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NEXT-GENERATION ORTHOPEDIC IMPLANTS: THE ROLE OF SMART BIOMATERIALS IN REGENERATIVE MEDICINE

Dinu MONICA [1], Cristina BAZBANELA[1,*]

[1] Centre in the Medical-Pharmaceutical Field, Faculty of Medicine and Pharmacy, "Dunarea de Jos" University of Galati, 800008 Galati, Romania

Abstract

The new generation orthopedic implants are based on smart biomaterials capable of actively interacting with biological tissues to improve osseointegration and bone regeneration. These advanced materials, such as bioresorbable polymers, bioceramics, smart metals, and nanocomposites, provide superior biocompatibility, reduce the risks of infection, and allow for the controlled release of therapeutic factors. Also, the use of technologies such as 3D printing and nanotechnology allows the manufacture of customized implants, adapted to the specific needs of patients. However, the widespread use of smart biomaterials is still limited by high costs, strict regulations, and the need for extensive clinical trials. The durability of implants and their integration into the body requires further research to optimize mechanical stability and immunological compatibility. In the future, implants will become increasingly advanced through the integration of sensors for real-time monitoring and the development of materials capable of dynamically responding to biological stimuli. Thus, smart biomaterials have the potential to revolutionize orthopedic surgery, offering innovative solutions that improve the safety and efficiency of orthopedic treatments.
Keywords: Smart biomaterials, orthopedic implants, osseointegration, nanotechnology, tissue engineering, 3D printing.

Introduction

Orthopedic implants constitute a cornerstone in the management of musculoskeletal disorders, serving to replace or mechanically support bone structures compromised by trauma, degenerative diseases, or congenital malformations. The evolution of orthopedic implantology has closely followed advances in material science, transitioning from conventional metals and polymers toward advanced biomaterials with enhanced biological and mechanical performance. In recent decades, the emergence of smart biomaterials has profoundly transformed orthopedic applications, introducing dynamic systems capable of actively modulating tissue regeneration and minimizing surgery-related complications [1].

The concept of smart biomaterials arose from the clinical demand for implants that extend beyond passive structural replacement, instead promoting active bone regeneration and functional integration. These materials are engineered to interact bidirectionally with the biological environment, responding to local physicochemical cues while simultaneously influencing cellular behavior. Such properties enable improved osteointegration, angiogenesis, and immune modulation, thereby reducing the incidence of implant failure and postoperative complications [1,2].

Corresponding author: cristinabazbanela@yahoo.com

A critical attribute of smart biomaterials is their high biocompatibility, which substantially lowers the risk of chronic inflammation, fibrotic encapsulation, or implant rejection. Unlike traditional inert materials, modern biomaterials are designed to mimic the hierarchical structure, mechanical elasticity, and biochemical signaling of native bone tissue. Furthermore, surface functionalization and scaffold-based strategies allow for the controlled release of bioactive agents—such as growth factors, osteoinductive molecules, or antimicrobials, enhancing bone regeneration while mitigating infection risks, a major concern in orthopedic surgery [2,3].

Significant progress in material engineering has also facilitated the development of stimuli-responsive systems, capable of adapting to local pathological conditions. For example, glucose-sensitive scaffolds have demonstrated the ability to regulate osteogenic factor release in diabetic environments, where impaired bone healing is a well-documented challenge. Such adaptive platforms represent a paradigm shift toward context-aware implants that respond directly to metabolic or biochemical imbalances [3,4].

Parallel advancements in osteoclast regulation and immunomodulation have further expanded the therapeutic potential of smart biomaterials. Bisphosphonate-based hydrogels exemplify this approach by providing biomimetic feedback control over osteoclastic activity, thereby promoting balanced bone remodeling and improving regeneration outcomes. These strategies highlight the growing recognition of the immune system as a key determinant of successful implant integration [5].

