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THREE-DIMENSIONAL PRINTING IN RHEUMATIC AND MUSCULOSKELETAL DISEASES: RHEUMATOLOGY-FIRST APPLICATIONS FROM PREOPERATIVE PLANNING TO PATIENT OPTIMIZATION AND PERSONALIZED DEVICES

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ABSTRACT

Objectives. Three-dimensional (3D) printing is expanding in musculoskeletal care, but its value in rheumatoid arthritis (RA), spondyloarthritis (SpA) and related rheumatic and musculoskeletal diseases (RMDs) is supported by uneven evidence. We reviewed rheumatology-first applications, emphasizing anatomical models, patient-specific instrumentation (PSI) and selected custom devices, personalized orthoses and perioperative risk modification.
Materials and Methods. Narrative clinical review informed by a structured PubMed/MEDLINE search (last search 22 February 2026) plus reference-list hand searching. Systematic reviews, controlled studies and clinically relevant case series were prioritized. Relevant non-RMD musculoskeletal evidence was included and labeled as indirect.
Outcomes. 3D printing most consistently supports procedural preparation (visualization, rehearsal, templating) and can improve technical accuracy in selected complex reconstructions using PSI. Personalized orthoses and assistive devices enable rapid customization that may improve comfort and adherence. Evidence is strongest for process endpoints. Long-term patient-reported outcomes and cost-effectiveness remain uncertain, particularly in RA/SpA cohorts. Safe use depends on clear intended use, segmentation quality assurance and traceability, and alignment with medication and infection-risk management.
Conclusions. In inflammatory arthritis care, 3D printing adds most when embedded within multidisciplinary governance and perioperative optimization. Priorities include RMD-specific comparative studies and standardized reporting of workflows and implementation outcomes.

KEYWORDS

3D Printing, Additive Manufacturing, Rheumatoid Arthritis, Spondyloarthritis, Patient-Specific Instrumentation, Orthoses

CITATION

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Abbreviations: 3D - three-dimensional, AM - additive manufacturing, RA - rheumatoid arthritis, SpA - spondyloarthritis, RMD - rheumatic and musculoskeletal disease, PSI - patient-specific instrumentation, csDMARD - conventional synthetic disease-modifying antirheumatic drug, bDMARD - biologic DMARD, tsDMARD - targeted synthetic DMARD, CT - computed tomography, MRI - magnetic resonance imaging.

Introduction

Rheumatoid arthritis (RA) and spondyloarthritis (SpA) remain major causes of chronic pain, disability, and irreversible structural damage despite advances in disease-modifying therapy [1]. Even within treat-to-target strategies, a subset of patients develops complex deformity, end-stage joint destruction, tendon imbalance, or axial involvement, requiring multidisciplinary care across rheumatology, orthopedic surgery, radiology, and rehabilitation. Altered anatomy (erosions, malalignment, ankylosis, prior surgery) can obscure landmarks and complicate planning, while immunomodulatory therapy and systemic inflammation increase perioperative vulnerability. Osteoporosis, frailty, sarcopenia, and multimorbidity further influence fixation choices, rehabilitation capacity, and functional recovery[2, 3].

Additive manufacturing (AM), commonly termed three-dimensional (3D) printing, has moved from prototyping to imaging-driven clinical tools that convert CT/MRI into anatomical models, patient-specific guides, and - more selectively - custom devices. In musculoskeletal practice, evidence most consistently supports improvements in procedural preparation and technical accuracy in selected scenarios, whereas patient-reported outcomes and cost-effectiveness remain less consistently demonstrated, particularly in RA/SpA-specific cohorts [4-7].

For inflammatory arthritis, 3D printing may enable precision and personalization through improved visualization and shared decision-making, more reproducible execution via patient-specific instrumentation, and scalable customization of orthoses and assistive devices to improve comfort and adherence [8-11]. Beyond direct clinical use, 3D printing also has established value in undergraduate and postgraduate anatomy education, which may indirectly support surgical training and procedural understanding [12]. Safe translation requires clear intended use, workflow governance, and quality assurance across imaging, segmentation, and production [13, 14]. This clinical review summarizes the current evidence and practical considerations for integrating 3D printing into perioperative optimization in medically complex, often immunosuppressed patients.

