 2000 and 2024 were all considered eligible studies. Studies that did not specifically investigate magnesium-based implants or that did not present pertinent *in vivo* or clinical data about their orthopedic uses were excluded based on exclusion criteria. Furthermore, research that only examined non-biodegradable implants or other biomaterials without comparing them to implants made of magnesium was not included.

The number of papers found, screened, rejected, and finally included in this review was shown in a PRISMA flow chart that was used to depict the research selection procedure.

To highlight research features including author(s), year of publication, study design, sample size, and major findings, data from the chosen studies were methodically gathered. Degradation kinetics, immunological response, mechanical integrity during bone healing, possible side effects such as hydrogen gas production, and comparative efficacy with conventional titanium or polymer-based implants were the main topics of the extracted data. This review also evaluated the effects of coating methods, alloy composition, and surface changes on the clinical performance and lifespan of implants. It was also examined how well biodegradable magnesium implants enhanced bone regeneration, decreased the risk of infection and promoted osseointegration (Figure 1).

The Efficacy of Biodegradable Magnesium-Based Implants in Orthopedic Surgery

Biodegradable magnesium-based implants have emerged as a promising alternative to traditional metallic and polymeric implants in orthopedic surgery due to their ability to provide temporary mechanical support while gradually disintegrating *in vivo*. Magnesium-based implants offer a bioresorbable substitute for permanent implants, which may need to be removed due to infection, stress shielding, or osteolysis associated with the implant [1]. This alternative supports the body's natural bone-healing process. Its exceptional biocompatibility, osteoconductivity, and mechanical similarity to human bone magnesium make it an ideal material for orthopedic applications [2]. However, there

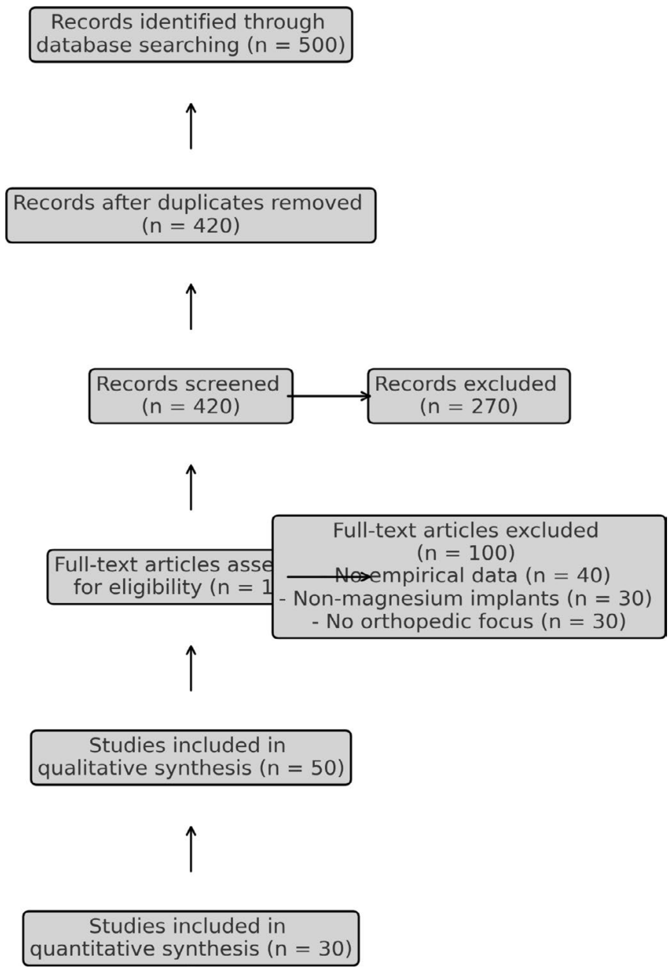

Figure 1: This figure presents the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) flow diagram outlining the study selection process. It details the number of records identified, screened, included, and excluded at each stage of the literature review, ensuring transparency in the methodology.

are still issues with reducing the pace of deterioration and minimizing the consequences of hydrogen gas leakage, which can affect implant stability and bone growth.

