Review article
https://doi.org/10.18019/1028-4427-2025-31-3-388-398

Smart orthopedic implants: the future of personalized joint replacement and monitoring

E. Kirolos

Faculty of Medicine and Surgery, Helwan University, Egypt

kiroloss.eskandar@gmail.com

Abstract

Introduction Smart orthopedic implants integrate advanced sensor technologies to revolutionize joint replacement and orthopedic care. These implants enable real-time monitoring of key parameters such as wear, load distribution, and infection indicators, facilitating early intervention and personalized treatment.

This review **aims** to evaluate the current advancements, clinical applications, challenges, and future directions of smart orthopedic implants.

Methods A systematic literature review was conducted following PRISMA guidelines, analyzing peer-reviewed studies published between February 2015 and January 2025. Sources were retrieved from PubMed, Scopus, Web of Science, and Google Scholar. Inclusion criteria focused on technological innovations, clinical applications, and regulatory considerations.

Results & Discussion Technological advancements in materials, sensor integration, wireless communication, and artificial intelligence have optimized implant functionality. Smart implants enhance postoperative monitoring, predict implant wear, and personalize rehabilitation. Despite their benefits, challenges such as biocompatibility, data security, battery life, and regulatory approval hinder widespread adoption. Addressing these issues through interdisciplinary research is critical for future developments.

Conclusion Smart orthopedic implants have the potential to transform musculoskeletal healthcare by enabling real-time patient monitoring and personalized treatment strategies. Continued innovation in materials, AI-driven analytics, and regulatory frameworks will be crucial for overcoming current limitations and ensuring their widespread clinical adoption.

Keywords: Smart orthopedic implants, Spinal implants, Trauma fixation, Sports medicine implants, Joint replacement, Integrated sensors, Real-time patient monitoring, Personalized healthcare

For citation: Kirolos E. Smart orthopedic implants: the future of personalized joint replacement and monitoring. *Genij Ortopedii*. 2025;31(3):388-398. doi: 10.18019/1028-4427-2025-31-3-388-398.

Обзорная статья
УДК [616.72 -77:004.9]-08-07
https://doi.org/10.18019/1028-4427-2025-31-3-388-398

Интеллектуальные ортопедические имплантаты: будущее персонализированной замены суставов и мониторинга

Э. Киролос

Факультет медицины и хирургии, Университет Хелуана, Египет

kiroloss.eskandar@gmail.com

Аннотация

Введение. Интеллектуальные ортопедические имплантаты объединяют передовые сенсорные технологии, чтобы произвести революцию в замене суставов и ортопедической помощи. Эти имплантаты позволяют в режиме реального времени контролировать ключевые параметры, такие как износ, распределение нагрузки и показатели инфекции, что облегчает проведение раннего вмешательства и персонализированное лечение.

Цель — оценить текущие достижения, клиническое применение, проблемы и будущие направления интеллектуальных ортопедических имплантатов.

Методы. В соответствии с рекомендациями PRISMA проведен систематический обзор литературы, в котором проанализированы рецензируемые исследования, опубликованные в период с февраля 2015 года по январь 2025 года. Источники отобраны в PubMed, Scopus, Web of Science и Google Scholar. Включены работы, описывающие технологические инновации, клиническое применение и нормативно-правовые аспекты.

Результаты и обсуждение. Технологические достижения в области материалов, интеграции датчиков, беспроводной связи и искусственного интеллекта позволили оптимизировать функциональность имплантатов. Умные имплантаты улучшают послеоперационный мониторинг, прогнозируют износ имплантатов и персонализируют реабилитацию. Несмотря на их преимущества, широкому внедрению препятствуют такие проблемы, как биосовместимость, безопасность данных, срок службы батарей и одобрение регулирующих органов. Решение этих проблем посредством междисциплинарных исследований имеет решающее значение для будущих разработок.

Заключение. Умные ортопедические имплантаты способны изменить систему лечения заболеваний опорно-двигательной системы обеспечивая мониторинг состояния пациента в реальном времени и персонализированные стратегии лечения. Постоянные инновации в области материалов, аналитика на основе искусственного интеллекта и нормативно-правовой базы будут иметь решающее значение для преодоления существующих ограничений и обеспечения их широкого клинического внедрения.

Ключевые слова: умные ортопедические имплантаты, спинальные имплантаты, фиксация травм, спортивные медицинские имплантаты, замена суставов, интегрированные датчики, мониторинг состояния пациента в реальном времени, персонализированное здравоохранение

Для цитирования: Киролос Э. Интеллектуальные ортопедические имплантаты: будущее персонализированной замены суставов и мониторинга. *Гений ортопедии*. 2025;31(3):388-398. doi: 10.18019/1028-4427-2025-31-3-388-398.

INTRODUCTION

Smart orthopedic implants represent a significant advancement in medical technology, combining therapeutic functions with diagnostic capabilities to enhance patient care. These implants are designed to monitor various physiological parameters in real-time, providing valuable data that can inform treatment decisions and improve outcomes [1]. By integrating sensors and communication technologies, smart implants can detect changes in pressure, force, strain, displacement, proximity, and temperature within the body, offering insights that were previously unattainable through traditional methods [2].

The evolution of orthopedic implants has been marked by a transition from purely mechanical devices to sophisticated systems capable of interactive functions. Traditional implants primarily served structural roles, such as replacing or supporting damaged bones and joints [3]. However, advancements in materials science, sensor technology, and wireless communication have enabled the development of smart implants that not only fulfill structural requirements but also monitor the biological environment. For instance, modern smart implants can measure mechanical loads and stresses, providing data on how the implant interacts with the surrounding tissues during different activities [4]. This information is crucial for assessing implant performance and longevity.