Materials and Methods

Study design and reporting framework. This article is best described as a systematized (structured) narrative clinical review, using a transparent and reproducible search with explicit eligibility criteria to map evidence relevant to rheumatology practice. Reporting was informed by PRISMA-ScR items where applicable (information sources, search strategy, selection, and data charting), without meta-analysis or formal risk-of-bias grading. The review was developed in line with ICMJE recommendations and the journal's guidance for review articles. The review was structured around rheumatology-first clinical pathways in rheumatoid arthritis (RA), spondyloarthritis (SpA), and related rheumatic and musculoskeletal diseases (RMDs), focusing on three-dimensional (3D) printing applications in: (i) imaging-derived anatomical models, (ii) patient-specific instrumentation (PSI) including templates and selected custom implants, and (iii) personalized orthoses and assistive devices. Perioperative risk modification and implementation considerations relevant to immunosuppressed patients were incorporated throughout.

Search strategy and information sources. A structured literature search was performed in PubMed/MEDLINE (last search: 22 February 2026). Controlled vocabulary and free-text terms for additive manufacturing and 3D printing were combined with disease terms (RA, SpA, inflammatory arthritis) and application terms (anatomical model, arthroplasty, osteotomy). Reference lists of key reviews and all eligible full-text articles were hand-searched to identify additional studies. The search was limited to English-language publications.

Eligibility criteria. We included English-language publications reporting clinical use of 3D-printed models, templates, PSI, custom implants or orthoses and assistive devices in musculoskeletal care. Eligible designs included systematic reviews, meta-analyses, randomized or controlled studies, non-randomized clinical studies, observational cohorts, and representative case series. Studies involving RA/SpA/RMD populations were prioritized. However, because disease-specific evidence is limited, high-quality musculoskeletal studies likely to generalize to inflammatory arthritis were also included and explicitly labeled as indirect evidence.

Study selection and data extraction. Titles and abstracts were screened for relevance, followed by full-text assessment. For each included study, we extracted: population (RMD-specific vs non-RMD), anatomy and procedure, 3D-printing application, printing approach and material category when reported, comparator (if any), and outcomes (technical accuracy and process measures, complications, patient-reported outcomes, adherence, and costs), together with key limitations.

Evidence synthesis and appraisal. Given heterogeneity in study designs and endpoints, findings were synthesized narratively. Evidence strength was summarized by application domain using an evidence map that distinguishes RMD-specific from indirect evidence and highlights clinically relevant endpoints for rheumatology practice. Formal risk-of-bias assessment was not performed.

Results

Across rheumatology-oriented practice, three application domains dominate the clinical literature:

(1) imaging-derived anatomical models supporting planning and communication

(2) patient-specific instrumentation (PSI), including cutting and drilling guides and - more selectively - plates for complex reconstruction, and

(3) personalized orthoses and assistive devices for chronic hand and foot impairment [8, 15]. Many publications prioritize technical or process endpoints (e.g. alignment accuracy, fluoroscopy exposure, operative metrics, planning changes) rather than long-term patient-reported outcomes and cost-effectiveness, and RA/SpA-specific cohorts are relatively underrepresented [16, 17]. Accordingly, results are organized by domain and interpreted through a rheumatology-first lens. (Table 1)

Table 1. Clinical applications of 3D printing relevant to rheumatology-oriented care

