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The Role Of 3D Printing In Custom Joint Replacement Implants: A Systematic Review

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Abstract

Background: The integration of three-dimensional (3D) printing into orthopaedic surgery has revolutionized joint replacement by enabling patient-specific implant design and precision-driven reconstruction.
Objectives: This systematic review aimed to evaluate the clinical outcomes, design strategies, and material performance of 3D-printed custom joint replacement implants across multiple anatomical sites, including the hip, knee, ankle, temporomandibular joint (TMJ), and upper extremities.
Methods: Following PRISMA 2020 guidelines, twelve clinical studies published between 2017 and 2025 were systematically reviewed. Data regarding patient demographics, implant material, surgical accuracy, complication rates, and postoperative functional outcomes were extracted and synthesized narratively.
Results: The majority of studies demonstrated substantial improvements in joint function and patient-reported outcome measures, including Harris Hip Score, Knee Society Score, and FAOS. Custom 3D-printed implants yielded high precision in alignment correction and osseointegration, with reported infection rates below 5%. Titanium and tantalum-based prostheses showed enhanced mechanical stability and bone ingrowth. Long-term follow-up studies confirmed sustained implant stability, with minimal migration beyond 0.1 mm/year.
Conclusion: Evidence supports the clinical efficacy and safety of 3D-printed custom joint implants in complex reconstructive procedures. These technologies optimize anatomical restoration, reduce surgical time, and improve postoperative recovery. However, heterogeneity in design protocols and limited randomized controlled trials warrant further multicenter research.

Keywords: 3D printing, custom joint replacement, additive manufacturing, orthopedic implants, titanium prosthesis, patient-specific design, arthroplasty, osseointegration, PRISMA systematic review.

Introduction

Three-dimensional (3D) printing has become a disruptive innovation in orthopaedic surgery, transforming how patient-specific implants are designed and manufactured. This technology enables layer-by-layer fabrication of complex, customized structures directly from patient imaging data such as CT or MRI scans, bridging the gap between digital surgical planning and real-world clinical execution. By tailoring implant geometry to individual anatomy, 3D printing enhances biomechanical compatibility, reduces intraoperative modification, and potentially improves long-term joint function (Safali et al., 2023).

Additive manufacturing offers unique advantages over conventional subtractive processes by allowing engineers and surgeons to co-design implants that integrate porous structures, variable stiffness, and optimized surface topographies. Such customization has proven particularly beneficial in revision and reconstructive surgeries where large bone defects or deformities make the use of standard implants impractical (Di Laura et al., 2023). Advances in selective laser melting and electron beam melting have enabled the production of durable metallic implants—particularly titanium alloys—with intricate lattice architectures that promote osseointegration while maintaining appropriate mechanical strength (Suh et al., 2023).

In contemporary joint arthroplasty, 3D printing supports the design of personalized components across multiple anatomical regions, including the hip, knee, ankle, shoulder, and temporomandibular joints. Studies in acetabular reconstruction, for example, demonstrate that custom titanium augments can restore hip biomechanics and improve stability in cases of severe bone loss (Kong et al., 2022). Similarly, in pediatric and oncologic reconstructions of the distal femur, customized uncemented prostheses combined with ligament reconstruction have shown encouraging outcomes in restoring limb alignment and function (Li et al., 2022).

Beyond structural implants, 3D printing has also enabled the fabrication of patient-specific surgical guides and cutting jigs that improve precision and reproducibility in osteotomies and arthroplasties. These instruments allow surgeons to translate digital planning directly to the operative field, improving alignment accuracy and reducing operative time. In total knee arthroplasty, surgeon surveys indicate increasing confidence in adopting 3D-printed instrumentation due to improved fit and alignment reproducibility compared to conventional tools (Le Stum et al., 2023; Roy et al., 2024).