Beyond joint replacement, smart orthopedic implants are being explored for applications in spine surgery, trauma fixation, and sports medicine. Personalization in joint replacement has become increasingly important as it allows for treatments tailored to individual patient needs. Smart implants facilitate this by providing continuous, patient-specific data that can guide personalized rehabilitation protocols and postoperative care [5]. For example, sensors within the implant can monitor the healing process and detect early signs of complications, such as infection or implant loosening, enabling timely interventions. This personalized approach not only enhances patient outcomes but also contributes to more efficient healthcare delivery by reducing the incidence of complications and the need for revision surgeries [6].

To ensure a comprehensive evaluation, this review follows a systematic methodology, incorporating studies from a diverse range of orthopedic specialties. By analyzing the latest technological advancements, clinical applications, and emerging challenges, this review provides a holistic overview of the role of smart orthopedic implants in modern medicine.

This review **aims** to evaluate the current advancements, clinical applications, challenges, and future directions of smart orthopedic implants.

METHODOLOGY

To conduct this comprehensive literature review on smart orthopedic implants, a systematic and structured approach was employed to ensure thorough and unbiased coverage of relevant research. The methodology adhered to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines to enhance transparency and reproducibility. The steps of the methodology are detailed below:

Literature Search Strategy

- A comprehensive search was conducted across multiple reputable scientific databases, including PubMed, Scopus, Web of Science, and Google Scholar.
- Search queries incorporated relevant keywords and Boolean operators to ensure a wide but precise retrieval of literature. The primary search terms included:
  — "Smart orthopedic implants";
  — "Joint replacement";
  — "Integrated sensors";
  — "Real-time patient monitoring";
  — "Personalized healthcare".
- Synonyms and related terms were also included, such as "intelligent implants", "biomechanical sensors" and "orthopedic innovations".

Inclusion and Exclusion Criteria

- Inclusion criteria were applied to identify studies relevant to the scope of the review:
  — Studies published in English;
  — Peer-reviewed articles, conference papers, and systematic reviews;
  — Publications focused specifically on smart orthopedic implants and their applications in joint replacement or patient monitoring;
  — Studies discussing technological innovations, clinical applications, or challenges associated with smart implants.
- Exclusion criteria were employed to refine the selection further:
  — Articles not available in full text;
  — Non-peer-reviewed sources, editorials, and opinion pieces;
  — Publications focusing solely on traditional orthopedic implants without integrating smart technologies.

Study Selection Process

— The initial database search yielded 164 articles;

— After removing duplicate entries, 116 articles remained;

— Titles and abstracts were screened independently by two reviewers to assess relevance. A total of 84 articles were selected for full-text review;

— The full-text evaluation led to the final inclusion of 66 studies based on their alignment with the inclusion criteria and their contribution to the objectives of the review.

Data Extraction and Management

- A standardized data extraction form was developed to ensure consistency across studies. Key data points included:
  — Publication details (authors, year, journal);
  — Study type (e.g., experimental, observational, or review);
  — Focus of the study (e.g., sensor technology, clinical outcomes, biocompatibility);
  — Key findings and conclusions.
- Extracted data were systematically organized into tables to facilitate synthesis and analysis.

Quality Assessment

- The quality of included studies was assessed using established tools tailored to the study type. For example:
  — Experimental studies were evaluated using the Cochrane risk-of-bias tool;
  — Observational studies were assessed with the Newcastle-Ottawa Scale (NOS);
- Studies with significant methodological limitations were noted but retained if they provided valuable insights.

Synthesis of Findings

- A narrative synthesis approach was adopted to summarize findings across diverse studies;
- Data were categorized into key themes, including technological innovations, clinical applications, real-time monitoring, and challenges associated with smart implants;
- Visual aids, such as the PRISMA flow diagram and summary tables, were employed to enhance clarity and presentation of the findings.

A PRISMA flow diagram (Figure 1) was used to illustrate the study selection process, including the number of records identified, screened, assessed for eligibility, and included in the final review. Reasons for exclusion at each stage were clearly documented.