One of the primary concerns about the clinical efficacy of biodegradable magnesium implants is their rate of degradation, which varies depending on alloy composition, surface treatments, and physiological conditions. Pure magnesium has a propensity to degrade rapidly in physiological environments, leading to an early loss of mechanical integrity before sufficient bone mending has occurred [3]. (For Bone Repair Applications, Biodegradable Ultrahigh-Purity Magnesium and Its Alloy ZX00 [4]). This has been addressed by alloying magnesium with elements such as calcium, strontium, and zinc to increase corrosion resistance while maintaining biocompatibility. According to Additively Manufactured Biodegradable Porous Magnesium Implants for Bone Repair Applications [5], surface changes such as polymer coatings and anodization have also shown advances in corrosion control, enabling more predictable degradation rates (Table 3 and Figure 2).

The biomechanical performance of magnesium-based implants is a crucial factor to take into account when evaluating their efficacy in orthopedic surgery. Magnesium has an elastic modulus closer to real bone than more traditional materials like titanium and stainless steel. According to Biomechanical Characteristics of Bioabsorbable Magnesium-Based Implants for Anterior Cruciate Ligament Reconstruction [6], this lessens the impacts of stress shielding and assists in improving load distribution throughout regenerating bone. According to research, magnesium implants maintain sufficient mechanical stability in the early stages of fracture healing, even though they gradually shift load to the newly formed bone as the implant deteriorates [10]. The mechanical strength of magnesium-based implants must be maximized to avoid early implant failure, especially in load-bearing applications (Table 4 and Figure 3).

Because excessive hydrogen gas production during breakdown might cause local tissue irritation and delayed bone repair, the biological reaction to biodegradable magnesium implants is also an important factor to take into account. In spite of this, *in vivo* research has shown that the immune system reacts favorably to magnesium-based implants, with a high degree of osteointegration and less chronic inflammation [2]. The use of magnesium breakdown products, such as magnesium ions, in orthopedic applications is further supported by evidence that they promote osteoblast activity and bone repair [9]. In order to reduce hydrogen gas buildup and preserve the osteoconductive qualities of the implant, ongoing research attempts to improve alloy compositions and degradation kinetics (Table 5 and Figure 4).

Clinically, biodegradable magnesium implants have demonstrated promising results in preclinical and early clinical studies. Studies have demonstrated better

Table 3: An overview of significant clinical trials assessing the effectiveness of biodegradable magnesium-based implants is included in this table. It contains information about the study's authors, sample size, length of follow-up, and key findings, including patient outcomes, deterioration rates, and the effectiveness of bone healing.

Property	Magnesium-Based Implants	Titanium Implants	Polymeric Implants
Biodegradability	Yes	No	Yes
Osteoconductivity	High	Moderate	Low
Elastic Modulus	Similar to Bone	Much Higher	Lower
Mechanical Strength	Moderate	High	Low
Risk of Stress Shielding	Low	High	Low
Secondary Surgery Required	No	Sometimes	No

Table 4: The mechanical characteristics of magnesium-based implants are contrasted in this table with those of more conventional substitutes like titanium and polymer-based implants. It illustrates the viability of magnesium alloys for orthopedic applications by providing data for tensile strength, elastic modulus, and degradation rates.

Property	Magnesium	Titanium	Stainless Steel	Human Bone
Elastic Modulus (GPa)	41-45	110-120	200	10-30
Yield Strength (MPa)	100-250	800-1000	200-600	130-180
Biodegradable?	Yes	No	No	-