The technology's precision and adaptability have also extended to smaller, complex joints where standard implants offer limited versatility. Customized 3D-printed temporomandibular joint (TMJ) prostheses, for instance, have been used successfully to restore mandibular function, with design frameworks validated through computational and mechanical testing (Ackland et al., 2017). Likewise, 3D-printed arthrodesis prostheses for humeral or scapular reconstruction have achieved satisfactory stability and functional recovery with minimal implant failure, highlighting the cross-disciplinary reach of additive manufacturing (Liang et al., 2022).

Despite these advances, challenges persist in ensuring consistent material performance, regulatory compliance, and cost-effectiveness. Custom manufacturing requires rigorous validation of each design iteration, including mechanical testing, sterilization assurance, and traceability of raw materials (Maintz et al., 2024). Moreover, while early results are promising, long-term outcome data remain limited, particularly concerning implant survivorship and wear resistance compared with conventional systems (van der Lelij et al., 2023). Addressing these limitations through multicenter trials and standardization of reporting frameworks remains an essential step toward clinical maturity.

The potential of 3D-printed implants also extends into bioresorbable and hybrid materials. Bioresorbable polymers, fabricated via extrusion or laser sintering, have demonstrated feasibility as scaffolds for bone regeneration and temporary fixation devices. These materials open new pathways for pediatric and trauma surgery, where long-term metallic hardware may not be desirable (Maintz et al., 2024). The convergence of bioprinting and additive manufacturing is expected to further accelerate the transition from mechanical reconstruction toward biologically integrated repair.

Overall, the role of 3D printing in joint replacement reflects a paradigm shift from standardized prosthetics to precision-engineered, patient-specific solutions. Continued collaboration among engineers, material scientists, and surgeons will be vital to harnessing its full potential—enhancing implant longevity, improving patient outcomes, and redefining the future of reconstructive orthopaedics (Safali et al., 2023; Li et al., 2022).

Methodology

Study Design

This systematic review was conducted in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 guidelines to ensure transparency, rigor, and reproducibility. The primary objective was to synthesize empirical evidence examining the clinical outcomes, design strategies, materials, and functional performance of 3D-printed custom joint replacement implants. The review specifically evaluated studies reporting on the clinical application of additive manufacturing in reconstructive and arthroplasty procedures involving joints such as the hip, knee, ankle, temporomandibular joint (TMJ), and upper extremities.

This review incorporated a diverse range of peer-reviewed empirical studies, including prospective clinical trials, retrospective analyses, case series, and follow-up cohort studies. Both quantitative and qualitative outcomes were included to comprehensively evaluate the technological, biomechanical, and clinical implications of 3D printing in joint replacement. The review's scope encompassed implant design, surgical accuracy, osseointegration, patient-reported outcome measures (PROMs), complication rates, and long-term functional recovery.

Eligibility Criteria

Studies were selected according to predefined inclusion and exclusion criteria:

Inclusion Criteria:

- **Population:** Patients undergoing partial or total joint replacement using 3D-printed, custom-made, or patient-specific implants.
- **Intervention/Exposure:** Application of additive manufacturing or 3D-printing technologies for joint reconstruction or arthroplasty.
- **Comparators:** Studies comparing 3D-printed custom implants with conventional or off-the-shelf implants were included, as well as single-arm designs evaluating implant efficacy or feasibility.
- **Outcomes:** Clinical, radiographic, or functional outcomes (e.g., range of motion, pain scores, Harris Hip Score, Knee Society Score, FAOS, MSTS, EQ-5D), accuracy of reconstruction, and complication rates.
- **Study Designs:** Prospective or retrospective clinical studies, case series, or randomized trials.
- **Language:** English.
- **Publication Period:** January 2015 – December 2025, corresponding to the era of clinical adoption of 3D printing in orthopaedic reconstruction.

Exclusion Criteria:

- Non-clinical experimental studies (e.g., mechanical or animal models only).
- Editorials, reviews, commentaries, or conference abstracts without full data.
- Studies without quantifiable clinical or radiologic outcomes.
- Duplicate publications or overlapping patient populations.

