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# THE FUTURE OF ORTHOPAEDIC SURGERY: INTEGRATING 3D PRINTING, AI, AND BIOPRINTING

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**ABSTRACT**

The integration of three-dimensional (3D) printing into orthopedic surgery has significantly influenced surgical planning, implant customization, and patient. outcomes. This review explores clinical applications and the future of 3D printing, bioprinting, artificial intelligence (AI), and future 4D printing technologies in orthopedics. The use of 3D-printed anatomical models and patient-specific surgical guides has been shown to reduce operative time, intraoperative blood loss, and radiation .exposure, while improving implant fit and. surgical precision. Custom-made implants offer individual solutions for reconstructions, especially in cases of severe bone loss and musculoskeletal oncology. Emerging innovations such as AI-assisted design and bioprinted scaffolds further enhance treatment strategies. Additionally, 4D printing. introduces smart implants capable of adapting to physiology, opening new possibilities orthopedic problems. Despite challenges related to cost and production time ongoing technological progress is paving the way for wider clinical adoption.

**KEYWORDS**

Orthopedic Surgery, 3d-Implants, Surgery, Bioprinting

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## 1. Introduction

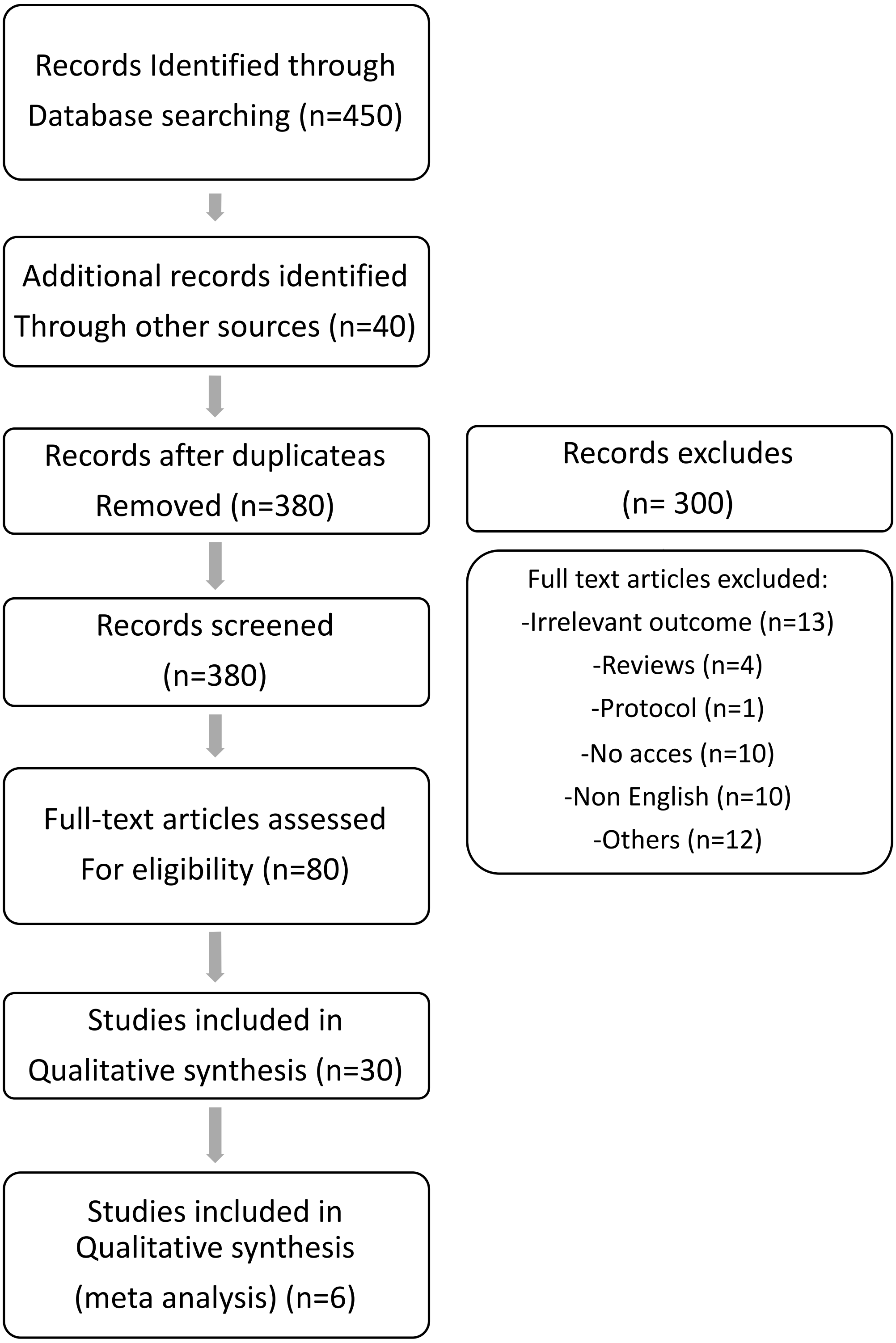
The adoption of 3D printing in orthopedic. surgery has significantly improved preoperative planning, surgical accuracy, and implant customization [1].