Application domain	Rheumatology-first use cases (examples)	Endpoints	Key requirements & pitfalls
Imaging-derived anatomical models	Complex deformity, erosive change, ankylosis, multidisciplinary discussion, patient education and shared decision-making	Improved 3D understanding, planning confidence, templating, potential changes in surgical approach, team communication [13, 15]	CT, MRI protocol + segmentation QA, verify landmarks in erosive, osteopenic bone, define intended use (education vs planning) [13, 14]
Patient-specific instrumentation (PSI): guides, templates	Corrective osteotomy, arthrodesis where landmarks are unreliable, complex fixation with poor bone stock, selected spinal deformity scenarios in SpA	Improved alignment, accuracy, reduced fluoroscopy, shorter operative time in some settings, more reproducible cuts, drill trajectories [17, 18]	Rigorous design validation, sterilization, biocompatibility, intraop fit check, avoid 'overtrust' - have bailout plan [13, 14]
Custom implants, plates (selected cases)	Salvage reconstruction with severe bone loss, rare complex wrist, foot reconstructions, when standard implants cannot restore anatomy	Better anatomic fit, porous structures for osseointegration, potential functional gains [5, 13, 19]	High regulatory burden, material certification, imaging precision, long lead-time, careful indication selection [5, 13, 19]
Personalized orthoses & assistive devices	RA hand splints, wrist, hand positioning, foot orthoses, rapid iteration for comfort, adherence-focused design	Improved comfort, ventilation, customization at scale, adherence, potential pain, function improvement [9, 10, 20]	Skin integrity monitoring (vasculopathy), training & follow-up, durability, hygiene, patient-centered outcomes [10, 21]
Rheumatology scenario	3D printing tool	Why it helps in RA and SpA	Outcomes commonly reported
RA hand, foot deformity (ulnar drift, MTP subluxation, hindfoot valgus)	Anatomic model, orthosis, occasional cut guide	Erosions and tendon imbalance distort landmarks, personalization improves fit, adherence and supports staged planning	Planning changes, comfort, adherence, pain, function (DASHHAQ), satisfaction [10, 22, 23]
SpA spinal deformity, ankylosis	Anatomic model, drilling guides in selected cases	Altered anatomy increases procedural complexity, models improve rehearsal and risk anticipation [24]	Accuracy, fluoroscopy time, complications (case series)[25-27]
Inflammatory arthritis undergoing arthroplasty	Model, templating, PSI in selected centers [18, 26]	Bone loss, deformity, prior hardware, improved visualization and component planning	Alignment, operative metrics, complications
Revision arthroplasty with bone loss	Model, custom augments, implants (selected) [13]	Defect-specific planning and reconstruction, requires strict governance and traceability	Implant fit, stability, reoperation, function
Rehabilitation for chronic pain, stiffness	Custom splints, orthoses, assistive devices [10, 22, 23]	Comfort, ventilation, rapid iteration, supports adherence and activity participation	Comfort, usability, PROMs, wear time

Clinical problem. In RA and SpA, anatomy is frequently distorted by erosions, subluxations, ankylosis, and previous surgery. In the hand and foot, small bones and complex joint relationships make three-dimensional understanding difficult on 2D imaging.

Strategies and existing evidence. CT- or MRI-derived segmentation can be converted into physical models for shared decision-making, rehearsal, implant templating, and guide fit checks [28]. Across musculoskeletal surgery, models most consistently influence planning confidence and may prompt approach

changes in complex cases [5, 13, 15, 29]. This planning value has also been reported in pediatric orthopedic surgery, where 3D-guided preoperative preparation may improve surgical execution in complex cases [30].

Practical points. Model fidelity depends on imaging parameters and segmentation quality. In inflammatory arthritis, erosions and osteopenia require careful landmark verification. Dual review by radiology and the proceduralist is advisable.

Comparative RA/SpA studies are limited. Future work should test whether planning changes translate into fewer complications and improved function in inflammatory arthritis cohorts.

Clinical problem. Corrective osteotomies, arthrodesis, and complex fixation in inflammatory arthritis can be challenging because conventional landmarks are unreliable and bone quality is reduced.

Strategies and existing evidence. Patient-specific guides aim to translate a virtual plan to accurate execution. The accuracy benefits of template-guided procedures have also been reported in other interventional fields, supporting the general principle that patient-specific templates can improve procedural precision [31]. Patient-specific instrumentation has also been evaluated in joint arthroplasty procedures, including shoulder arthroplasty, where it may improve the accuracy of component positioning [32]. In orthopedics, systematic reviews suggest improved technical accuracy for selected procedures and potential reductions in fluoroscopy exposure [17]. Standardized three-dimensional alignment analysis may further improve preoperative planning and reproducibility of deformity correction strategies [33]**.** Evidence in arthroplasty is mixed in general populations, but rheumatology-relevant subgroups may be those with severe deformity or revision anatomy [16, 17, 26, 34].