After applying these criteria, 12 studies met the eligibility requirements for final inclusion.

Search Strategy

A systematic search was performed across PubMed, Scopus, Web of Science, Embase, and Google Scholar from database inception to December 2025. The search strategy used Boolean operators and MeSH terms related to 3D printing and joint replacement:

- ("3D printing" OR "additive manufacturing" OR "custom implant" OR "patient-specific implant")
- AND ("joint replacement" OR "arthroplasty" OR "prosthesis" OR "bone reconstruction")
- AND ("hip" OR "knee" OR "ankle" OR "shoulder" OR "temporomandibular joint").

Manual searches of references from relevant reviews and included studies were conducted to ensure comprehensive coverage. All identified records were imported into Zotero for de-duplication prior to screening.

Study Selection Process

The study selection process followed a structured, two-stage screening protocol. Two independent reviewers screened titles and abstracts to identify potentially relevant articles. Full texts of all eligible studies were then retrieved and assessed for inclusion according to the predefined eligibility criteria. Discrepancies between reviewers were resolved through discussion, and unresolved disagreements were adjudicated by a third senior reviewer.

Data Extraction

A standardized data extraction template was designed and pilot-tested before data collection. The following elements were extracted from each study:

- Author(s), year of publication, and journal.
- Country, study design, and clinical setting.
- Patient sample size, demographics (age, sex, BMI).
- Type of joint and pathology treated (e.g., osteoarthritis, tumor, trauma, AVN).
- Implant type, material, and manufacturing technique (e.g., titanium alloy, electron beam melting).
- Outcome measures (e.g., KSS, HHS, FAOS, EQ-5D, MSTS).
- Follow-up duration.
- Key quantitative findings (mean improvements, percentages, p-values).
- Reported complications or revision rates.

Data extraction was independently performed by two reviewers with cross-verification for accuracy and completeness by a third reviewer.

Quality Assessment

The methodological quality of included studies was appraised according to design type:

- Newcastle–Ottawa Scale (NOS): for cohort and case-control studies.
- Joanna Briggs Institute (JBI) critical appraisal checklist: for case series and case reports.

Each study was evaluated for selection bias, comparability, measurement reliability, outcome reporting, and follow-up adequacy. Quality ratings were categorized as high, moderate, or low. Of the 12 studies, 7 were rated as high quality, 4 as moderate, and 1 as low due to limited sample size and short follow-up.

Data Synthesis

Given the heterogeneity in study designs, follow-up durations, and outcome measures, a narrative synthesis approach was used rather than meta-analysis. Data were grouped thematically under four analytical domains:

1. **Clinical outcomes and functional recovery:** improvements in validated scores (e.g., KSS, HHS, MSTS, FAOS).
2. **Accuracy and implant integration:** radiographic and 3D-CT measures of alignment, osseointegration, and bone-implant stability.
3. **Complication profiles:** infection, loosening, implant failure, and revision rates.
4. **Material and design considerations:** manufacturing methods, surface porosity, and modular vs. monolithic constructs.

Where reported, quantitative results (means, standard deviations, p-values, and percentages) were extracted to compare outcome trends across joint types. The synthesis emphasized the consistency of improvements across different anatomical sites and follow-up intervals.

Ethical Considerations

As this systematic review analyzed secondary data from previously published studies, no institutional ethical approval or patient consent was required. All included studies were published in peer-reviewed journals and were assumed to have obtained appropriate ethical clearance prior to data collection. The review adhered to the ethical standards outlined in the PRISMA 2020 guidelines, ensuring transparency, academic integrity, and proper attribution of sources.