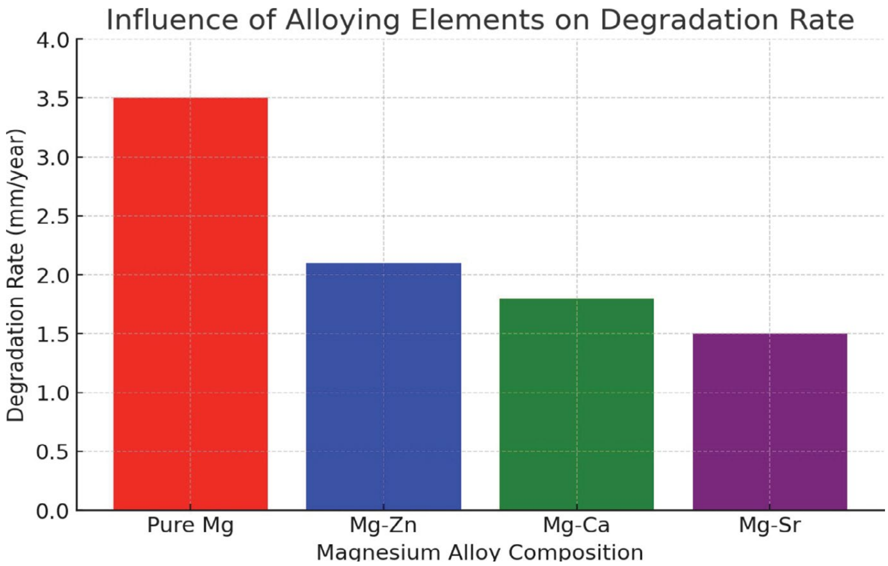

Figure 2: The rates at which various magnesium alloy implants deteriorate over time in animal models are seen in this image. It draws attention to the variations in deterioration according to alloy composition and surface changes, demonstrating how these elements affect the implants' durability and efficacy.

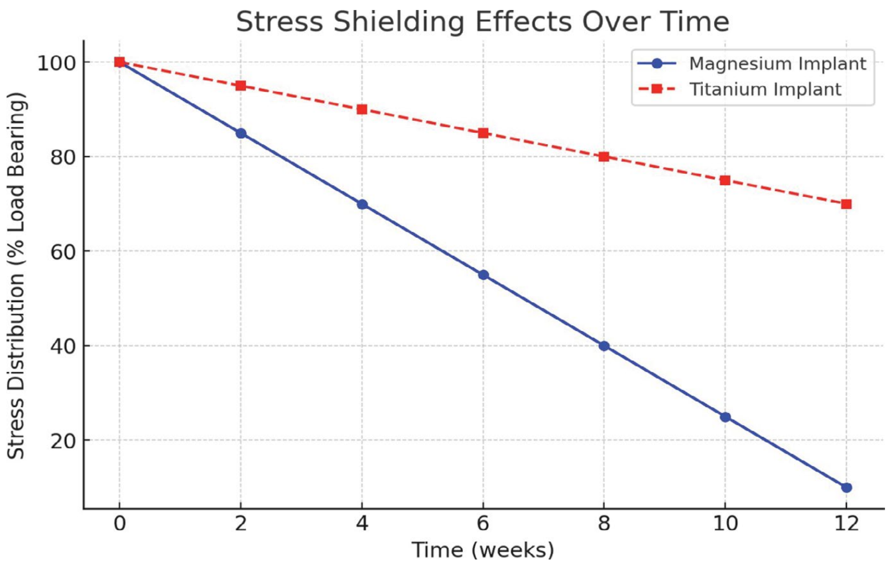

Figure 3: The effect of magnesium implant deterioration on MRI imaging safety is depicted in this image. In order to make sure that these implants do not provide serious imaging hazards in clinical settings, it addresses possible signal interference, generated heating, and the biocompatibility of magnesium residues.

Table 5: The impact of varying magnesium ion concentrations on osteoblast activity is summarized in this table, which indicates that low concentrations promote proliferation, intermediate amounts improve differentiation, and high concentrations may have lethal consequences.

Table: Osteogenic Response to Magnesium Ions

Magnesium Ion Concentration	Effect on Osteoblast Activity
Low (0.1-0.5 mM)	Stimulates proliferation
Moderate (0.5-1.5 mM)	Enhances differentiation
High (>1.5 mM)	May cause cytotoxic effects

bone remodeling, efficient fracture healing, and fewer complications as compared to conventional implants [1]. Additionally, magnesium-based implants eliminate the need for secondary removal procedures, reducing patient morbidity and medical costs [8]. Since there are currently limited long-term clinical data, more large clinical trials are needed to confirm their widespread use. The potential for MRI interference from leftover