Rheumatology-first indications. PSI is most defensible when anatomy is severely distorted, when malposition carries high consequence (nonunion, instability, early revision), or when navigation is unavailable.

Governance and QA. Intraoperative guides are medical devices. Minimum QA includes independent segmentation verification, test-fit on a printed model, and traceability documentation.

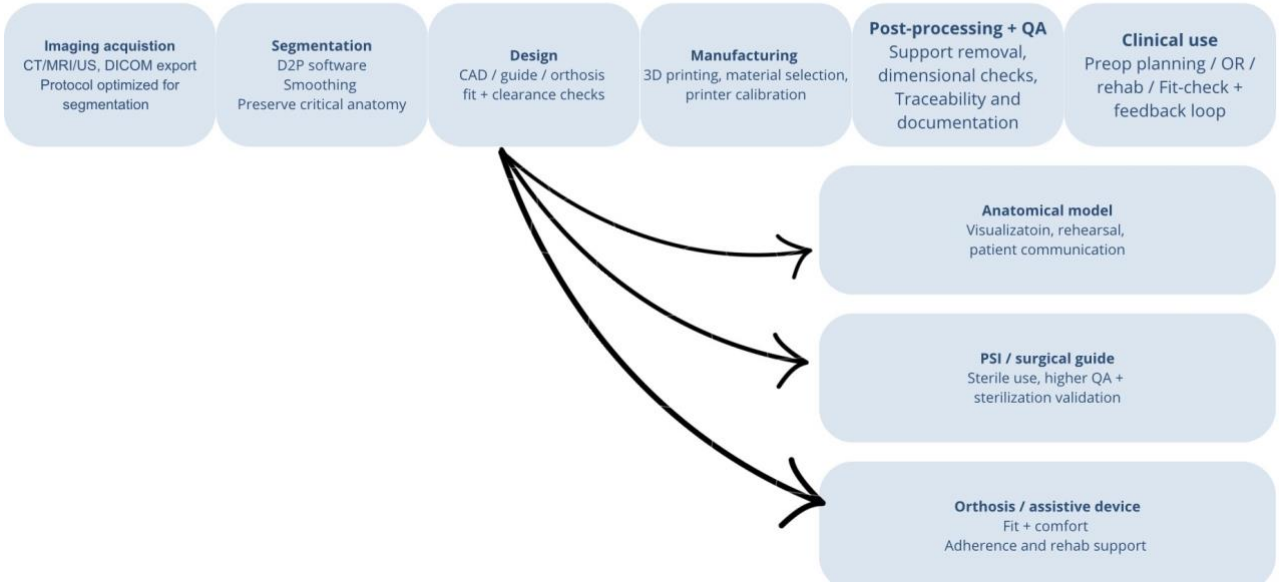

Fig. 1. *Pragmatic imaging-to-print workflow for point-of-care 3D printing in rheumatology. Key governance checkpoints include intended-use classification, independent segmentation verification for sterile-field tools, and documentation (concept informed by Wake et al., 2019, Bastawrous et al., 2022).*

Beyond accuracy, impacts on PROMs and cost-effectiveness remain inconsistent, RA/SpA-specific trials are needed.

Custom implants and plates

Clinical problem. Severe bone loss in revision arthroplasty or complex defects can exceed the capabilities of standard augments.

Strategies and evidence. Custom metal implants and plates can match defect geometry and optimize fixation. Evidence is largely case series and illustrative workflows, emphasizing regulatory and safety considerations.

Implementation cautions. These solutions require robust institutional governance, device classification, certified materials, manufacturing traceability, and post-implant surveillance. They should be reserved for highly selected cases and experienced centers.

Long-term survivorship and infection risk in immunosuppressed cohorts require dedicated reporting.