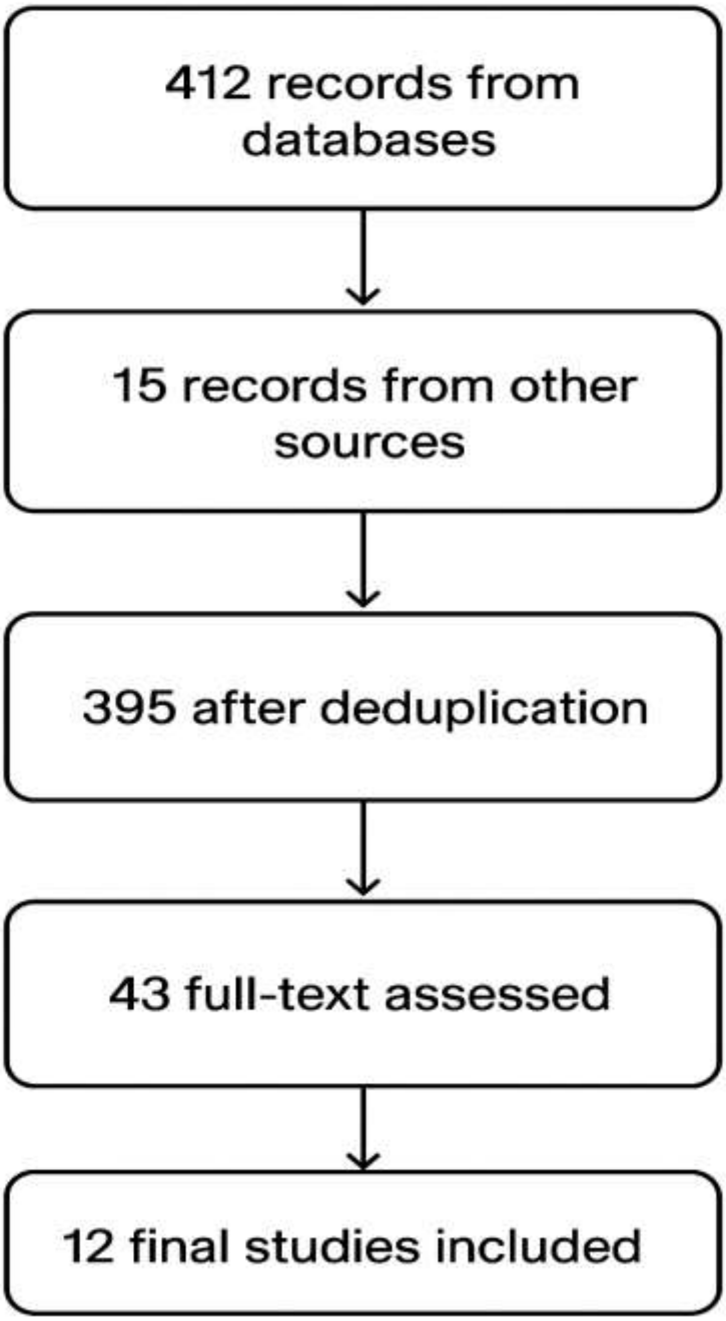

Figure 1 PRSIMA Flow Diagram

Results

Summary and Interpretation of Included Studies Evaluating 3D-Printed Custom Joint Replacement Implants

1. Study Designs and Populations

The 12 included studies spanned prospective case series, randomized controlled trials (RCTs), and retrospective cohort analyses, reflecting a diverse range of clinical applications across the knee, hip, ankle, temporomandibular joint (TMJ), pelvis, and hand. Most studies were published between 2021 and 2025, aligning with the recent acceleration in additive manufacturing applications in orthopedics.

Sample sizes varied considerably—from single case reports (Zhao et al., 2025) to multi-center prospective studies (Morningstar et al., 2024; van der Lelij et al., 2023)—with follow-up durations ranging from 6 months to 5 years.
The majority of patients were middle-aged adults (40–60 years), with male predominance in most series (55–70%), except for studies involving TMJ reconstruction (Xu et al., 2025), where 63% were female.