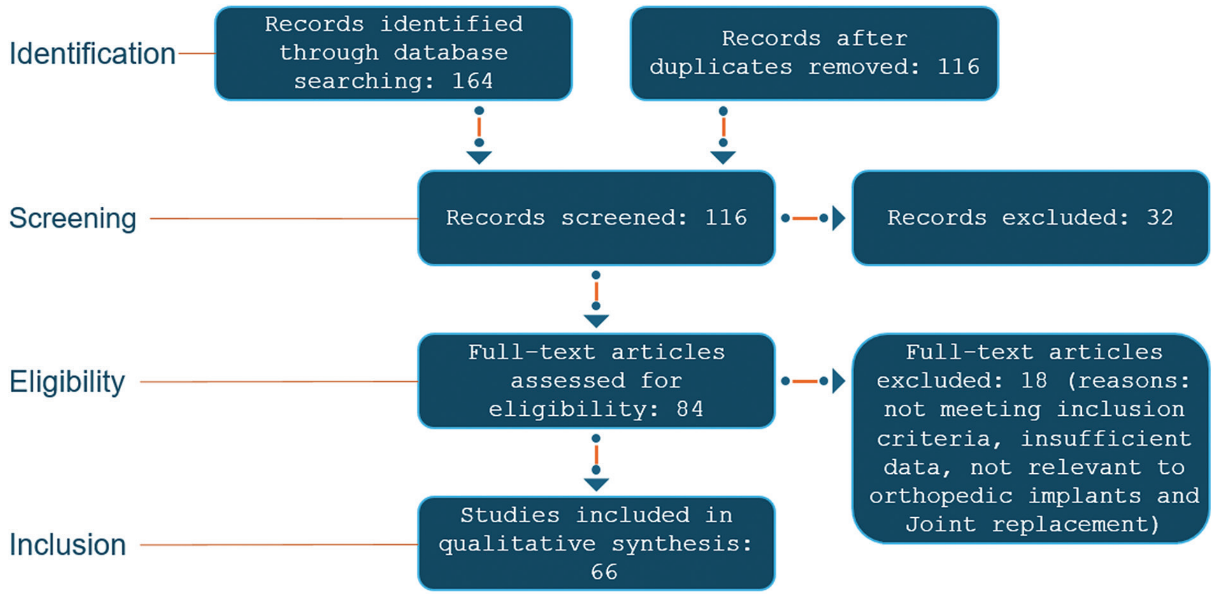

Fig. 1. Illustrates the PRISMA flow diagram

RESULTS AND DISCUSSION

Technological Innovations in Smart Implants

Smart orthopedic implants have undergone significant technological advancements, particularly in the integration of various sensor types, material selection, design considerations, and wireless communication technologies [7]. These innovations aim to enhance the functionality and efficacy of implants in monitoring patient health and improving clinical outcomes.

A variety of sensors have been incorporated into smart implants to monitor physiological and mechanical parameters. Strain gauges are commonly used to measure mechanical load and stress on the implant, providing data on pressure applied during different activities [8]. Temperature sensors monitor local temperature around the implant to detect signs of inflammation or infection. Accelerometers track patient movements and activity levels, ensuring proper usage and adherence to rehabilitation protocols. pH sensors detect changes in pH levels, indicating infection or tissue response to the implant [2]. Additional developments include biosensors capable of detecting biochemical markers that signal early complications, such as osteolysis or metallosis, further improving diagnostic precision (Table 1).

Table 1

Comparison of Smart Implant Technologies Based on Functionality, Application, and Advantages

Technology	Function	Application	Advantages
Strain Gauges	Measure stress/load	Joint replacements	Early detection of implant wear
Temperature Sensors	Detect infection	Trauma fixation	Timely intervention for inflammation
Accelerometers	Monitor movement	Spinal implants	Optimize rehabilitation adherence
Biosensors	Detect biomarkers	Various implants	Advanced infection diagnostics
5G/IoMT	Wireless communication	All smart implants	Faster, real-time data transmission

The selection of materials and design of smart implants are critical to their performance and biocompatibility. Implants are typically made from materials such as titanium, stainless steel, and various polymers designed to integrate well with bone and tissue. These materials are chosen for their strength, durability, and compatibility with the human body to minimize the risk of rejection and complications [9]. Recent advances have introduced bioactive coatings that promote osseointegration, further enhancing the longevity and stability of implants. The design must also accommodate the integration of sensors and electronic components without compromising the structural integrity of the implant. Advancements in microelectronics and nanotechnology have enabled the development of smaller, more efficient sensors and power sources, making smart implants less intrusive and more comfortable for patients [10].

Wireless communication and data transmission technologies are integral to the functionality of smart implants, enabling real-time monitoring and data collection. Smart implants are equipped with wireless communication capabilities, such as Bluetooth or Near Field Communication (NFC), allowing them to transmit data to external devices like smartphones, tablets, or computers [11]. This facilitates remote monitoring by healthcare providers, enabling timely adjustments to treatment plans without the need for frequent in-person visits. Emerging communication technologies, such as 5G and Internet of Medical Things (IoMT), offer faster, more secure data transfer, enhancing real-time decision-making in orthopedic care. Some implants also have onboard data storage, allowing them to store information locally until it can be downloaded during a follow-up appointment. Advanced algorithms and software can analyze this data to detect patterns, predict potential issues, and provide recommendations for personalized care [12].

Real-Time Monitoring Capabilities

Smart orthopedic implants have significantly advanced real-time monitoring capabilities, offering detailed insights into implant wear, early infection detection, and the measurement of load distribution and stress. These functionalities are pivotal in enhancing patient outcomes and extending implant longevity [7].

One of the primary advantages of smart implants is their ability to monitor wear and tear in real-time. By integrating strain gauges and other sensors, these implants can detect minute deformations and stresses that occur during daily activities [1]. This continuous monitoring allows for the early identification of potential issues, such as implant loosening or material degradation, enabling timely medical interventions to prevent further complications [13]. AI-powered predictive modeling is now being employed to analyze wear trends, allowing for proactive maintenance and early intervention strategies.

Early detection of infections is another critical function of smart implants. Infections can lead to severe complications if not promptly addressed. Smart implants equipped with temperature and pH sensors can monitor the local environment around the implant site [1]. Elevations in temperature or shifts in pH levels can indicate the onset of an infection, allowing healthcare providers to initiate treatment before the condition worsens [14]. Advanced biosensors capable of detecting inflammatory cytokines and bacterial activity are now being explored, offering a more precise and earlier detection of infections.

Measuring load distribution and stress on implants is essential for assessing their performance and ensuring patient safety. Smart implants utilize embedded sensors to capture data on the forces exerted during various physical activities [15]. This information is invaluable for understanding how different movements affect the implant and surrounding tissues. For instance, in joint replacements, monitoring load distribution can inform personalized rehabilitation protocols, ensuring that patients engage in activities that promote healing without overloading the implant [16]. Real-time biomechanical feedback allows for dynamic adjustments in patient rehabilitation plans, further enhancing recovery outcomes.

The integration of these monitoring capabilities into orthopedic implants represents a significant advancement in personalized medicine [17]. By providing continuous, real-time data, smart implants enable healthcare providers to tailor treatments to individual patient needs, promptly address complications, and optimize rehabilitation strategies. This proactive approach not only enhances patient outcomes but also contributes to the longevity and success of the implants [5]. As these technologies continue to evolve, integration with cloud-based analytics and AI-driven diagnostics will further refine personalized patient care.

