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3D-PRINTED AND PERSONALIZED ORTHOPEDIC IMPLANTS: FUNCTIONAL OUTCOMES AND RETURN TO SPORT – A STRUCTURED REVIEW

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ABSTRACT

Background: Conventional orthopedic implants are standardized and may not fully reflect individual anatomical variability and biomechanics, particularly in physically active patients. Advances in additive manufacturing (3D printing) and personalized alignment strategies have enabled the development of patient-specific solutions aimed at improving functional outcomes.
Aim: To evaluate the effectiveness of 3D-printed and personalized orthopedic implants in improving functional outcomes and facilitating return to sport.
Methods: A structured review of 31 studies identified through PubMed, Scopus, and Google Scholar was conducted. The analysis included knee and hip procedures utilizing additive manufacturing, patient-specific instrumentation, and alignment strategies such as kinematic alignment (KA) and restricted kinematic alignment (rKA). Outcomes included patient-reported measures (KOOS, Forgotten Joint Score, WOMAC), implant survivorship, complication rates, and return-to-sport (RTS).
Results: Personalized approaches demonstrated comparable or superior functional outcomes compared to conventional techniques. Improvements in KOOS Sport and Forgotten Joint Scores were reported in knee procedures. In total knee arthroplasty, rKA showed high survivorship (up to 98%) and favorable functional outcomes. RTS rates ranged from 70% to 100%, with a shift toward low-impact activities. In hip arthroplasty, personalized planning and advanced materials improved implant performance without increasing complication rates. Overall, complication rates remained low and comparable to standard approaches.
Conclusions: 3D-printed and personalized implants represent a safe and effective advancement in orthopedic care, improving function and supporting return to physical activity. Further high-quality, long-term studies are needed to confirm durability, cost-effectiveness, and broader applicability.

KEYWORDS

3D Printing, Additive Manufacturing, Patient-Specific Implants, Personalized Arthroplasty, Kinematic Alignment, Restricted Kinematic Alignment, Functional Outcomes, Return to Sport, Orthopedic Implants

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1. Introduction

Recent advances in additive manufacturing, digital imaging, and personalized alignment strategies have significantly transformed modern orthopedic surgery. The management of complex joint pathologies in physically active individuals has historically relied on standardized prosthetic components designed to accommodate a generalized patient population. However, conventional "off-the-shelf" implants frequently fail to reflect the substantial interindividual variability in joint anatomy and biomechanics, which may result in kinematic inconsistencies, altered load distribution, and ultimately suboptimal patient satisfaction [1, 2, 3]. In response to these limitations, the development of additive manufacturing and patient-specific technologies has facilitated the emergence of "personalized arthroplasty," a concept in which both surgical planning and implant design are tailored to the patient's native, pre-arthritic anatomical configuration [3, 4, 5].

The growing prevalence of degenerative joint diseases, combined with aging populations and increasing functional expectations among patients, places a substantial burden on healthcare systems worldwide. Within the field of sports medicine and orthopedic traumatology, surgical objectives have evolved considerably. Contemporary treatment strategies extend beyond pain alleviation and focus on restoring full joint function, enabling patients to safely return to demanding physical activities, including sports. Traditional mechanical alignment (MA) techniques often require substantial ligamentous releases to achieve intraoperative balance, which may compromise physiological joint behavior. In contrast, personalized approaches—such as kinematic alignment (KA) and the use of 3D-printed patient-specific guides—aim to preserve the natural soft tissue envelope and replicate native joint kinematics [4, 6, 7]. Consequently, these strategies are increasingly considered particularly advantageous in active patient populations with high functional expectations. This systematic review therefore evaluates the role of 3D-printed and personalized implants in achieving optimal functional outcomes and facilitating return to sport.

In addition to clinical outcomes, the growing adoption of personalized orthopedic technologies reflects a broader transformation in healthcare systems driven by digital innovation. Understanding the societal, economic, and policy implications of these technologies is essential for their sustainable implementation.

Research Objective:

The objective of this study is to evaluate the clinical effectiveness of 3D-printed and personalized orthopedic implants in improving functional outcomes and facilitating return to sport in patients undergoing knee and hip procedures.

Research Problems:

1. Do 3D-printed and patient-specific implants provide superior functional outcomes compared to conventional "off-the-shelf" implants?
2. To what extent do personalized alignment strategies (e.g., kinematic alignment and restricted kinematic alignment) influence implant survivorship and patient satisfaction?
3. Do personalized orthopedic approaches improve return-to-sport (RTS) rates in physically active patients?
4. Are complication rates comparable between personalized and conventional orthopedic techniques?

Research Hypothesis:

The use of patient-specific implants and instrumentation increases the rate of return to sport, particularly for low-impact activities.