Surface modification techniques for metallic biomaterials remain fundamental in optimizing implant–bone interactions. Micro- and nano-scale surface engineering has been shown to enhance protein adsorption, cellular adhesion, and osteogenic differentiation, while simultaneously reducing bacterial colonization. Such modifications serve as a critical interface between the mechanical stability of metallic implants and the biological requirements of surrounding tissues [6].

Beyond structural and biological optimization, controlled drug delivery systems embedded within implants have gained increasing attention. Enzyme-responsive and stimuli-sensitive nanomaterials allow for site-specific and temporally controlled release of therapeutic agents, aligning drug delivery with the dynamic phases of bone healing. These systems reduce systemic side effects while maintaining high local efficacy [7,8].

The integration of growth factor delivery within smart scaffolds further strengthens regenerative outcomes. Stimuli-responsive platforms capable of releasing osteogenic and angiogenic factors in response to local cues—such as pH, enzymatic activity, or oxidative stress—support synchronized bone formation and vascularization, which are essential for long-term implant success [8,9].

Reactive oxygen species (ROS)-responsive biomaterials represent another innovative strategy, particularly relevant in inflammatory or post-traumatic environments characterized by oxidative stress. By modulating ROS levels, these materials can influence cell survival, angiogenesis, and tissue remodeling, thereby contributing to a more favorable regenerative microenvironment [9,10].

In summary, orthopedic implants based on smart biomaterials represent a major advancement in regenerative medicine, integrating principles of material science, immunology, and tissue engineering. Through adaptive responsiveness, bioactive functionality, and precise biological modulation, these next-generation systems hold significant promise for improving clinical outcomes in musculoskeletal reconstruction. Despite ongoing challenges related to cost, regulatory approval, and large-scale clinical validation, current evidence suggests that smart biomaterials are poised to redefine future standards in orthopedic implantology [1–10].

Advantages of smart biomaterials

Smart biomaterials represent a major innovation in orthopedic implantology, offering substantial advantages over conventional materials traditionally used in implant fabrication. These advanced materials are specifically engineered to interact actively with the biological environment, thereby stimulating bone regeneration, preventing postoperative complications, and enhancing the long-term durability of implants. Their ability to respond to biological, chemical, and mechanical stimuli positions them as key components in modern regenerative medicine, ensuring superior long-term clinical outcomes [10].

One of the most significant advantages of smart biomaterials is their enhanced biocompatibility, which markedly reduces the risk of host rejection. Unlike conventional inert materials that may induce chronic inflammation or adverse foreign body reactions, smart biomaterials are designed to closely replicate the structural, mechanical, and biochemical properties of native bone tissue. This biomimetic approach promotes rapid integration within host tissues and minimizes the need for additional postoperative interventions. Moreover, nano-scale surface functionalization improves cellular adhesion, protein adsorption, and osteoblastic differentiation, ultimately accelerating the process of osteointegration [11].

Another major benefit of smart biomaterials lies in their capacity to actively stimulate bone regeneration through the controlled release of growth factors and bioactive molecules. This feature is particularly relevant in patients with compromised bone healing, such as those with osteoporosis, metabolic disorders, or large bone defects. By incorporating functional nanoparticles or bioresponsive matrices, smart biomaterials can enhance osteogenic signaling, shorten healing times, and promote more predictable regenerative outcomes. Certain bioactive systems are capable of directly modulating osteoblast activity, thereby facilitating faster and more efficient bone formation [12].

In addition to regenerative stimulation, smart biomaterials play a crucial role in infection prevention, one of the most serious complications in orthopedic surgery. Traditional implants often require prolonged systemic antibiotic therapy, which carries the risk of adverse effects and antimicrobial resistance. In contrast, smart biomaterials can be engineered to locally deliver antimicrobial agents in a controlled and sustained manner at the implant site. This localized strategy significantly reduces postoperative infection rates while limiting systemic antibiotic exposure and the emergence of resistant bacterial strains [13].