This technology. facilitates patient-specific solutions, improving both outcomes and surgical efficiency [1,2]. One of its most important applications is in preoperative planning, where 3D-printed models enhance visualization and allow. precise implant positioning. A systematic review confirmed that 3D printing reduces operative time, intraoperative blood loss, and the number of fluoroscopy scans required during surgery [1,2]. Beyond planning, patient specific instruments (PSI) and custom. implants have transformed orthopedic procedures. Research highlights that custom cutting guides improve implant positioning and reduce the number of surgical trays needed, leading to simplified procedures in total. knee and hip arthroplasties [1,2]. Additionally, custom-made implants enable the reconstruction of extensive bone defects in musculoskeletal oncology, providing better anatomical fit and long-term stability [1,2,4,6,10]. Despite these advantages, cost, regulatory challenges, and material. limitations remain key disadvantages. Studies indicate that the cost of 3D-printed. implants and surgical guides remains a significant hurdle, requiring. further cost reduction before routine implementation [1,2,4,10,15]. Looking ahead, bioprinting and AI-driven implant designs are emerging as key innovations that could further revolutionize orthopedic surgery [1,2,4,6,10,14,15,17,20].

## 2. Methodology

The paper analyzes the literature in PubMed and Google Scholar databases for October 2014- February 2025 using the phrases “3D printing in orthopedics”, “custom implants”, “etiology”, “preoperative planning”, “diagnosis”, “bioprinting”, “artificial intelligence”, “implant materials”, “smart implants”, “regenerative medicine”, “anatomical models”, “orthopedic surgery”, “surgical outcomes”, “AI-assisted surgery”. The inclusion criteria were determined by the relevance to the topic and the presence of specific keywords. Publications that did not fall within the mentioned date range were rejected. We exclusively analyzed papers written in English. Finally, our publication contains 22 articles. The literature selection process was conducted according to PRISMA guidelines. A total of 450 records were identified through database searches, with an additional 40 obtained from other sources. After removing duplicates and irrelevant records, 80 full-text articles were assessed for eligibility. Ultimately, 30 studies were included in the qualitative synthesis, and 6 were eligible for quantitative analysis.

**Identification of Studies via Databases and Registers**



### 3. Fundamentals of 3D Printing in Orthopedics

**3.1** 3D printing, also called additive manufacturing, prints objects layer by layer from a digital design [1,2,4,6,10,13,15,17,20]. Initially designed for industrial prototyping, it has now been widely adopted in orthopedics for implant fabrication and surgical planning [2,5,6]

### 3.2 Types of 3D Printing Used in Orthopedics:

- Selective Laser Sintering (SLS) → Used for producing porous titanium scaffolds for implants, improving osseointegration [5,12].
- Stereolithography (SLA) → Enables high-precision anatomical models and patient-specific surgical guides [5,6].
- Fused Deposition Modeling (FDM) → Frequently used for biodegradable scaffolds and bone regeneration research [5,11,12].

### 3.3 Materials Used in 3D-Printed Orthopaedic Implants

Metals: Titanium and Cobalt-Chromium Alloys are most commonly used materials in 3D printed load-bearing implants, such as hip stems, knee components, and spinal cages. These metals provide high strength, corrosion resistance, and good osseointegration. Study´s highlighted that between 2010 and 2015, approximately 40% of 3D-printed medical devices approved by the FDA were titanium-based implants. Other metallic materials, such as cobalt-chromium alloys, are used for articulating joints due to their high wear resistance [6,12].