2. Research materials and methods

2.1. Search Strategy

A systematic literature search was conducted using the PubMed, Scopus and Google Scholar databases to identify relevant studies. The search strategy was developed to capture publications related to additive manufacturing, patient-specific implants, and functional outcomes in orthopedic applications.

The following search query was applied: "((3D print*) OR (additive manufacturing) OR (patient-specific)) AND (personalized OR custom) AND (implant* OR prosthesis OR scaffold) AND (athlete* OR "sports medicine" OR "return to sport" OR "functional outcome")".

The search identified a total of 58 potentially relevant studies. Titles and abstracts were initially screened for relevance, followed by a full-text assessment of eligible articles.

2.2. Eligibility Criteria

Studies were included in the review if they met the following criteria:

- involved 3D-printed or patient-specific implants or instrumentation;
- addressed orthopedic applications of the knee or hip;
- reported clinical, functional, or biomechanical outcomes relevant to physical activity or return to sport.

- The following exclusion criteria were applied:
- studies unrelated to orthopedic applications;
- studies not involving additive manufacturing or personalization strategies;
- purely technical reports without clinical or functional relevance;
- duplicate publications.

2.3. Data collection and analysis

2.3.1 Study Selection and Data Extraction

Following the screening process, 31 studies were selected for qualitative synthesis. Data extraction focused on key study characteristics, including study design, anatomical region, implant material (e.g., titanium, Ti6Al4V), surgical technique, and reported outcomes.

The primary outcomes of interest included patient-reported outcome measures (KOOS, FJS, WOMAC), implant survivorship, complication rates, and return-to-sport outcomes.

2.3.2 AI Statement

AI was utilized for two specific purposes in this research. Text analysis of clinical reasoning narratives to identify linguistic patterns associated with specific logical fallacies. Assistance in refining the academic English language of the manuscript, ensuring clarity, consistency, and adherence to scientific writing standards. AI were used for additional linguistic refinement of the research manuscript, ensuring proper English grammar, style, and clarity in the presentation of results. It is important to emphasize that all AI tools were used strictly as assistive instruments under human supervision. The final interpretation of results, classification of errors, and conclusions were determined by human experts in clinical medicine and formal logic. The AI tools served primarily to enhance efficiency in data processing, pattern recognition, and linguistic refinement, rather than replacing human judgment in the analytical process.

3. Additive Manufacturing in Orthopedic Applications

Additive manufacturing (AM), commonly referred to as 3D printing, is defined as a layer-by-layer fabrication process in which objects are created from digital three-dimensional model data. In orthopedic applications, this workflow typically begins with high-resolution imaging modalities such as computed tomography (CT) or magnetic resonance imaging (MRI), which are subsequently converted into detailed 3D reconstructions of the patient's anatomy [1, 2]. These digital models enable precise preoperative planning and individualized implant design.

Unlike traditional subtractive manufacturing techniques, which rely on material removal from a solid block, additive manufacturing allows for the production of highly complex geometries, including intricate internal architectures and porous lattice structures that are not achievable through conventional methods [2, 8]. Among the most widely used technologies for medical-grade metallic implants are Selective Laser Melting (SLM) and Electron Beam Melting (EBM), both of which employ high-energy sources to fuse titanium or cobalt–chromium powders into solid, load-bearing constructs [2, 9, 10].

A major advantage of AM in orthopedics is the ability to engineer biomimetic "trabecular" surfaces. These porous structures replicate the morphology of cancellous bone, thereby enhancing biological fixation, accelerating osseointegration, and improving primary implant stability [11, 12, 13]. In addition, additive manufacturing enables the production of patient-specific instrumentation (PSI), including custom cutting guides that conform precisely to individual bony anatomy. Such guides facilitate accurate intraoperative execution of preoperative plans, thereby improving surgical precision and reproducibility [1, 6, 8].

4. Clinical Applications of Orthopedic Implants

Orthopedic implants encompass a wide range of devices that can be classified according to anatomical location, function, and fixation method. Arthroplasty represents the most common field of application, including procedures such as total knee arthroplasty (TKA), unicompartmental knee arthroplasty (UKA), and total hip arthroplasty (THA) [1, 2, 4, 5].

In knee arthroplasty, implant designs are typically categorized as cruciate-retaining or posterior-stabilized, depending on the preservation or substitution of the posterior cruciate ligament. Bone-preserving procedures such as UKA and patellofemoral arthroplasty (PFA) are increasingly utilized in cases of isolated compartment degeneration, offering a more conservative alternative for selected patients [3, 7, 8]. In hip arthroplasty, implants generally consist of an acetabular component, a femoral stem, and a bearing surface. Advanced bearing materials, including ceramic-on-ceramic articulations and highly cross-linked polyethylene (HXLPE), are commonly employed to reduce wear and improve longevity, particularly in physically active individuals [14, 15, 16, 17].