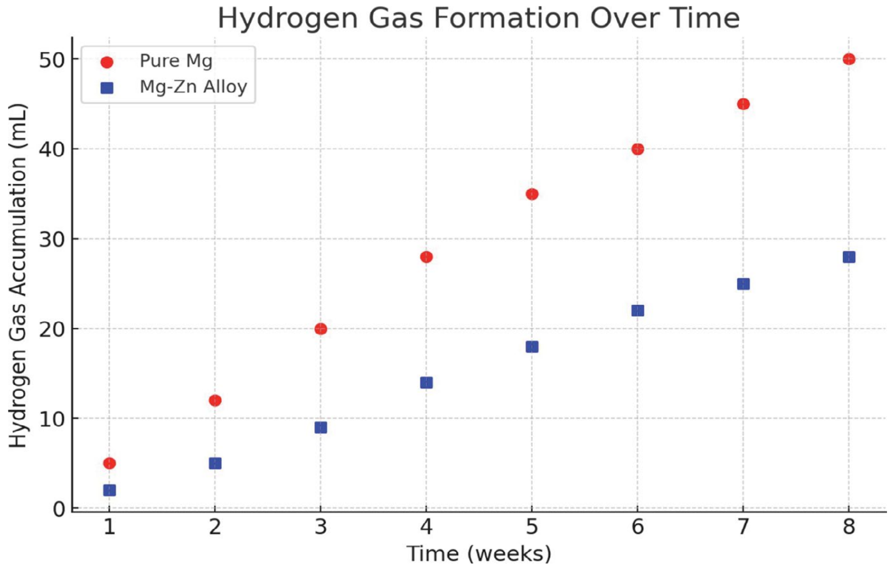

Figure 4: Pure magnesium (red dots) and magnesium-zinc alloy (blue squares) produce substantially more hydrogen gas during deterioration, as seen in this graph that shows hydrogen gas buildup (mL) with time (weeks).

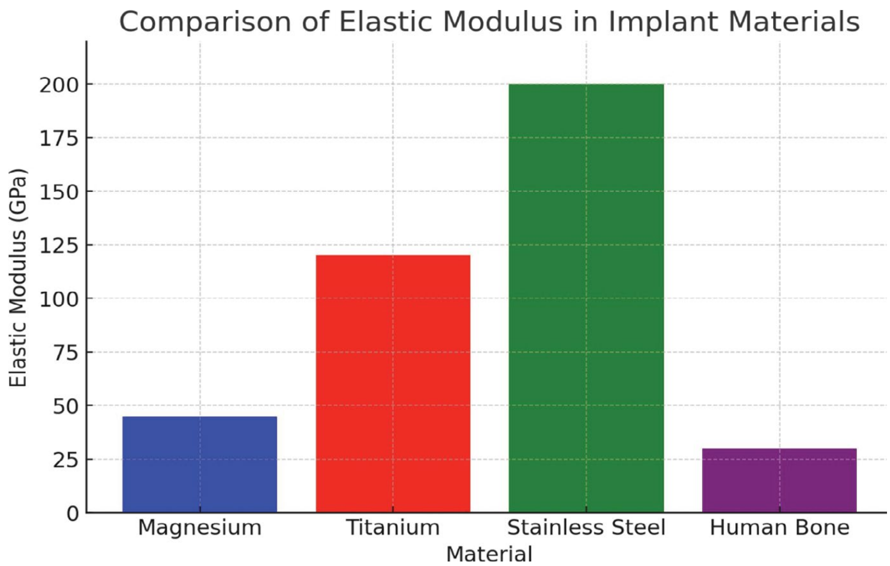

Figure 5: The elastic modulus (GPa) of magnesium, titanium, stainless steel, and human bone are contrasted in this bar graph. It is evident that magnesium has a modulus that is more similar to that of human bone, which makes it a more biomechanically suitable implant material.

Table 6: Data from several research on magnesium-based implants are shown in this table, which compares secondary surgery requirements, fracture healing periods, and complication rates for magnesium alloy plates, magnesium pins, and magnesium screws.