Personalized orthoses and assistive devices

Clinical problem. Orthoses can reduce pain and improve function in RA, but adherence is limited by discomfort, heat, skin irritation, and poor fit - especially when swelling fluctuates [10, 21, 23, 35].

Strategies and existing evidence. 3D-printed orthoses allow scalable customization, ventilation patterns, and rapid iteration. Reviews report high acceptability and feasibility, with emerging trials showing potential comfort, usability advantages versus conventional materials in selected conditions [21, 22, 36-38]. Similar benefits have also been investigated for 3D-printed insoles and foot-support devices, particularly in relation to plantar biomechanics and comfort [39]**.**

Rheumatology-first design principles. Devices should accommodate swelling variation, protect vulnerable skin, avoid pressure on erosive joints, and prioritize daily-function goals (grip aids, energy conservation). Recent engineering studies also describe customized wrist-hand orthoses designed specifically to optimize fit, ventilation, and usability [38]. Automated production workflows may also shorten fabrication time while maintaining user satisfaction, which is relevant for scalable orthosis delivery [40]. Collaboration with occupational, hand therapy is essential. Beyond rheumatology, 3D-printed upper-limb orthoses have also been explored in broader rehabilitation settings, supporting the feasibility of personalized splint design [41]**.**

Implementation. Smartphone scanning or clinic-based 3D scanning can support remote manufacturing and local fitting [42]. Outsourcing is feasible with data governance and traceability [43].

RA-specific comparative trials remain uncommon. Future studies should report standardized PROMs (HAQ, DASH/QuickDASH, PROMIS), wear time, and durability.

5. Perioperative optimization and medication management

Clinical problem. In RA/SpA, procedural outcomes depend on medical optimization: infection risk under immunosuppression, glucocorticoid exposure, comorbidities, bone health, and functional reserve.

Strategies and existing evidence. Contemporary professional guidance supports structured perioperative management of antirheumatic medications for elective procedures [44]. The 3D-print workflow can facilitate earlier optimization because it creates a defined planning timeline and enhances patient counseling [2, 3].

Recommendations. Establish a multidisciplinary pathway (rheumatology -surgery-anesthesia-rehabilitation) with explicit medication plans, infection prevention, and bone-health management. Table 2 summarizes a pragmatic checklist.

Optimal alignment of 3D printing timelines with medication holding, restart schedules has not been systematically studied. Implementation research should evaluate cancellations, complications, and disease flares.