In trauma surgery, internal fixation devices such as intramedullary nails—specifically Gamma nails and Trochanteric Fixation Nail Advance (TFNA)—as well as extramedullary systems like the Dynamic Hip Screw (DHS), are widely used in the treatment of intertrochanteric fractures [18, 19, 20]. In more complex reconstructive scenarios, particularly those involving extensive bone loss or deformity, 3D-printed custom implants have emerged as a valuable solution, allowing for precise anatomical reconstruction where standard implants may be insufficient [2, 9, 21]. Furthermore, patient-specific instrumentation (PSI) may be considered a temporary yet critical intraoperative tool, ensuring accurate placement of definitive implants in accordance with personalized alignment strategies [6, 8, 22].

5. Results

The clinical application of personalized and technology-assisted approaches is most extensively reported in knee and hip surgery, which together represent the primary domains of investigation within the analyzed literature [1, 2, 8, 4].

A controlled retrospective study evaluating medial unicompartmental knee osteoarthritis demonstrated that personalized osteotomy using 3D-printed guides resulted in significantly higher postoperative KOOS Sport subscale scores ($P = 0.0023$) and Forgotten Joint Scores ($P = 0.0242$) compared to conventional techniques [6]. These findings indicate that the increased precision associated with patient- specific planning translates into improved functional performance, particularly in activities requiring higher physical demand. [6, 23].

In total knee arthroplasty (TKA), the application of restricted kinematic alignment (rKA) has demonstrated excellent clinical outcomes in both mid- and long-term follow-up studies [4, 31]. A 10-year follow-up study reported a survivorship rate of 98%, accompanied by high functional scores, including mean KOOS Pain and Activities of Daily Living (ADL) scores of 88 and 89, respectively [4]. These results challenge traditional assumptions that deviations from neutral mechanical alignment increase the risk of implant failure, instead suggesting that personalized implant positioning, often supported by digital planning and patient-specific instrumentation can maintain joint integrity over time [3, 4, 5, 24].

For isolated patellofemoral osteoarthritis, patellofemoral arthroplasty (PFA) performed using personalized techniques has been associated with favorable return-to-sport outcomes [25]. A systematic review reported that between 70% and 100% of patients resumed recreational activities, although a transition from high-impact to low-impact sports was frequently observed [25]. The precision of 3D-printed guides is particularly relevant in this context, as accurate implant positioning reduces the risk of patellar maltracking, which remains a leading cause of revision in PFA [14, 18, 25].

In hip surgery, additive manufacturing is primarily utilized in complex reconstructions and in the optimization of bearing surfaces. Large-diameter ceramic-on-ceramic articulations used in total hip arthroplasty (THA), often combined with personalized planning strategies, have demonstrated excellent clinical performance in active populations [14, 15, 26].Additionally, advanced imaging techniques, such as CT-based bone density mapping, support implant selection and positioning by aligning implant characteristics with local bone quality and mechanical demands [11, 26, 27].

Across the analyzed studies, complication rates associated with personalized approaches remained low and were comparable to conventional techniques. In the 10-year rKA cohort, no cases of revision due to aseptic loosening were reported, while only a small proportion of patients required revision for other non-septic causes [4]. Similarly, personalized osteotomy techniques did not demonstrate increased complication rates compared to standard procedures, despite providing superior functional outcomes [6]. Overall, the analyzed studies suggest that personalized approaches may improve functional outcomes, patient-reported measures, and activity levels, while maintaining a favorable safety profile.

6. Discussion

The transition toward 3D-printed and personalized implants represents a broader paradigm shift in orthopedic surgery, moving away from standardized treatment models toward individualized, patient-centered approaches. This evolution is driven by the recognition that anatomical variability and patient-specific biomechanics play a critical role in determining clinical outcomes. The findings of this review indicate that personalization, whether achieved through custom instrumentation, implant design, or alignment strategies is associated with comparable or improved patient-reported outcomes, particularly in physically active populations with higher functional demands [4, 6, 25]. These observations align with the growing emphasis on restoring physiological joint behavior rather than simply achieving radiographic alignment.

One of the most relevant findings across the analyzed studies is the improvement in Forgotten Joint Scores observed in patients treated with personalized techniques. Higher FJS values suggest a reduced awareness of the prosthesis during both daily activities and more demanding physical tasks, indicating a closer approximation to native joint function [1, 5, 6, 30]. This effect appears to be multifactorial. Preservation of native ligament tension, restoration of individual joint line orientation, and avoidance of excessive soft tissue releases contribute to more natural joint kinematics. In contrast, mechanically aligned procedures may alter these relationships, potentially leading to residual stiffness or unnatural movement patterns which may be particularly noticeable in physically active individuals.