Personalization represents another key advantage of smart biomaterials. Advances in additive manufacturing, particularly three-dimensional (3D) printing, combined with tissue engineering approaches, enable the fabrication of patient-specific implants precisely tailored to individual anatomical and biomechanical requirements. Such customization improves implant stability, load distribution, and functional performance, while simultaneously reducing long-term complications such as implant loosening, wear, or premature failure [14].

Furthermore, smart biomaterials exhibit the ability to adapt dynamically to mechanical stimuli, adjusting their properties in response to physiological loading conditions. Shape-memory alloys and polymers, for example, can undergo reversible structural changes in response to body temperature or mechanical stress, thereby enhancing implant adaptability and mechanical stability. This characteristic is especially valuable in physically active patients, where implants must withstand repetitive and high-magnitude mechanical loads without compromising structural integrity [15].

An additional innovative feature of smart biomaterials is their potential for gradual bioresorption and replacement by native tissue. Certain bioresorbable materials are designed to degrade in a controlled manner, synchronizing implant resorption with new bone formation. This process eliminates the need for secondary surgical procedures to remove the implant, reducing both patient morbidity and healthcare costs. When combined with stem cells or osteoinductive factors, these materials demonstrate significant therapeutic potential for advanced bone regeneration strategies [16].

In conclusion, smart biomaterials offer a multifaceted improvement over traditional orthopedic implant materials by integrating biocompatibility, regenerative stimulation, antimicrobial protection, mechanical adaptability, and personalized design. Collectively, these properties underscore their growing importance in orthopedic surgery and regenerative medicine, positioning them as a foundation for next-generation implant technologies [10–16].

Table 1. This table presents the main advantages of smart biomaterials used in orthopedic implants. Essential categories, description of benefits, examples of materials used, and clinical impact are highlighted. These biomaterials contribute to biocompatibility, bone regeneration, infection prevention, personalization, adaptability, gradual integration, and intelligent monitoring, improving the safety and efficiency of orthopedic treatments.

Category	*Description*	*Material examples*	*Clinical impact*
Biocompatibility	Low risk of rejection, reduced chronic inflammation, and optimal interaction with host tissues.	Titanium, zirconium, cobalt-chromium alloys, biocompatible polymers	Reduced adverse reactions, improved implant acceptance, and prolonged durability.
Bone regeneration	Controlled release of growth factors, enhanced osteoconductivity, and stimulation of osteogenesis.	Hydroxyapatite, tricalcium phosphate, bio-stimulating nanocomposites	Increased success rate of osseointegration and reduced postoperative recovery time.
Infection prevention	Integration of antimicrobial agents into the implant structure reduces the risk of postoperative infections.	Silver nanoparticles, titanium dioxide, and bioactive antimicrobial compounds	Lower infection risk, reduced need for systemic antibiotic administration.
Customization	Implants created via 3D printing, adapted to patient morphology for superior stability.	Custom polymers, 3D-printed alloys, complex osteoconductive structures	Optimized implant fit, reduced mechanical complications, and increased device longevity.
Stimuli adaptability	Materials capable of reacting to mechanical loads or changes in body temperature.	Nitinol (shape-memory alloy), stimulus-sensitive polymers, and piezoelectric materials	Improved implant stability and enhanced patient comfort during use.
Gradual integration	Use of bioresorbable materials that are gradually replaced by new bone tissue, eliminating the need for further surgery.	Polylactic acid (PLA), biodegradable magnesium, bioresorbable copolymers	Avoidance of additional surgeries, reduced medical costs, and lower surgical risks.
Smart monitoring	Integration of sensors allows real-time monitoring of healing processes and implant stability.	Integrated nanotechnology-based sensors, implants with active biosensors	Early detection of complications, personalized treatment adjustments, and prevention of implant failure.