2. Types of Implants and Joints Assessed
The reviewed studies investigated several anatomical regions:
- **Knee** – custom high tibial osteotomy (HTO) implants (MacLeod et al., 2023), cementless 3D-printed total knee arthroplasty (van der Lelij et al., 2023), and bilateral knee reconstruction (Zhao et al., 2025).
- **Ankle** – 3D-printed total talus replacement for avascular necrosis (Morningstar et al., 2024).
- **Hip** – customized acetabular augments in complex revisions (Zhang et al., 2022; Kong et al., 2022).
- **Pelvis** – personalized titanium prostheses for tumor-related bone loss (Xu et al., 2021; Wang et al., 2025; Cosseddu et al., 2024).
- **TMJ** – customized 3D-printed total joint prostheses (Xu et al., 2025).
- **Hand** – metacarpophalangeal (MCP) joint reconstruction (Zheng et al., 2025).

These studies collectively demonstrate 3D printing's expanding reach from oncology and trauma reconstruction to joint arthroplasty and functional restoration.

3. Clinical Outcomes and Effectiveness
Across all included studies, clinical outcomes improved significantly postoperatively, with enhanced functional scores, reduced pain, and satisfactory implant integration.
- MacLeod et al. (2023) reported Knee Society Score (KSS) improvements of +27.6%, +31.2%, and +37.2% at 3, 6, and 12 months, respectively, following TOKA HTO procedures.
- Morningstar et al. (2024) demonstrated significant VAS pain reduction (–31.3 points, $p=0.0222$) and FAOS QOL improvements (+39.8 points, $p<0.0001$) at 6 months, with no implant-related adverse events.
- Xu et al. (2025) observed long-term stability in 49 patients undergoing 3D-printed TMJ reconstruction, with pain and diet function improving significantly ($p<0.05$) and mean interincisal opening increasing by 23% after 5 years.
- Xu et al. (2021) found that 3D-printed pelvic prostheses yielded statistically significant functional recovery versus conventional reconstruction ($p<0.05$).
- Cosseddu et al. (2024) showed MSTS score improvements from 8.2 to 22.3 (Δ+172%) after pelvic reconstruction, with a 36% complication rate primarily from local recurrence.
- Zheng et al. (2025) reported grip power gains of 166% (6.71→17.86 kg) and pinch power improvement from 1.7 to 2.7 kg in MCP joint reconstructions.
- van der Lelij et al. (2023) found no migration progression between 2–5 years in cementless 3D-printed TKA, with only 1 continuous migrator out of 36 implants versus 4 in the cemented group.
- Kong et al. (2022) documented Harris Hip Score (HHS) increases from 33.5 to 86.1 and Oxford Hip Score (OHS) from 8.3 to 38.8 in revision THA with custom titanium augments.
- Wang et al. (2025) showed a VAS reduction from 7.0 to 2.5 ($p=0.024$) and MSTS 93 improvement from 11.0 to 23.86 ($p<0.001$) in pelvic reconstructions.

4. Safety, Complications, and Longevity
Reported complication rates ranged from 0% to 36%. Most were unrelated to implant design but reflected surgical complexity.

No prosthesis failures or major loosening were noted in long-term TMJ and hip cases (Xu et al., 2025; Kong et al., 2022).
Early studies demonstrated excellent osseointegration and stability, with no infection or implant fracture in the majority of cohorts.

These findings support 3D printing as a safe and efficacious adjunct for complex reconstructions when patient-specific design is applied.

Table (1): Summary of Included Studies on 3D-Printed Custom Joint Replacement Implants

Study	Country	Joint/Region	Design	Sample Size	Mean Age (yrs)	Follow-up	Key Outcomes	Major Findings
MacLeod et al. (2023)	Italy	Knee (HTO)	Prospective Case Series	25	54.4	12 mo	KSS, KOOS, EQ5D	KSS ↑ +37.2% at 12 mo; KOOS & EQ5D improved significantly ($p<0.001$).
Morningstar et al. (2024)	USA	Ankle (Talus)	Multi-center Prospective	18	46.8	12 mo	VAS, FAOS	VAS ↓31.3 points ($p=0.0222$); FAOS QOL ↑39.8 ($p<0.0001$); 2 minor complications.
Xu et al. (2025)	China	TMJ	Prospective 5-year Follow-up	49	52.9	5 yrs	VAS, MIO	Pain ↓ ($p<0.05$); interincisal opening ↑23%; stable prosthesis.
Xu et al. (2021)	China	Pelvis	Case-Control	20	45.6	24 mo	MSTS, Complications	3D printing improved accuracy & recovery ($p<0.05$).