Data-Driven Optimization of Patient Outcomes

The integration of artificial intelligence (AI) and machine learning (ML) into smart orthopedic implants has ushered in a new era of data-driven optimization in patient care. These technologies enable the analysis of real-time data, facilitating personalized treatment strategies and enhancing clinical outcomes [18].

AI and ML algorithms are adept at processing vast amounts of data generated by smart implants, identifying patterns, and predicting potential complications [19]. For instance, by analyzing sensor data on joint movement and load distribution, AI can detect anomalies indicative of implant wear or misalignment, facilitating early interventions. This predictive capability enhances patient outcomes by preventing issues before they become clinically significant [20].

Personalized rehabilitation plans are another significant benefit of AI integration. Data from smart implants inform tailored rehabilitation protocols, adjusting exercises based on real-time feedback [21]. This approach ensures that patients engage in activities that promote optimal recovery while avoiding movements that could jeopardize implant integrity. Such individualized care accelerates healing and improves overall patient satisfaction [22].

Integrating implant data with electronic health records (EHRs) creates a comprehensive patient profile, enhancing clinical decision-making. This amalgamation allows healthcare providers to monitor patient progress remotely, adjust treatment plans in real-time, and maintain detailed records of implant performance [23]. Moreover, the continuous data flow from smart implants to EHRs facilitates large-scale analyses, contributing to improved implant designs and personalized treatment strategies [24].

The integration of AI and ML into smart orthopedic implants represents a significant advancement in personalized medicine. By providing continuous, real-time data, smart implants enable healthcare providers to tailor treatments to individual patient needs, promptly address complications, and optimize rehabilitation strategies [25]. This proactive approach not only enhances patient outcomes but also contributes to the longevity and success of the implants.

Applications in Specific Orthopedic Conditions

Smart orthopedic implants represent a significant advancement in the treatment of various musculoskeletal conditions, offering real-time data and personalized therapeutic interventions. Their applications are particularly notable in knee and hip replacements, spinal implants, and the management of trauma and sports-related injuries [26].

In knee arthroplasty, the advent of smart implants has transformed postoperative care. Devices such as the Persona IQ® have been developed to function similarly to standard knee replacements but with integrated sensor technology. These sensors are embedded within the tibial stem and are capable of measuring a range of parameters, including range of motion, step count, and walking speed [27]. The collected data is wirelessly transmitted to healthcare providers, enabling continuous remote monitoring of the patient's progress. This real-time feedback allows for the timely identification of any deviations from expected recovery patterns, facilitating prompt interventions when necessary [28]. Moreover, the personalized data supports the customization of rehabilitation protocols, ensuring that exercises are tailored to the individual's specific needs and capabilities, thereby promoting optimal recovery outcomes [29].

Similarly, in hip arthroplasty, smart implants are being utilized to enhance patient outcomes. These devices integrate sensor technology to monitor various parameters, providing valuable data that can be used to tailor postoperative care and rehabilitation [1]. In spinal surgery, the application of smart implants is emerging as a promising innovation. These devices are designed to monitor parameters such as load distribution and alignment, providing real-time data that can assist surgeons in optimizing implant placement and postoperative care [17].

In the realm of trauma and sports medicine, smart implants hold significant potential for transforming patient care. In fracture management, for instance, smart implants can monitor the stability of the fixation and the progress of bone healing, allowing for timely interventions if complications arise. In sports medicine, smart implants can provide data on joint loading and movement patterns, aiding in the optimization of rehabilitation protocols and the prevention of re-injury [30, 31].

Challenges and Limitations

The advancement of smart orthopedic implants introduces several challenges and limitations that must be addressed to ensure their efficacy and safety. Key concerns include biocompatibility and long-term durability of integrated sensors, battery life and energy efficiency of the implants, and data privacy alongside cybersecurity issues [32].

Biocompatibility is a critical factor in the development of smart implants. The integration of sensors and electronic components within these devices necessitates materials that are not only functional but also compatible with human tissue. Materials such as polyethylene, titanium, and parylene have been utilized due to their favorable biocompatibility profiles [33]. However, the presence of electronic components can elicit foreign body reactions, including inflammatory responses and fibrous encapsulation, which may compromise sensor functionality over time [34]. For instance, histological changes in the tissue surrounding the implant, such as inflammation and fibrous tissue formation, can impair biosensor activity, leading to potential device failure. Additionally, concerns have been raised regarding the potential cytotoxic, genotoxic, or pyrogenic effects of implant failure, particularly in younger patients [35].

The longevity of smart implants is closely tied to their power management systems. Many devices rely on batteries to power integrated sensors and communication modules. Ensuring adequate battery life while maintaining a compact implant size presents a significant engineering challenge [36]. Microelectromechanical systems (MEMS)-based technologies have been employed to reduce the size of sensors and associated circuitry, thereby decreasing power consumption. However, operating at higher frequencies to achieve this reduction can lead to increased energy absorption by surrounding tissues, potentially causing heating and signal attenuation [37]. Exploring alternative power sources, such as energy harvesting from body movements or wireless power transmission, may offer solutions but also introduce additional complexities in design and safety considerations [38].

Data privacy and cybersecurity are paramount concerns in the deployment of smart implants. These devices collect and transmit sensitive patient data, including physiological parameters and activity levels, which must be protected from unauthorized access and breaches [39]. The increasing prevalence of cyber threats in healthcare necessitates robust security measures to safeguard this information. Ethical considerations also arise regarding the ownership and use of the data generated by these implants. Ensuring compliance with data protection regulations and maintaining patient trust are critical for the widespread adoption of smart implant technologies [40]. Furthermore, the integration of wireless communication systems within implants introduces potential vulnerabilities that could be exploited, underscoring the need for comprehensive cybersecurity strategies in the design and implementation of these devices [41].