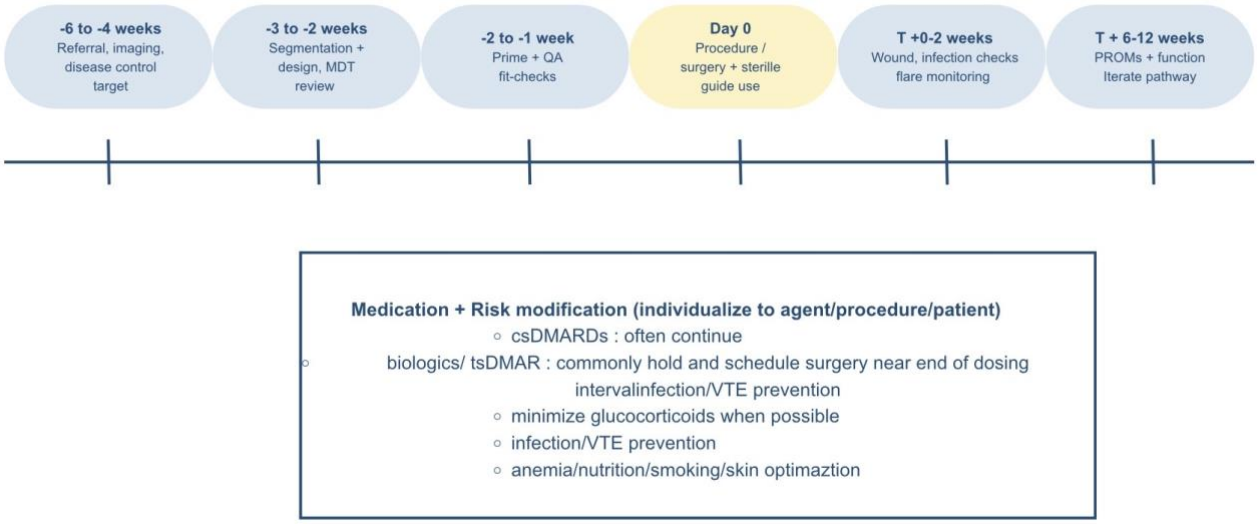

Fig. 2. *Perioperative optimization framework aligning 3D-print-enabled planning with risk modification and antirheumatic medication management. Timing and medication decisions should follow contemporary rheumatology - orthopaedic guidance (Goodman et al., 2022) and be individualized to the patient and procedure.*

Discussion

3D printing should be considered a pathway enabler rather than a universal upgrade. Evidence from other highly tailored template-based procedures, including vascular applications, supports the broader translational value of patient-specific design workflows [45]**.** In rheumatology-first practice, its highest-value uses are (i) severe anatomical complexity (advanced deformity, revision surgery, ankylosis) and (ii) personalized orthoses, assistive devices that improve adherence [9, 10, 23, 46].

Strength of evidence. Benefits are most consistent for technical, process endpoints (planning changes, accuracy, fluoroscopy reduction) and for acceptability, usability of orthoses. Long-term PROM benefits and cost-effectiveness remain uncertain, and RA/SpA-specific cohorts are underrepresented [20, 22].

Implementation and equity. Access varies widely. Hub-and-spoke models and remote scanning may expand access but require robust data governance, clear device labeling, and QA. Broader medical 3D-printing literature also shows that successful implementation depends on standardized workflows, material selection, and reproducibility across the imaging-to-manufacturing pathway [47, 48]. Similar implementation patterns have been described in other surgical specialties, including otolaryngology and head and neck surgery [49]. Applications in orthognathic and craniofacial planning further support the role of 3D printing in complex anatomy and preoperative visualization [50].

Regulatory and safety. Intended-use classification (model vs guide vs implant), sterilization validation, and traceability are critical. Standard operating procedures should document segmentation QA, version control, and fit checks.

A rheumatology-first implementation should explicitly account for immunosuppression and systemic inflammation. For sterile-field uses, preoperative checkpoints should include skin integrity (ulcers, steroid atrophy), recent infection history, vaccination status, and a coordinated plan for glucocorticoid minimization and biologic holding and restart, following contemporary perioperative medication guidance [2, 3, 47]. For orthoses, low-cost customization can reduce pressure points and shear, but requires early follow-up to detect dermatitis, wound breakdown or neuropathic injury - issues that may be amplified in vasculitis, diabetes or long-standing RA [10, 22, 23]. Finally, shared decision-making should address the opportunity cost of printing versus flare risk and surgical delays. Tracking cancellations, flare rates, and device-related adverse events will help identify where 3D printing truly improves outcomes [13, 14].

Author recommendations. Prioritize orthoses and shared-decision models first (scalable, low risk), develop governance for guide-based procedures (higher risk and benefit), and reserve custom implants for specialized referral centers [9, 10].

Table 2. Practical preoperative optimization checklist for RMD patients supported by 3D printing