Polymers: Polyetheretherketone (PEEK) is widely used in spinal and trauma implants due to its lightweight properties and mechanical strength comparable to cortical bone. However, "PEEK is bioinert, limiting its ability to bond with bone, which has led to modifications incorporating bioactive coatings and porosity enhancements. Additionally, biodegradable polymers such as polylactic acid (PLA) and polycaprolactone (PCL) are being investigated for temporary scaffolds that disintegrate as new bone forms [11,12].

Ceramics: Calcium Phosphate ceramics, including hydroxyapatite (HA) and tricalcium phosphate (TCP), are used for bone graft substitutes and coatings on metallic implants. These materials closely resemble natural bone mineral composition, improving osseointegration and bioactivity. Research indicates that hydroxyapatite scaffolds fabricated using 3D printing show promising results in bone regeneration, particularly in maxillofacial and orthopedic surgery. However, the brittleness of ceramics limits their use in load-bearing applications [6,12].

### 4. Role of 3D-Printed Anatomical Models in Surgery and Discussion

Preoperative planning is a critical aspect of orthopedic surgery, particularly in complex procedures requiring high precision. 3D-printed anatomical models allow surgeons to visualize bone structures in detail, enhancing surgical decision-making and implant positioning. These models help anticipate potential intraoperative challenges and improve procedural accuracy [1,3,6,10,13]. Studies highlighted that the use of 3D-printed anatomical models for preoperative planning has been associated with reduced surgical time and improved medical outcomes in complex hip replacements and cranial fractures. Additionally, these models helped shape implants prior to surgery, leading to a better fit and reduced procedural adjustments. [1,2,3,6].

### 4.1 Reduction in Surgical Time and Intraoperative Errors

3D-printed models enhance surgical efficiency by allowing preoperative simulations. Research suggests that preoperative simulations using 3D models improve the accuracy of surgical interventions and enable surgeons to optimize their approach, leading to better outcomes. Several studies report a reduction in operative time when using 3D-printed guides [1,4,6] Furthermore the use of patient-specific anatomical models has been linked to decreased intraoperative blood loss and a lower need for fluoroscopic guidance, minimizing radiation exposure for both patients and surgeons [1.3.6,7]. Several case studies have demonstrated the impact of 3D printing on surgical accuracy. Studies reported that customized 3D-printed models used in spinal surgery helped surgeons plan precise screw placements and helped reducing errors in pedicle screw placement. The same studies found that fluoroscopy time was significantly reduced, lowering the risks associated with prolonged radiation [1,2,3,6,7,8,9,14,16,18]. In complex acetabular reconstructions, 3D-printed models enabled surgeons to select the most suitable implant configurations before surgery, improving postoperative stability [3].

### 4.2 Patient-Specific Surgical Guides

Patient-specific instruments (PSI) have become essential in orthopedic surgery, particularly in total knee and hip arthroplasty, spinal surgery, and trauma reconstructions. PSI are designed based on preoperative 3D imaging, allowing for precise surgical execution, optimized implant positioning, and improved overall outcomes [4,6,7,8]. One major advantage of PSI is the reduction of intraoperative steps and surgical time. Research has shown that the required osteotomies and steps are performed on the 3D image in the software, then a 3D model is manufactured, which theoretically reduces intraoperative time, blood loss, and the number of instruments needed in inventory. However, clinical studies have produced mixed results regarding PSI's superiority over conventional techniques [4,6,7,8,9]. While PSI improves preoperative accuracy, multiple studies indicate that postoperative functional outcomes are comparable to standart techniques. A randomized study evaluating 40 total knee replacement (TKR) cases found no significant difference in hip-knee-ankle alignment angles between PSI and standart cases. Similar studies have questioned whether PSI provides superior mechanical alignment and long-term benefits [4,6,7,9]. Despite these debates, PSI continues to be valuable in complex surgical cases, particularly for surgeons with less experience or in procedures requiring precise alignment.