Addressing these challenges requires a multidisciplinary approach, combining expertise in materials science, biomedical engineering, cybersecurity, and clinical practice. Ongoing research and development efforts are focused on enhancing the biocompatibility and durability of implant materials, improving energy efficiency and exploring alternative power solutions, and implementing robust data protection mechanisms. Through these concerted efforts, the potential of smart orthopedic implants to improve patient outcomes can be fully realized [42, 43].

Regulatory and Ethical Considerations

The integration of smart implants into orthopedic practice necessitates careful navigation of regulatory frameworks and ethical considerations to ensure patient safety, data security, and informed consent [44].

Regulatory approval processes for smart implants are complex and multifaceted. In the United States, the Food and Drug Administration (FDA) oversees the evaluation and authorization of these devices. Depending on the risk classification of the implant, different regulatory pathways may be applicabl [45]. For instance, devices deemed to have moderate risk may undergo the 510(k) premarket notification process, which requires demonstrating substantial equivalence to a legally marketed predicate device. This pathway is generally less burdensome than the premarket approval (PMA) process, which is reserved for higher-risk devices and necessitates more extensive clinical evidence [46]. The FDA has been working to provide clearer guidance on the regulatory requirements for smart medical devices, acknowledging the unique challenges they present [47].

Ethical implications of continuous patient monitoring via smart implants are significant. While these devices offer the potential for real-time health monitoring and early detection of complications, they also raise concerns about patient autonomy and the potential for over-surveillance [48]. Continuous data collection may lead to information overload for both patients and healthcare providers, and there is a risk that patients may feel their privacy is being infringed upon. Moreover, the psychological impact of constant health monitoring should not be underestimated, as it may induce anxiety or alter patient behavior. It is essential to balance the benefits of continuous monitoring with respect for patient autonomy and privacy [49, 50].

Addressing patient consent and data ownership is crucial in the deployment of smart implants. Patients must be fully informed about what data will be collected, how it will be used, who will have access to it, and the measures in place to protect their privacy [51]. Clear and comprehensive consent processes are essential to ensure that patients understand and agree to the data practices associated with their implants. Furthermore, issues of data ownership must be clarified; patients should have rights to access their data and control its use [52]. This includes the ability to withdraw consent and have their data deleted if they so choose. Healthcare providers and device manufacturers must navigate these issues carefully to maintain trust and comply with data protection regulations [53].

Future Directions and Research Gaps

The field of smart orthopedic implants is poised for significant advancements, driven by emerging technologies and interdisciplinary collaboration. Innovations such as self-healing materials, bioelectronics, and bioprinting are at the forefront of research, aiming to enhance implant functionality and patient outcomes [54].

Self-healing materials represent a promising avenue in orthopedic implant development. These materials have the intrinsic ability to repair damage without external intervention, potentially extending the lifespan of implants and reducing the need for revision surgeries [55]. Incorporating self-healing polymers or composites into implant design could allow for the automatic repair of microcracks or other minor damages that occur over time, maintaining the structural integrity and performance of the implant. Research in this area is ongoing, with studies exploring various self-healing mechanisms and their applicability to load-bearing orthopedic devices [56].

Bioelectronics is another emerging field with significant implications for smart implants. The integration of electronic components with biological systems enables real-time monitoring and therapeutic interventions [57]. For instance, bioelectronic implants can be designed to monitor bone healing processes and deliver electrical stimulation to promote tissue regeneration. Recent advancements have led to the development of multifunctional bone implants that combine sensing capabilities with therapeutic actuation systems, offering a comprehensive approach to patient care [58, 59].

Bioprinting, particularly three-dimensional (3D) bioprinting, holds significant potential in creating custom smart implants tailored to individual patient anatomies. This technology allows for the precise fabrication of complex structures using bioinks composed of cells and biomaterials [60]. In orthopedic applications, 3D bioprinting can be utilized to produce scaffolds that mimic the native bone architecture, facilitating better integration and promoting tissue regeneration. Moreover, bioprinting enables the customization of implants to match patient-specific defect sites, potentially improving surgical outcomes and reducing recovery times [61].

The successful development and implementation of these advanced technologies necessitate close collaboration between orthopedic surgeons, engineers, and data scientists. Surgeons provide critical clinical insights and define the functional requirements of implants, while engineers contribute expertise in materials science, biomechanics, and device design [62]. Data scientists play a pivotal role in analyzing the vast amounts of data generated by smart implants, developing algorithms to interpret sensor outputs, and creating predictive models to inform clinical decision-making [63]. This interdisciplinary approach ensures that smart implants are designed with a comprehensive understanding of both clinical needs and technological capabilities, ultimately leading to more effective and personalized patient care [64].

Despite these promising developments, several research gaps remain. Further studies are needed to optimize the properties of self-healing materials for orthopedic applications, ensuring they can withstand the mechanical demands of load-bearing implants. The long-term biocompatibility and stability of bioelectronic components within the human body require thorough investigation [65]. Additionally, while bioprinting has demonstrated potential, challenges related to the vascularization of printed tissues and the scalability of the technology must be addressed. Ongoing research and collaboration across disciplines will be essential to overcome these challenges and fully realize the potential of smart orthopedic implants [66].

CONCLUSION

In conclusion, smart orthopedic implants represent a groundbreaking innovation at the intersection of medicine, engineering, and data science, offering a transformative approach to joint replacement and musculoskeletal care. By integrating advanced sensors, wireless communication, and real-time data analytics, these implants provide unprecedented capabilities for monitoring wear, detecting complications, and optimizing treatment outcomes. The incorporation of emerging technologies, such as self-healing materials, bioelectronics, and bioprinting, alongside interdisciplinary collaboration, underscores the vast potential of smart implants to enhance orthopedic care and improve patient quality of life. Despite challenges related to biocompatibility, data security, and regulatory hurdles, the ongoing evolution of smart implant technologies highlights a promising future where personalized, data-driven, and patient-centered solutions become the cornerstone of healthcare. Embracing these innovations will not only redefine orthopedic practices but also pave the way for a new era of intelligent healthcare systems designed to deliver better outcomes and quality of life for patients worldwide.