Domain	What to assess	Actionable steps before procedure (examples)
Inflammation & disease activity	Disease control, flares, active synovitis and enthesitis	Coordinate treat-to-target, avoid elective surgery during uncontrolled disease, document baseline function and goals
Antirheumatic medication plan	csDMARDs, biologics, JAK inhibitors, glucocorticoids	Align with perioperative medication guidance, plan timing of holds and restarts, minimize chronic steroids when feasible, document rationale [2, 3]
Infection prevention	Skin lesions, dental and urinary infection, prior prosthetic infection, MRSA risk	Treat active infection, optimize skin, consider decolonization per local protocol, perioperative antibiotics per procedure and risk
Bone health	Osteoporosis, prior fractures, vitamin D, calcium, bisphosphonates, denosumab	Assess fracture risk, treat osteoporosis, ensure vitamin D sufficiency, plan fixation strategy for poor bone quality
Comorbidities & anesthesia risk	CV disease, lung disease, renal disease, diabetes, obesity, sarcopenia	Pre-op medical optimization, smoking cessation, glycemic control, nutrition, prehabilitation referral when indicated
Thrombosis and bleeding risk	History of VTE, anticoagulants, antiplatelets	Coordinate perioperative anticoagulation plan, mechanical, chemical prophylaxis as appropriate
Rehabilitation and adherence	Hand therapy access, splint, social support	Define rehab plan pre-op, schedule early therapy, teach orthosis wear schedule and skin checks, set PROM targets [10, 21]
3D printing workflow & governance	Intended use, image quality, QA, device classification	Standardize imaging, dual-review segmentation, document intended use, sterilization validation for guides, traceability and outcomes audit [13, 14]
Domain	What to assess	Actionable steps (examples)
Inflammation control	Disease activity, recent flares, infection history	Aim for remission, low activity when feasible, coordinate timing, defer elective procedures during active infection
Antirheumatic medication	csDMARD, bDMARD, tsDMARD schedule, glucocorticoids	Plan continuation, holding per guideline, local protocol, document restart timing, minimize chronic glucocorticoid dose where possible [2, 3]
Infection prevention	Skin integrity, urinary infections, vaccination, glycemia	Treat active infections, optimize glycemia, smoking cessation, update vaccines, consider decolonization per local policy
Bone & muscle health	Osteoporosis risk, vitamin D, sarcopenia	DEXA when appropriate, calcium, vitamin D, treat osteoporosis, prehabilitation, choose fixation strategy mindful of bone quality
Thrombosis & mobility	VTE risk, baseline mobility, fall risk	Plan prophylaxis and early mobilization, coordinate rehab, assess assistive device needs
3D-print workflow QA	Segmentation validation, fit check, sterility, traceability	Independent landmark verification, model test-fit, define sterilization, maintain version control [13, 14]

Document: indication, imaging source and date, device type, material, QA sign-off, sterilization (if applicable), and patient counseling notes. For orthoses: fitting parameters, wear schedule, skin monitoring advice, and follow-up plan[10, 21].

Implementation considerations (condensed).

Start with low-risk, high-yield applications (anatomic models for counseling and staged planning, assistive devices). Define intended use, ownership, and documentation requirements before scaling to intraoperative guides or implants.

Minimum quality and safety checklist:

- Standardize imaging acquisition and segmentation. Verify critical anatomy with a second reviewer for sterile-field use.
- Document indication, imaging date, device type, material, QA sign-off, and sterilization validation (if applicable).
- Track a small dashboard (turnaround time, remake rate, device-related adverse events, user satisfaction).
- Clarify data governance for outsourcing (DICOM transfer, storage, vendor agreements, traceability).
- Align printing timelines with perioperative optimization and medication holding and restart plans.

Evidence in rheumatology-specific cohorts remains limited. Key gaps include: (I) comparative studies in RA/SpA populations with standardized endpoints (PROMs, complications, revision, cost), (II) consistent reporting of workflow, segmentation QA, sterility, and regulatory classification, (III) durability, adherence and usability outcomes for 3D-printed orthoses, (IV) implementation studies assessing access, turnaround time, and real-world cost-effectiveness, (V) post-market surveillance and safety reporting for patient-specific guides and implants.