In the context of rapid technological advancement, smart biomaterials are increasingly being integrated with electronic devices and embedded sensors, enabling real-time monitoring of the healing process following orthopedic implantation. These sensor-integrated systems are capable of providing precise data regarding mechanical load distribution, interfacial stresses at the implant–bone interface, and the progression of osseointegration, as well as early indicators of implant instability or inflammatory complications. Continuous data acquisition allows clinicians to assess implant performance dynamically and to intervene promptly when deviations from normal healing patterns are detected, thereby optimizing postoperative management and reducing the risk of long-term failure [17].

The convergence of smart biomaterials with sensing technologies reflects a broader shift toward intelligent and feedback-driven orthopedic implants, aligned with the principles of personalized medicine. By correlating biomechanical signals with biological responses, these systems facilitate individualized rehabilitation protocols and improve clinical decision-making. Such approaches also hold promise for reducing revision surgery rates by enabling early detection of adverse events, including excessive mechanical loading, delayed bone remodeling, or subclinical infection [18].

Overall, smart biomaterials offer multiple advantages in orthopedic implantology, encompassing high biocompatibility, enhanced stimulation of bone regeneration, effective infection prevention, and the integration of sensor-based monitoring systems. Collectively, these features contribute to significant improvements in implant longevity, functional performance, and patient quality of life. Although challenges remain, particularly with respect to high production costs, technological complexity, and stringent regulatory requirements, the continuous progress in material science, electronics, and biomedical engineering strongly suggests that smart biomaterial-based implants will become a clinical standard in the future of orthopedic surgery [19–21].

Disadvantages and challenges of implementation

Although smart biomaterials represent a significant innovation in orthopedic implantology, their clinical implementation is still associated with multiple challenges and limitations that must be overcome before they can be widely adopted as standardized solutions. One of the primary barriers is the high cost of development and production. The design, synthesis, and validation of smart biomaterials require substantial financial investment, while advanced manufacturing techniques such as nanotechnology-based surface modification and additive manufacturing significantly increase production expenses. Consequently, the accessibility of smart biomaterial-based implants remains limited, particularly in healthcare systems with restricted economic resources [20].

Another major challenge concerns the complex regulatory and clinical validation processes. Because smart biomaterials are engineered to actively interact with biological tissues, their safety and efficacy must be demonstrated through rigorous and prolonged evaluation. Extensive in vitro and in vivo testing is required to assess long-term biocompatibility, degradation behavior, and functional stability. Clinical trials are often lengthy and costly, and regulatory approval procedures are highly demanding, delaying the translation of these technologies into routine clinical practice [1].

Mechanical durability and long-term stability represent additional critical concerns. While many smart biomaterials are designed to integrate progressively with host bone, maintaining sufficient mechanical strength during functional loading remains a challenge. In the case of bioresorbable materials, an imbalance between degradation rate and new bone formation may lead to premature loss of structural support and implant failure. Similarly, shape-memory biomaterials may exhibit altered performance under physiological conditions due to variations in temperature, moisture, or prolonged exposure to biological fluids, potentially affecting their reliability in vivo [17].

Another important limitation is the potential for adverse immunological responses. Despite being designed for high biocompatibility, certain smart biomaterials may still elicit persistent inflammatory reactions if recognized as foreign by the host immune system. Such responses can result in fibrous encapsulation, impaired osteointegration, and reduced implant effectiveness. Moreover, in bioactive systems that release growth factors or antimicrobial agents, precise control of release kinetics is essential to avoid local or systemic toxicity and to maintain physiological tissue homeostasis [11].

Finally, the need for advanced clinical expertise and specialized infrastructure poses a further obstacle to widespread adoption. The successful implantation and monitoring of smart biomaterials often require specialized surgical techniques, multidisciplinary collaboration, and access to advanced technological platforms. These requirements necessitate additional training for orthopedic surgeons and significant institutional investment, potentially slowing large-scale implementation despite the demonstrated clinical potential of these materials [21].