Conflict of interest *The authors declare that they have no competing interests.*

Funding *Not applicable.*

Ethics approval and consent to participate *Not applicable.*

Consent for publication *Not applicable.*

Availability of data and material *Data sharing not applicable to this article as no data-sets were generated or analyzed during the current study.*

REFERENCES

1. Abyzova E, Dogadina E, Rodriguez RD, et al. Beyond Tissue replacement: The Emerging role of smart implants in healthcare. *Mater Today Bio*. 2023;22:100784. doi: 10.1016/j.mtbio.2023.100784.
2. Yogev D, Goldberg T, Arami A, et al. Current state of the art and future directions for implantable sensors in medical technology: Clinical needs and engineering challenges. *APL Bioeng*. 2023;7(3):031506. doi: 10.1063/5.0152290.
3. Wu Y, Liu J, Kang L, et al. An overview of 3D printed metal implants in orthopedic applications: Present and future perspectives. *Heliyon*. 2023;9(7):e17718. doi: 10.1016/j.heliyon.2023.e17718.
4. Hossain N, Mahmud MZA, Hossain A, et al. Advances of materials science in MEMS applications: A review. *Results Eng*. 2024;22(2):102115. doi: 10.1016/j.rineng.2024.102115.
5. Luo Y. Toward Fully Automated Personalized Orthopedic Treatments: Innovations and Interdisciplinary Gaps. *Bioengineering (Basel)*. 2024;11(8):817. doi: 10.3390/bioengineering11080817.
6. Iyengar KP, Kariya AD, Botchu R, et al. Significant capabilities of SMART sensor technology and their applications for Industry 4.0 in trauma and orthopaedics. *Sensors Int*. 2022;(3):100163. doi: 10.1016/j.sintl.2022.100163.
7. Kelmers E, Szuba A, King SW, et al. "Smart Knee Implants: An Overview of Current Technologies and Future Possibilities". *Indian J Orthop*. 2022;57(5):635-642. doi: 10.1007/s43465-022-00810-5.
8. Wang J, Chu J, Song J, Li Z. The application of impantable sensors in the musculoskeletal system: a review. *Front Bioeng Biotechnol*. 2024;12:1270237. doi: 10.3389/fbioe.2024.1270237.
9. Abd-Elaziem W, Darwish MA, Hamada A, Daoush WM. Titanium-Based alloys and composites for orthopedic implants Applications: A comprehensive review. *Materials & Design*. 2024;241:112850. doi: 10.1016/j.matdes.2024.112850.