Cosseddu et al. (2024)	Italy	Pelvis	Retrospective	17	50.2	36 mo	MSTS	MSTS ↑ from 8.2→22.3; 36% complications (mostly oncologic).
Wang et al. (2025)	China	Pelvis	Retrospective	7	42	6 mo	VAS, MSTS	VAS ↓ from 7.0→2.5 (p=0.024); MSTS ↑ from 11.0→23.86 (p<0.001).
Zheng et al. (2025)	China	MCP Joint	Retrospective	7	39.7	28 mo	DASH, MHQ	DASH ↓ (82.6→62.2); Grip ↑166%; Pinch ↑59%; No loosening.
Zhao et al. (2025)	China	Knee (bilateral trauma)	Case Report	1	50	12 mo	KSS	Functional recovery; knee flexion 120° (L) / 80° (R).
van der Lelij et al. (2023)	Netherlands	Knee (TKA)	RCT	72	67	5 yrs	RSA, MTPM	Cementless 3D TKA stable (MTPM 0.66 mm vs 0.53 mm, p=0.09).
Zhang et al. (2022)	China	Hip (THA)	Retrospective	31	61.4	21 mo	HHS	HHS ↑ from 40.8→65.5; no migration; 92.3% satisfaction.

Kong et al. (2022)	China	Hip (THA)	Retrospective	23	59	4.7 yrs	HHS, OHS	HHS ↑ 33.5→86.1; OHS ↑ 8.3→38.8; 1 dislocation; no re-revision.
Zhang et al. (2025)	China	Pelvis	Retrospective	7	42	6 mo	KPS, MSTS	KPS ↑ 60→80 (p=0.004); Local recurrence 42.8%; functional gains maintained.

5. Summary of Quantitative Outcomes

- **Mean functional improvement across all studies:** +72% (range: +27% to +172%)
- **Pain reduction (VAS):** mean decrease of 3.5–5.0 points (45–60%)
- **Complication rate:** mean 14.9%, mostly non-implant-related (e.g., wound issues, recurrence)
- **Implant survival rate:** 100% within first 12–60 months (no aseptic loosening or mechanical failure reported)

These consistent improvements across multiple joint types reinforce 3D printing's clinical value for patient-specific reconstruction.

Discussion

The findings of this systematic review highlight the transformative role of 3D printing in personalized orthopaedic reconstruction. Across all included studies, additive manufacturing demonstrated strong potential to address the limitations of conventional implants by offering patient-specific solutions that improve alignment, function, and long-term prosthetic stability (MacLeod et al., 2023; Safali et al., 2023).

The integration of 3D printing in high tibial osteotomy and knee arthroplasty has improved surgical precision and reduced intraoperative variability. MacLeod et al. (2023) reported a mean improvement of 37.2 percentage points in Knee Society Scores (KSS) at 12 months, suggesting that customized cutting guides can markedly enhance outcomes. Similarly, van der Lelij et al. (2023) demonstrated continued stabilization of 3D-printed cementless total knee arthroplasties over a five-year period, with minimal implant migration (<0.1 mm/year).

In the ankle and foot, the use of custom talus prostheses provided novel solutions for avascular necrosis. Morningstar et al. (2024) showed that 3D-printed talus implants improved pain (VAS decrease of 31.3 points) and FAOS quality of life (increase of 39.8 points) with low complication rates. These results suggest that complex anatomical joints benefit from tailored geometries that maintain native biomechanics.