For example, in spinal and cranial surgery, PSI has been linked to reduced surgical complexity and improved accuracy in screw placements, leading to better patient outcomes [1,2,3,4,6,7,8,9,10,13,16,18]. The cost-effectiveness of PSI remains a key problem, as custom manufacturing increases cost. While some reports suggest PSI can reduce operating time, others argue that the additional costs of 3D printing doesn´t justify routine clinical use unless used in complex cases. [1,2,3,4,6,7,8,9,10,15].

### 4.3 Custom-Made Implants and Prosthetics

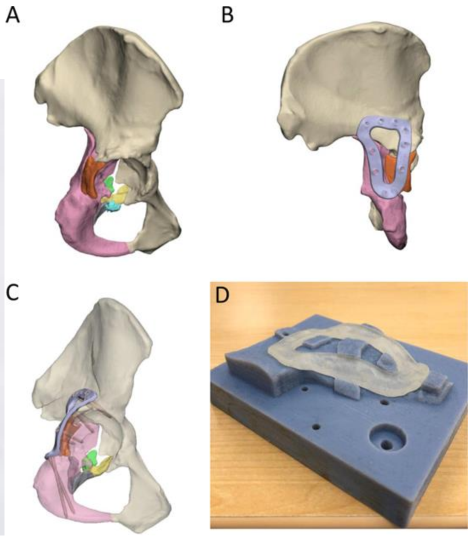
Custom-made 3D-printed implants have revolutionized orthopedic surgery by providing patient specific solutions for cases involving severe bone loss, complex fractures, and musculoskeletal oncology [3,4,6,7,9,10,14,15,18,20]. Traditional implants often fail to match the anatomical structure of individual patients, leading to higher complication rates and implant failures [3,6,10,14]. Recent advancements have enabled customized implants tailored to each patient's specific anatomy, improving functional recovery. A study on sacral and pelvic malignant bone tumors demonstrated that satisfactory functional and oncological outcomes can be achieved using 3D-printed prostheses, highlighting their importance in complex reconstructions [6,10,13,14]. The benefits of custom 3D-printed implants include:

- Better anatomical fit, reducing implant misalignment and post-surgical complications.
- Porous structures that enhance osseointegration, improving bone-implant bonding.
- Flexibility in material choice, allowing titanium, polymers, or ceramics depending on the surgical requirement [3,6,9,10,12,14,15,20]. Several studies emphasized that patient-specific implants reduce surgical time and enable more precise bone resection in oncological cases, reducing operation risks [6,10,12,14]. Musculoskeletal oncology has been one of the leading fields in the use of 3D custom implants. In a case study involving a patient with osteosarcoma, a custom-designed pelvic implant successfully restored function while maintaining oncological safety [10]. Similarly, in hip and knee revisions, custom acetabular implants have been used to reconstruct severe bone defects, improving prosthetic longevity compared to standard implants [3,6,10,14].

Despite their advantages, custom implants face challenges, including:

- High manufacturing costs, limiting accessibility.
- Regulatory hurdles, requiring extensive approval before clinical use.
- Long production times, which may not be suitable for urgent cases [3,6,10,14,15,20].

However, future advancements in bioprinting and AI-designed implants are expected to further reduce production costs and improve outcomes, making custom implants a mainstream solution in orthopedics [3,6,9,10,12,14,15,17,20].




**5. Results**

One of the major advantages of 3D printing in orthopedic surgery is its ability to reduce operative time. Studies indicate that using 3D-printed surgical guides and preoperative models decreases intraoperative adjustments, leading to more efficient procedures [1,3,4,6,7,10,12,14,15,17,20].

A meta-analysis of eight studies confirmed that a significant reduction in operation time of

19.85% was observed in the 3D printing group compared to conventional methods, demonstrating the efficiency of this technology [1,2,3,6,10,12,14,15,16,17,20].

The primary reasons for reduced surgical time include:

- Better understanding of pathological anatomy, allowing for improved preoperative planning.
- Pre-selection of implants and fixation hardware, reducing intraoperative decision-making.
- Pre-bending and shaping of plates and prosthetics, minimizing manual adjustments during surgery [1,4,6,10,14,16].