10. Juanola-Feliu E, Miribel-Català PL, Páez Avilés C, et al. Design of a customized multipurpose nano-enabled implantable system for in-vivo theranostics. *Sensors (Basel)*. 2014;14(10):19275-19306. doi: 10.3390/s141019275.
11. Cao Z, Chen P, Ma Z, et al. Near-Field Communication Sensors. *Sensors (Basel)*. 2019;19(18):3947. doi: 10.3390/s19183947.
12. Serrano LP, Maita KC, Avila FR, et al. Benefits and Challenges of Remote Patient Monitoring as Perceived by Health Care Practitioners: A Systematic Review. *Perm J*. 2023;27(4):100-111. doi: 10.7812/TPP/23.022.
13. Windolf M, Varjas V, Gehweiler D, et al. Continuous Implant Load Monitoring to Assess Bone Healing Status-Evidence from Animal Testing. *Medicina (Kaunas)*. 2022;58(7):858. doi: 10.3390/medicina58070858.
14. Fulton II MR, Zubair M, Taghavi S. Laboratory Evaluation of Sepsis. 2023. In: *StatPearls [Internet]*. Treasure Island (FL): StatPearls Publishing; 2023. Available at: https://www.ncbi.nlm.nih.gov/books/NBK594258/. Accessed Feb 5, 2025.
15. Gaobotse G, Mbunge E, Batani J, Muchemwa B. Non-invasive smart implants in healthcare: Redefining healthcare services delivery through sensors and emerging digital health technologies. *Sensors Int*. 2022;3:100156. doi: 10.1016/j.sintl.2022.100156.
16. Eghan-Acquah E, Bavil AY, Bade D, et al. Enhancing biomechanical outcomes in proximal femoral osteotomy through optimised blade plate sizing: A neuromusculoskeletal-informed finite element analysis. *Comput Methods Programs Biomed*. 2024;257:108480. doi: 10.1016/j.cmpb.2024.108480.
17. Ledet EH, Liddle B, Kradinova K, Harper S. Smart implants in orthopedic surgery, improving patient outcomes: a review. *Innov Entrep Health*. 2018;5:41-51. doi: 10.2147/IEH.S133518.
18. Tariq A, Gill AY, Hussain HK. Evaluating the potential of artificial intelligence in orthopedic surgery for value-based healthcare. *Int J Multidisc Sci Arts*. 2023;2(2):27-35. doi: 10.47709/ijmdsa.v2i1.2394.
19. Vora LK, Gholap AD, Jetha K, et al. Artificial Intelligence in Pharmaceutical Technology and Drug Delivery Design. *Pharmaceutics*. 2023;15(7):1916. doi: 10.3390/pharmaceutics15071916.
20. Wang C, He T, Zhou H, et al. Artificial intelligence enhanced sensors - enabling technologies to next-generation healthcare and biomedical platform. *Bioelectron Med*. 2023;9(1):17. doi: 10.1186/s42234-023-00118-1.
21. Sumner J, Lim HW, Chong LS, et al. Artificial intelligence in physical rehabilitation: A systematic review. *Artif Intell Med*. 2023;146:102693. doi: 10.1016/j.artmed.2023.102693.
22. Chirayath A, Dhaniwala N, Kawde K. A Comprehensive Review on Managing Fracture Calcaneum by Surgical and Non-surgical Modalities. *Cureus*. 2024;16(2):e54786. doi: 10.7759/cureus.54786.
23. Adeniyi NO, Arowoogun JO, Chidi R, et al. The impact of electronic health records on patient care and outcomes: A comprehensive review. *World J Adv Res Rev*. 2024;21(2):1446-1455. doi: 10.30574/wjarr.2024.21.2.0592
24. Ghazizadeh E, Naseri Z, Deigner HP, et al. Approaches of wearable and implantable biosensor towards of developing in precision medicine. *Front Med (Lausanne)*. 2024;11:1390634. doi: 10.3389/fmed.2024.1390634.
25. Andriollo L, Picchi A, Iademarco G, et al. The Role of Artificial Intelligence and Emerging Technologies in Advancing Total Hip Arthroplasty. *J Pers Med*. 2025;15(1):21. doi: 10.3390/jpm15010021.
26. Akhtar MN, Haleem A, Javaid M, et al. Artificial intelligence-based orthopaedic perpetual design. *J Clin Orthop Trauma*. 2024;49:102356. doi: 10.1016/j.jcot.2024.102356.
27. Iyengar KP, Gowers BTV, Jain VK, et al. Smart sensor implant technology in total knee arthroplasty. *J Clin Orthop Trauma*. 2021;22:101605. doi: 10.1016/j.jcot.2021.101605.
28. Abdulmalek S, Nasir A, Jabbar WA, et al. IoT-Based Healthcare-Monitoring System towards Improving Quality of Life: A Review. *Healthcare (Basel)*. 2022;10(10):1993. doi: 10.3390/healthcare10101993.
29. Li X, He Y, Wang D, Rezaei MJ. Stroke rehabilitation: from diagnosis to therapy. *Front Neurol*. 2024;15:1402729. doi: 10.3389/fneur.2024.1402729.
30. Jeyaraman M, Jayakumar T, Jeyaraman N, Nallakumarasamy A. Sensor Technology in Fracture Healing. *Indian J Orthop*. 2023;57(8):1196-1202. doi: 10.1007/s43465-023-00933-3.
31. Al-Shalawi FD, Mohamed Ariff AH, Jung DW, et ak. Biomaterials as Implants in the Orthopedic Field for Regenerative Medicine: Metal versus Synthetic Polymers. *Polymers (Basel)*. 2023;15(12):2601. doi: 10.3390/polym15122601.
32. Kim SJ, Wang T, Pelletier MH, Walsh WR. 'SMART' implantable devices for spinal implants: a systematic review on current and future trends. *J Spine Surg*. 2022;8(1):117-131. doi: 10.21037/jss-21-100.
33. Teo AJT, Mishra A, Park I, et al. Polymeric Biomaterials for Medical Implants and Devices. *ACS Biomater Sci Eng*. 2016;2(4):454-472. doi: 10.1021/acsbiomaterials.5b00429.
34. Capuani S, Malgir G, Chua CYX, Grattoni A. Advanced strategies to thwart foreign body response to implantable devices. *Bioeng Transl Med*. 2022;7(3):e10300. doi: 10.1002/btm2.10300.
35. Noskovicova N, Hinz B, Pakshir P. Implant Fibrosis and the Underappreciated Role of Myofibroblasts in the Foreign Body Reaction. *Cells*. 2021;10(7):1794. doi: 10.3390/cells10071794.
36. Roy S, Azad ANMW, Baidya S, et al. Powering solutions for biomedical sensors and implants inside the human body: A comprehensive review on energy harvesting units, energy storage, and wireless power transfer techniques. *IEEE Transa Power Electron*. 2022;37(10):12237-12263. doi: 10.1109/tpel.2022.3164890.
37. Nazir S, Kwon OS. Micro-electromechanical systems-based sensors and their applications. *Appl Sci Converg Technol*. 2022;31:40-45. doi: 10.5757/ASCT.2022.31.2.40.
38. Ávila BYL, Vázquez CAG, Baluja OP, et al. Energy harvesting techniques for wireless sensor networks: A systematic literature review. *Energy Strategy Reviews*. 2025;57:101617. doi: 10.1016/j.esr.2024.101617.
39. Jaime FJ, Muñoz A, Rodríguez-Gómez F, Jerez-Calero A. Strengthening Privacy and Data Security in Biomedical Microelectromechanical Systems by IoT Communication Security and Protection in Smart Healthcare. *Sensors (Basel)*. 2023;23(21):8944. doi: 10.3390/s23218944.
40. Alanazi AT. Clinicians' Perspectives on Healthcare Cybersecurity and Cyber Threats. *Cureus*. 2023;15(10):e47026. doi: 10.7759/cureus.47026.
41. Williams PA, Woodward AJ. Cybersecurity vulnerabilities in medical devices: a complex environment and multifaceted problem. *Med Devices (Auckl)*. 2015;8:305-316. doi: 10.2147/MDER.S50048.
42. Subramaniam S, Akay M, Anastasio MA, et al. Grand Challenges at the Interface of Engineering and Medicine. *IEEE Open J Eng Med Biol*. 2024;5:1-13. doi: 10.1109/OJEMB.2024.3351717.
43. Anyanwu EC, Osasona F, Akomolafe OO, et al. Biomedical engineering advances: A review of innovations in healthcare and patient outcomes. *Int J Sci Res Arch*. 2024;11(1):870-882. doi: 10.30574/ijsra.2024.11.1.0139
44. Rovere G, Bosco F, Miceli A, et al. Adoption of blockchain as a step forward in orthopedic practice. *Eur J Transl Myol*. 2024;34(2):12197. doi: 10.4081/ejtm.2024.12197.
45. Jazowski SA, Winn AN. The Role of the FDA and Regulatory Approval of New Devices for Diabetes Care. *Curr Diab Rep*. 2017;17(6):40. doi: 10.1007/s11892-017-0871-6.
46. Premarket notification [510(k)]. In: Wreh E. *Medical Device Regulation*. Elsevier; 2023:57-89.
47. *U.S. Food and Drug Administration. FDA proposes framework to advance credibility of AI models used for drug and biological product submissions*. 2025. Available at: https://www.fda.gov/news-events/press-announcements/fda-proposes-framework-advance-credibility-ai-models-used-drug-and-biological-product-submissions. Accessed Feb 5, 2025.