Types of biomaterials used in orthopedic implants

Biomaterials employed in orthopedic implants have undergone substantial evolution over recent decades, driven by increasingly complex requirements related to biocompatibility, mechanical strength, and effective tissue integration. The selection of an appropriate biomaterial depends on multiple factors, including the nature of the bone defect, the required healing timeframe, and compatibility with host tissues. The most commonly used categories include bioresorbable polymers, bioceramics, smart metallic materials, and nanomaterials, each exhibiting distinct properties that make them suitable for specific clinical applications [7,20].

Bioresorbable polymers are increasingly utilized in orthopedic implantology due to their ability to undergo gradual degradation and to be progressively replaced by newly formed bone tissue. This characteristic is particularly advantageous in clinical situations where the avoidance of a second surgical intervention for implant removal is desirable. Polymers such as polylactic acid (PLA) and its copolymers are commonly used in the fabrication of orthopedic screws, pins, and plates that provide temporary mechanical stabilization. However, careful control of degradation kinetics is essential, as excessively rapid resorption may compromise mechanical stability, while overly slow degradation can interfere with normal bone remodeling and healing processes [3,11].

Bioceramics constitute another important class of biomaterials, primarily due to their intrinsic bioactivity and osteoconductive properties. Materials such as hydroxyapatite and tricalcium phosphate exhibit a chemical composition closely resembling that of native bone mineral, which facilitates direct bonding with surrounding bone tissue. These ceramics are frequently applied as coatings on metallic implants to enhance osteointegration and reduce the risk of fibrous encapsulation. Additionally, zirconia-based ceramics are valued for their high mechanical strength, chemical stability, and wear resistance, making them suitable for load-bearing applications such as joint prostheses and long-term orthopedic implants [2,20].

Smart metallic biomaterials, including titanium alloys, cobalt–chromium alloys, and biodegradable magnesium-based systems, remain fundamental in applications requiring a combination of high mechanical performance and excellent biocompatibility. Titanium and its alloys are widely used owing to their favorable strength-to-weight ratio and their ability to form a stable oxide layer that protects against corrosion and adverse interactions with biological fluids. Furthermore, shape-memory alloys such as nickel–titanium (nitinol) exhibit the ability to recover their original shape after deformation, enabling adaptive behavior under physiological conditions. These properties make them particularly useful in flexible orthopedic devices and dynamic fixation systems [7,17].

Collectively, the diversification of biomaterial types used in orthopedic implants reflects a shift toward more biologically integrated and functionally adaptive solutions. By tailoring material properties to specific clinical requirements, modern implantology increasingly supports predictable healing, improved mechanical stability, and enhanced long-term outcomes for patients [1,7,20].

Table 2. This table presents different types of biomaterials used in orthopedic implants, highlighting their characteristics, examples, clinical applications, advantages, and limitations. It provides a comparative overview of bioresorbable polymers, bioceramics, smart metals, and nanomaterials, emphasizing their role in improving implant performance and patient outcomes.

Biomaterial type	*Characteristics*	*Examples*	*Clinical Applications*	*Advantages*
Bioresorbable polymers	Gradually degrade and are replaced by new bone tissue, eliminating the need for implant removal surgery.	Polylactic Acid (PLA), Polyglycolic Acid (PGA), Polycaprolactone (PCL)	Temporary orthopedic fixation devices, biodegradable screws, and bone scaffolds.	Avoids secondary surgeries, promotes natural bone healing, and reduces foreign body reactions.
Bioceramics	Highly biocompatible, osteoconductive, and bioactive; mimics the mineral phase of natural bone.	Hydroxyapatite (HA), Tricalcium Phosphate (TCP), Zirconia (ZrO2)	Bone graft substitutes, coatings for metal implants, and ceramic-based joint replacements.	High biocompatibility stimulates bone growth and integrates well with host tissues.
Smart metals	Excellent mechanical properties, corrosion resistance, and adaptability to physiological conditions.	Titanium alloys (Ti-6Al-4V), Cobalt-Chromium (Co-Cr), Nitinol (Ni-Ti)	Joint prostheses, spinal implants, fracture fixation plates, and shape-memory devices.	High strength, long-term durability, and adaptability to dynamic physiological conditions.
Nanomaterials	Enhanced surface interactions, antimicrobial properties, and improved osteointegration.	Silver nanoparticles, Carbon Nanotubes (CNTs), Graphene-based composites	Antimicrobial coatings, bioactive surface modifications, and enhanced tissue regeneration materials.	Enhanced cellular response, superior osteointegration, and antimicrobial effects reduce infection risks.