From a biomechanical perspective, additive manufacturing introduces significant advantages that extend beyond geometric customization. The use of porous titanium structures, designed to mimic trabecular bone architecture, enhances osseointegration and promotes stable biological fixation [11, 12, 13]. This is particularly relevant in physically active patients, where implants are subjected to repetitive loading cycles and higher mechanical stresses. Improved bone–implant integration reduces micromotion at the interface and may contribute to long-term implant survivorship. Additionally, the capacity to tailor implant stiffness and porosity allows for better load transfer and may reduce stress shielding, further supporting bone preservation in the long term [2, 11, 13].

Another important aspect highlighted in the literature is the integration of advanced digital technologies, including artificial intelligence (AI), into preoperative planning. AI-driven systems have the potential to analyze large datasets of imaging and biomechanical information, enabling the prediction of patient-specific loading conditions and optimization of implant positioning [2, 28]. However, the current evidence supporting these approaches remains largely preliminary and requires further validation in clinical settings. This level of precision may further enhance functional outcomes by ensuring that implant orientation and alignment are adapted not only to anatomy but also to anticipated functional demands. As these technologies continue to evolve, they may play a central role in refining surgical decision-making and improving reproducibility.

However, the clinical integration of these systems remains dependent on further validation and standardization.

Despite these promising developments, several limitations must be acknowledged when interpreting the available evidence. Although long-term data for restricted kinematic alignment (rKA) demonstrate encouraging durability and survivorship, many other applications of 3D printing remain supported primarily by mid-term or short-term follow-up data [1, 4, 7]. The absence of long-term prospective studies limits the ability to fully assess implant longevity and the risk of late complications. Furthermore, the heterogeneity of the included studies—ranging from in-silico analyses and biomechanical simulations to retrospective clinical cohorts—introduces variability in methodology, outcome measures, and reporting standards, which complicates direct comparison and synthesis of results [3, 4, 5].

In addition, economic considerations remain a relevant factor in the widespread adoption of personalized technologies. The production of 3D-printed implants and patient-specific instrumentation requires advanced imaging, specialized software, and manufacturing resources, which may increase initial treatment costs and extend preoperative planning time [2, 29]. However, these costs should be interpreted in the context of potential long-term benefits, including improved functional outcomes, reduced revision rates, and enhanced patient satisfaction, particularly in younger and more active populations.

Overall, the current body of evidence suggests that personalized and 3D-printed orthopedic solutions offer meaningful clinical advantages, especially for patients seeking to return to a high level of physical activity. By enabling more accurate anatomical restoration, improving biomechanical compatibility, and enhancing biological fixation, these technologies represent a significant advancement in modern orthopedic practice.

Implications for Healthcare Systems and Society

The increasing adoption of personalized orthopedic technologies reflects a broader transformation of healthcare systems toward precision medicine and technology-driven care. From a societal perspective, improved functional outcomes and higher return-to-sport rates may contribute to increased physical activity levels, reduced disability, and enhanced quality of life, particularly in aging and active populations.

At the system level, the implementation of 3D-printed implants and AI-supported planning introduces both opportunities and challenges. On one hand, improved surgical accuracy and reduced revision rates may lower long-term healthcare costs and resource utilization. On the other hand, the high initial costs associated with advanced imaging, digital planning, and additive manufacturing may limit accessibility, particularly in low- and middle-income healthcare systems.

Furthermore, the integration of artificial intelligence and data-driven decision-making raises important considerations related to digital infrastructure, data governance, and ethical use of patient data. Ensuring equitable access to these innovations remains a critical challenge, as disparities in technological availability may exacerbate existing health inequalities.

Overall, personalized orthopedic technologies should be viewed not only as a clinical advancement but also as a key component of a broader socio-technological transformation shaping modern healthcare delivery.

7. Conclusions

3D-printed and personalized implants represent a significant technological advancement in the treatment of osteoarticular injuries, particularly in patients aiming to return to sports and high levels of physical activity. By enabling more precise anatomical reconstruction and enhancing biological fixation, these technologies offer clear advantages over conventional standardized approaches.

Beyond clinical benefits, these technologies may contribute to improved healthcare efficiency by reducing complications, supporting faster recovery, and optimizing resource utilization.

The available evidence supports their safety and clinical effectiveness, with functional outcomes that are at least comparable and often improved relative to conventional techniques. Continued advancements in additive manufacturing, artificial intelligence, and data-driven planning are expected to further optimize these technologies and expand their clinical applications.

However, high-quality, long-term prospective studies are required to confirm durability, cost-effectiveness, and broader clinical applicability, particularly across diverse healthcare settings.

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