48. Cohen IG, Gerke S, Kramer DB. Ethical and Legal Implications of Remote Monitoring of Medical Devices. *Milbank Q*. 2020;98(4):1257-1289. doi: 10.1111/1468-0009.12481.
49. Nijor S, Rallis G, Lad N, Gokcen E. Patient Safety Issues From Information Overload in Electronic Medical Records. *J Patient Saf*. 2022;18(6):e999-e1003. doi: 10.1097/PTS.0000000000001002.
50. Zhong L, Cao J, Xue F. The paradox of convenience: how information overload in mHealth apps leads to medical service overuse. *Front Public Health*. 2024;12:1408998. doi: 10.3389/fpubh.2024.1408998.
51. Camara C, Peris-Lopez P, Tapiador JE. Security and privacy issues in implantable medical devices: A comprehensive survey. *J Biomed Inform*. 2015;55:272-289. doi: 10.1016/j.jbi.2015.04.007.
52. Shah P, Thornton I, Kopitnik NL, Hipskind JE. Informed Consent. 2024. In: *StatPearls [Internet]*. Treasure Island (FL): StatPearls Publishing; 2025. Available at: https://www.ncbi.nlm.nih.gov/books/NBK430827/. Accessed Feb 5, 2025.
53. Chiruvella V, Guddati AK. Ethical Issues in Patient Data Ownership. *Interact J Med Res*. 2021;10(2):e22269. doi: 10.2196/22269.
54. Intravaia JT, Graham T, Kim HS, et al. Smart Orthopedic Biomaterials and Implants. *Curr Opin Biomed Eng*. 2023;25:100439. doi: 10.1016/j.cobme.2022.100439.
55. Bandyopadhyay A, Mitra I, Goodman SB, et al. Improving Biocompatibility for Next Generation of Metallic Implants. *Prog Mater Sci*. 2023;133:101053. doi: 10.1016/j.pmatsci.2022.101053.
56. Kanu NJ, Gupta E, Vates UK, et al. Self-healing composites: A state-of-the-art review. *Compos A Appl Sci Manuf*. 2019;121:474-486. doi: 10.1016/j.compositesa.2019.04.012.
57. Yao G, Gan X, Lin Y. Flexible self-powered bioelectronics enables personalized health management from diagnosis to therapy. *Sci Bull (Beijing)*. 2024;69(14):2289-2306. doi: 10.1016/j.scib.2024.05.012.
58. Luo S, Zhang C, Xiong W, et al. Advances in electroactive biomaterials: Through the lens of electrical stimulation promoting bone regeneration strategy. *J Orthop Translat*. 2024;47:191-206. doi: 10.1016/j.jot.2024.06.009.
59. Boys AJ, & Keene ST. Bioelectronic interfacial matching for superior implant design. *Cell Rep Phys Sci*. 2024;5(8):101877. doi: 10.1016/j.xcrp.2024.101877.
60. Mirshafiei M, Rashedi H, Yazdian F, et al. Advancements in tissue and organ 3D bioprinting: Current techniques, applications, and future perspectives. *Materials & Design*. 2024;240:112853. doi: 10.1016/j.matdes.2024.112853.
61. Selim M, Mousa HM, Abdel-Jaber G, et al. Innovative designs of 3D scaffolds for bone tissue regeneration: Understanding principles and addressing challenges. *Eur Polym J*. 2024;215:113251. doi: 10.1016/j.eurpolymj.2024.113251.
62. Kulkarni PG, Paudel N, Magar S, et al. Overcoming Challenges and Innovations in Orthopedic Prosthesis Design: An Interdisciplinary Perspective. *Biomed Mater Devices*. 2023:1-12. doi: 10.1007/s44174-023-00087-8.
63. Shajari S, Kuruvinashetti K, Komeili A, Sundararaj U. The Emergence of AI-Based Wearable Sensors for Digital Health Technology: A Review. *Sensors (Basel)*. 2023;23(23):9498. doi: 10.3390/s23239498.
64. Schrimpff C, Link E, Fisse T, et al. Mental Models of Smart Implant Technology: A Topic Modeling Approach to the Role of Initial Information and Labeling. *Health Commun*. 2025:1-13. doi: 10.1080/10410236.2024.2447548.
65. Shekhawat D, Singh A, Banerjee M, et al. Bioceramic composites for orthopaedic applications: A comprehensive review of mechanical, biological, and microstructural properties. *Ceram Int*. 2020;47(3):3013–3030. doi: 10.1016/j.ceramint.2020.09.214.
66. Yuan X, Wang Z, Che L, et al. Recent developments and challenges of 3D bioprinting technologies. *Int J Bioprinting*. 2024;10:1752. doi: 10.36922/ijb.1752.

The article was submitted 29.01.2025; approved after reviewing 04.02.2025; accepted for publication 31.03.2025.

Статья поступила 29.01.2025; одобрена после рецензирования 04.02.2025; принята к публикации 31.03.2025.

Information about the author:

Eskandar Kirolos — BSc, MBBCh, and MA, kiroloss.eskandar@gmail.com, https://orcid.org/0000-0003-0085-3284.