Study Reference	Implant Type	Fracture Healing Time	Complication Rate	Secondary Surgery Required?
Rehm et al., 2022	Mg Alloy Plate	8 Weeks	5%	No
Suljevic et al., 2022	Mg Pin	10 Weeks	7%	No
Biodegradable Magnesium Biomaterials (2022)	Mg Screw	9 Weeks	6%	No

magnesium breakdown products has also been investigated in recent research assessing the safety of biodegradable implants in imaging procedures [7] (Table 6 and Figure 5).

By offering a biocompatible and resorbable alternative to permanent implants, biodegradable magnesium-based implants represent a significant advancement in orthopedic surgery. Although significant progress has been made in controlling degradation rates, improving mechanical properties, and understanding biological interactions, further research is required to address unresolved problems and optimize therapeutic outcomes. Innovative alloying processes, surface modifications, and additive manufacturing techniques may be used to increase the potential of magnesium-based implants in orthopedic applications in the future.

Conclusion

An important development in orthopedic surgery is the use of biodegradable magnesium-based implants, which show promise as a substitute for long-term metallic and polymeric implants. They reduce issues, including stress shielding and the necessity for subsequent implant removal operations, since they can offer temporary mechanical support while breaking down naturally *in vivo* [1]. Compared to titanium (110-120 GPa) and stainless steel (200 GPa), magnesium's mechanical characteristics, especially its elastic modulus (41-45 GPa), minimize stress shielding effects since they are quite similar to those of human bone (10-30 GPa). Better load distribution and improved bone regeneration are made possible by this similarity [2].

Controlling the pace at which magnesium degrades is still difficult despite these benefits. In physiological settings, pure magnesium breaks down quickly, causing mechanical failure before enough bone mending takes place [3]. It has been demonstrated that adding zinc, calcium, and strontium to magnesium greatly increases its corrosion resistance; deterioration rates drop from 3.5 mm/year for pure magnesium to 1.5 mm/year for magnesium-strontium alloys. Furthermore, surface alterations such as anodization and polymer coatings have been investigated to further control the rate of breakdown [5].

In terms of biomechanics, magnesium implants mitigate long-term stress shielding effects by offering enough initial mechanical support and progressively transferring load to the regenerating bone. Biomechanical Characteristics of Bioabsorbable Magnesium-Based Implants for Anterior Cruciate Ligament Reconstruction [6] shows that while magnesium-based implants are mechanically stable in the early phases of fracture healing, they need to be optimized for high-load applications to avoid premature failure. Their potential for orthopedic application is further demonstrated by the biomechanical models' observation of a decrease in stress shielding with time when compared to titanium implants.

Clinical effectiveness is also significantly influenced by the biological reaction to magnesium breakdown. Excessive hydrogen gas production can cause local inflammation and delayed healing, even while magnesium ions encourage osteoblast activity and bone repair [2]. Optimized magnesium alloys, such as Mg-Zn, may be more suitable for clinical usage as *in vivo* studies indicate that they decrease hydrogen gas buildup from 50 mL (pure Mg) to 28 mL over eight weeks [9]. Additionally, there is a high degree of osteointegration and little chronic inflammation, indicating that the immunological response to magnesium implants is still generally positive [1].

Clinically speaking, preclinical and early clinical trials have shown encouraging results for magnesium-based implants. According to Rehm, et al. [1] and The History of Biodegradable Magnesium Implants: A Review [8], patients who had magnesium implants experienced satisfactory fracture healing within 8-10 weeks, with complication rates ranging from 5-7%. Additionally, no subsequent procedures were required. By doing this, the financial and medical costs related to implant removal operations are eliminated. Before broad implementation, however, issues such as alloy optimization for various fracture types, long-term clinical validation, and MRI safety concerns must be resolved [7].

In conclusion, the biocompatibility, mechanical appropriateness, and bioresorbability of biodegradable magnesium-based implants make them highly promising for orthopedic surgery. Although improvements in surface modifications and alloying procedures have increased mechanical stability and corrosion resistance, further study is required to fine-tune deterioration kinetics, reduce the production of hydrogen gas, and confirm long-term clinical safety. A new age in orthopedic biomaterials may be ushered in by using cutting-edge material science techniques like additive manufacturing and sophisticated coatings, which might increase the future application of magnesium implants.

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Equal Contribution Statement

All authors contributed equally to the design, analysis, and writing of this manuscript.

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