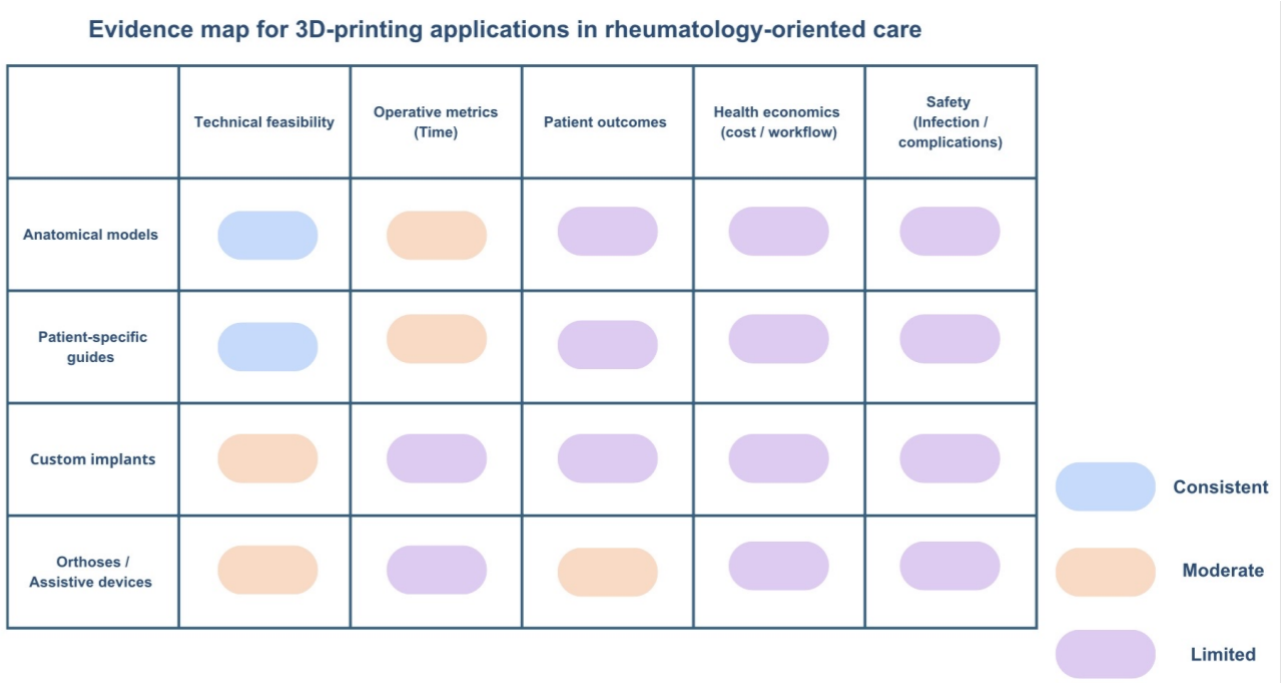

Fig. 3. *Qualitative evidence map summarizing where 3D printing has the strongest vs most limited evidence across application domains and outcome types in rheumatology-oriented care.*

Areas of uncertainty

Evidence in RA/SpA-specific cohorts is sparse, most data extrapolate from broader orthopaedic populations.

Downstream clinical outcomes (complications, revisions, PROMs, cost-effectiveness) are inconsistently reported and rarely powered for RMD subgroups.

Workflow variability (imaging parameters, segmentation thresholds, QA methods, materials and sterilization) limits comparability across studies.

Regulatory classification and documentation for point-of-care manufacturing remain heterogeneous between jurisdictions and institutions.

Research priorities: pragmatic RA/SpA comparative studies with standardized PROMs (HAQ, DASH/QuickDASH, PROMIS), registry-based complication tracking, and reporting standards for segmentation QA, sterility, and traceability.

Conclusions

3D printing is increasingly relevant to rheumatology-first care pathways, particularly for advanced deformity, revision scenarios, and personalized orthoses, assistive devices that support long-term function. The greatest near-term gains are achieved when 3D printing is embedded within multidisciplinary governance and perioperative optimization for immunosuppressed patients. Future studies should prioritize RA/SpA-specific comparative outcomes, standardized workflow, QA reporting, and pragmatic evaluations of cost, access, and implementation [10, 21].

Conflict of Interest: The authors declare no conflict of interest.

Author's Contributions:

Conceptualization - N.S.K.. Methodology - N.S.K. and M.K. Literature search and data curation - T.B., K.C., K.W., M.N.. Writing - original draft preparation - N.S.K., M.S., M.N.. Writing - review and editing - all authors. Visualization - figures and graphical content - M.K., G.S., M.P., D.K.. Supervision, N.S.K. All authors have read and agreed to the published version of the manuscript.

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