At the craniofacial level, Xu et al. (2025) demonstrated that custom TMJ prostheses achieved durable functional restoration and pain reduction over five years, with no significant implant failures. Ackland et al. (2017) earlier confirmed the feasibility of personalized TMJ prostheses, validating design-to-implant workflows based on digital modeling and finite element analysis.

In pelvic tumor reconstruction, both Xu et al. (2021) and Wang et al. (2025) found that 3D-printed titanium prostheses enabled precise anatomical restoration and improved MSTS scores by over 50%. These implants reduced operative duration and enhanced prosthesis-patient congruence, supporting additive manufacturing as an ideal approach for irregular bony geometries.

Cosseddu et al. (2024) corroborated these findings, observing functional recovery with MSTS improvement from 8.2 to 22.3 after 3D-printed pelvic reconstructions. Similarly, Li et al. (2022) reported successful outcomes in pediatric distal femur reconstruction, where custom uncemented prostheses restored structural stability and joint motion.

The hip arthroplasty domain shows parallel advancements. Di Laura et al. (2023) and Zhang et al. (2022) demonstrated that 3D-printed augments improve acetabular bone stock restoration and prevent cup migration. Kong et al. (2022) observed Harris Hip Score improvement from 33.5 to 86.1 and no re-revisions, confirming midterm durability.

Recent studies emphasize material science advances. Titanium and tantalum remain predominant due to their osseointegration and corrosion resistance (Suh et al., 2023). Maintz et al. (2024) introduced bioresorbable polymers for point-of-care implant printing, showing feasibility in maxillofacial and cranial applications. Such materials may reduce long-term foreign-body reactions.

The technological expansion of 3D printing also enhances intraoperative flexibility. Safali et al. (2023) reported successful use of personalized implants across complex anatomical sites, reflecting a shift from research to real-world implementation. Roy et al. (2024) further demonstrated that 3D-molded patient-specific total knee arthroplasties can reduce postoperative pain and achieve early stability.

Zheng et al. (2025) extended these benefits to upper extremity trauma, with 3D-printed MCP prostheses improving grip strength from 6.7 kg to 17.9 kg. Zhao et al. (2025) also confirmed functional knee restoration in bilateral trauma, demonstrating 120° and 80° flexion at one year. These results affirm the adaptability of 3D printing across diverse anatomical reconstructions.

Overall, consistent evidence supports that additive manufacturing improves fit, function, and patient satisfaction across all major joints. However, challenges remain in standardizing design protocols and regulatory pathways (Le Stum et al., 2023). Surgeon training and multidisciplinary collaboration are critical to ensure safe translation from digital models to clinical outcomes.

Future directions should include long-term comparative trials evaluating cost-effectiveness, material wear, and mechanical endurance across different 3D printing modalities. The convergence of computational modeling, AI-assisted design, and biocompatible printing materials promises to further personalize orthopaedic reconstruction (Liang et al., 2022). As the technology matures, patient-specific 3D-printed implants are poised to redefine reconstructive surgery standards.

Conclusion

This systematic review establishes that 3D printing offers substantial advantages in the customization, precision, and functional outcomes of joint replacement surgeries. Across multiple anatomical regions, 3D-printed implants demonstrated improved alignment accuracy, osseointegration, and patient-reported functional recovery. These benefits were achieved with minimal complications and enhanced long-term implant stability.

Nonetheless, limitations in study standardization, long-term follow-up, and cost analyses underscore the need for future multicenter randomized trials. The integration of advanced imaging, simulation, and biomaterials into additive manufacturing continues to drive progress toward truly personalized orthopaedic reconstruction.

Limitations

This review is limited by heterogeneity in study designs, outcome measures, and follow-up durations, precluding meta-analytical synthesis. The predominance of small cohort studies and case series introduces selection bias. Additionally, cost analyses and regulatory considerations were inconsistently reported. Despite these limitations, the synthesis provides robust insights into current clinical performance trends of 3D-printed joint implants.

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