Another crucial advantage of 3D printing is its role in minimizing intraoperative blood loss. Studies have shown a 25.73% reduction in blood loss when 3D-printed models were used for surgical planning [1,2,4,6,10].

**5.1 Reduction in Fluoroscopy Usage and Radiation Exposure**

Radiation exposure during orthopedic procedures is a major concern for both patients and surgeons. A review found that the use of 3D printing resulted in a 23.80% reduction in fluoroscopy time, significantly lowering radiation risks [1,6,7]. This reduction was particularly in fracture fixation procedures, such as Calcaneal fractures, Distal radius fractures and Humeral fractures. By pre-planning screw trajectories and implant positioning with 3D models, surgeons were able to limit the number of intraoperative X-ray scans [1,6,10].

**5.2 Patient Satisfaction and Post-Operative Recovery**

The adoption of 3D printed implants in orthopedic surgery has led to improvements in functional outcomes. Studies suggest that patient-specific implants improve biomechanics, enhance mobility, and reduce pain levels compared to standard implants [1,6,16]. A study evaluating custom total knee arthroplasty (TKA) implants reported that patients who received patient-specific implants demonstrated improved knee function and a higher Forgotten Joint Score, indicating better post-operative comfort and mobility. This highlights the role of personalized 3D-printed implants in achieving better outcomes [4,6,9].

**5.3 Faster Rehabilitation and Reduced Recovery Time**

3D-printed implants enhance early rehabilitation by improving implant fit and stability, allowing for quicker weight-bearing and functional recovery. Research shows that patients receiving 3D printed orthopedic implants had a shorter hospital stay and resumed daily activities faster than those with conventional implants. Additionally, early postoperative physiotherapy showed better adherence in patients fitted with customized implants, likely due to better alignment and reduced post-surgical discomfort [4,6,9,18]. One case study in hip arthroplasty found that patients with 3D-printed acetabular components reported reduced pain and improved range of motion at three month follow-up compared to those with standard implants. This suggests that custom implants facilitate faster recovery and improved joint function [3,6,9,10,14]. Studies indicate that patient satisfaction rates are higher with 3D-printed implants, particularly in joint replacement and spinal fusion surgeries. A survey on postoperative outcomes in customized spinal implants found that patients reported reduced post-surgical discomfort and a greater ability to perform daily tasks compared to traditional spinal fusion techniques. This suggests that 3D printing contributes to long-term improvements in quality of life [9,10,14,18]. Despite these outcomes, long term studies comparing 3D-printed implants to standard implants are still limited. Some reports indicate that while early recovery is improved, long-term functional benefits require further clinical validation. Additionally, cost remains a major factor in patient accessibility, limiting its use [1,2,10,15].

| Area | Key Findings | Reduction / Improvement |
|---|---|---|
| Operative Time | Improved planning and reduce surg**ery time** | Down 19.85% 19.85% |
| Blood Loss | Enhanced precision during surgery | Down 25.73% 25.73% |
| Radiation Exposure | Fewer fluoroscopy scans due to pre-planned screw paths | Down 23.80% 23.80% |
| Patient Satisfaction | Better fit, comfort, and joint function with custom implants | Higher Satisfaction, Less Pain |
| Recovery Time | Faster rehab, shorter hospital stays, improved mobility | Faster Recovery |
| Limitations | High cost, limited long-term data | - |

## 6. Bioprinting and AI in Orthopedics

Bioprinting has emerged as one of the most promising innovations in orthopedics, offering solutions for bone regeneration, cartilage repair, and soft tissue reconstruction. Unlike traditional 3D printing, bioprinting uses living cells, growth factors, and biomaterials to create functional tissues [12,15,19]. A study highlighted that 3D bioprinting provides precise cell placement and control over the speed, resolution, and structure of printed tissue, making it a powerful tool. Additionally, bio printed bone scaffolds using calcium phosphate and hydrogel materials have shown promising results in promoting osteogenesis and integration with native bone tissue [12,15,19]. Recent advancements in vascularized bio printed tissue are helping overcome challenges related to nutrient deficiency and integration of complex implants [12,15,16]. These innovations enhance the potential of bio printed constructs for use in orthopedic surgery, particularly in bone defect repairs and cartilage regeneration [12,19]. Artificial intelligence is playing an increasingly important role in optimizing 3D printing. AI can analyze patient-specific anatomical data and generate optimized designs for prosthetics and implants [17,19,21,22]. In a recent case study on hip revision surgery, AI-assisted planning was used to determine the ideal size and position of the acetabular cup, while 3D printed modules were created to fit osseous defects, achieving stable fixation and improved functional outcomes [17]. Moreover, AI integration in preoperative planning allows for real-time measurement and intraoperative guidance, improving surgical precision and reducing the risk of implant misalignment [16,17,19,21,22]. The combination of AI and bioprinting is expected to revolutionize orthopedics by enabling:

- Automated, patient-specific implant designs.
- Bio printed bone and cartilage constructs.
- Robotic-assisted surgeries using AI-generated 3D models for enhanced precision [12,17,16,19].

Despite these advancements, bioprinting and AI-assisted implants still require extensive clinical validation. The long-term mechanical stability and biological integration of bio printed constructs must be further studied before widespread adoption [1,12,15,19].

### 7. 4D Printing and Smart Implants

4D printing is an evolution of 3D printing, incorporating a fourth dimension „time" to create materials that can change shape, properties and function in response to external stimuli such as temperature, humidity, or mechanical stress. The technology has potential in orthopedic applications, particularly in self-adaptive implants, shape-memory prosthetics, and dynamic scaffolds for bone regeneration. A key feature of 4D printing is its ability to develop implants that adjust to physiological conditions, improving implant integration [21,22]. One of the most promising aspects of 4D printing in orthopedics is the use of shape memory polymers and alloys. These materials allow implants to be compressed or altered during insertion and then expand or reshape post-implantation to better fit anatomical structures. For instance, self-expanding spinal implants have been designed using 4D-printed nickel-titanium (NiTi) shape-memory alloys, which expand at body temperature, eliminating the need for additional surgical fixation [21,22]. Beyond shape transformation, 4D-printed smart implants are being developed to adjust their biomechanical properties in response to mechanical loads. For example 4D-printed joint replacements that alter stiffness based on movement patterns or Self healing hydrogels that regenerate tissue damage in load-bearing implants. Studies have shown that 4D bio-printed scaffolds using hydrogel-based biomaterials can mimic natural bone's mechanical behavior, aiding in bone defect healing and cartilage regeneration [21,22] However, ongoing research in bioprinting and smart biomaterials is expected to accelerate clinical adoption, making self-adaptive implants and dynamic scaffolds a reality in the future.

### 8. Conclusions

The integration of 3D printing technology in orthopedic surgery marks a huge advancement toward personalized medicine, therefore significantly enhancing patient-specific treatments, surgical precision, and efficiency. By Producing customized implants and anatomical models, additive manufacturing has improved biomechanical compatibility, surgical accuracy, and implant longevity. These benefits play a important role in reducing complications, they are crucial for faster recovery times, and improve overall patient outcomes. Despite its clear advantages, widespread clinical use of 3D printing has challenges to face. High costs, extended production times, and complex regulatory pathways remain important barriers. Nevertheless, ongoing research and progress in bioprinting for Joint and bone regeneration, AI-driven implant customization, and evolving policy are addressing these limitations. These advancements are laying the way for wider accessibility and integration of 3D printing in daily orthopedic care. Looking ahead, innovations such as 4D printing, smart biomaterials, and AI-assisted design tools are in the pipeline to further revolutionize personalized orthopedic treatments. For example, AI is already improving implant design by analyzing patient-specific biomechanical data to optimize results. Simultaneously, bioprinting techniques are evolving toward the generation of functional bone and cartilage tissues, while 4D printing introduces dynamic, self-adaptive implants capable of responding to physiological changes. Ultimately, the future of these technologies will depend strongly on continued collaboration between engineers, surgeons, researchers, and regulatory authorities. 3D and 4D printing will continue to optimize orthopedic care, expand their clinical applications, and redefine the landscape of orthopedic surgery.

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Investigation – Karolina Krowiak, Karol Bednarz
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Writing – review and editing – Wiktoria Hander, Karol Bednarz
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All authors have read and agreed with the published version of the manuscript.

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