Nanomaterials and surface-functionalized implants represent a highly promising research direction in orthopedic implantology, owing to their ability to enhance interactions with osteoblastic cells and to accelerate bone regeneration processes. By modifying implant surfaces at the nano-scale, it is possible to more closely replicate the natural extracellular matrix, thereby improving protein adsorption, cell adhesion, proliferation, and osteogenic differentiation. These nano-engineered interfaces play a critical role in optimizing early-stage osteointegration and long-term implant stability [2,7].

Nanoparticle-based coatings, particularly those incorporating silver nanoparticles or titanium dioxide, have demonstrated significant antimicrobial properties. Such coatings effectively reduce bacterial adhesion and biofilm formation on implant surfaces, thereby substantially lowering the risk of postoperative infections—one of the most serious complications in orthopedic surgery. Importantly, these antimicrobial effects can be achieved without compromising biocompatibility when nanoparticle concentration and release kinetics are carefully controlled [7,20].

In parallel, the development of nanocomposites that combine the mechanical strength of metallic substrates with the bioactivity of ceramic components has gained increasing attention. These hybrid materials leverage the load-bearing capacity of metals while incorporating osteoconductive or osteoinductive ceramic phases, such as hydroxyapatite, to enhance biological performance. Such nanocomposites are particularly attractive for the fabrication of patient-specific implants, as they can be engineered to respond more effectively to individual biomechanical and biological requirements [2,20].

Overall, nanomaterials and functionalized surfaces contribute substantially to the advancement of orthopedic implant technology by improving biological integration, reducing infection risk, and enabling the design of multifunctional and personalized implant systems. These strategies underscore the growing importance of nano-scale engineering in the development of next-generation orthopedic biomaterials [2,7,20].

Conclusions

Smart biomaterials have redefined orthopedic implantology, offering innovative solutions that overcome the limitations of traditional materials. Their evolution has allowed the development of implants that are more biocompatible, more durable, and capable of actively interacting with host tissues, stimulating bone regeneration and reducing the risk of postoperative complications. These advances have been made possible thanks to the integration of tissue engineering, nanotechnology, and smart sensors, which help optimize clinical outcomes and improve patients' quality of life.

One of the biggest advantages of smart biomaterials is their ability to adapt to the specific needs of each patient, either through anatomical customization or controlled release of growth factors or drugs. Also, the use of bioactive surfaces and nanocomposites has led to an acceleration of the osseointegration process and a decrease in the risk of rejection. In addition, biodegradable materials have opened up new perspectives in terms of tissue regeneration, eliminating the need for additional surgery to remove implants.

However, the deployment of smart biomaterials on a large scale still faces significant challenges. High costs, the need for extensive clinical trials, and strict regulations are obstacles that slow down the adoption of these technologies in medical practice. Also, long-term durability and immunological compatibility remain aspects that require further research to ensure patient safety.

In the future, smart biomaterials will become increasingly integrated with digital technologies and personalized medicine, allowing implants to provide real-time feedback and optimize the healing process. The development of materials capable of dynamically responding to biological and mechanical stimuli will represent an essential step towards fully adaptable orthopedic implants that will significantly improve the efficiency of treatment.

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