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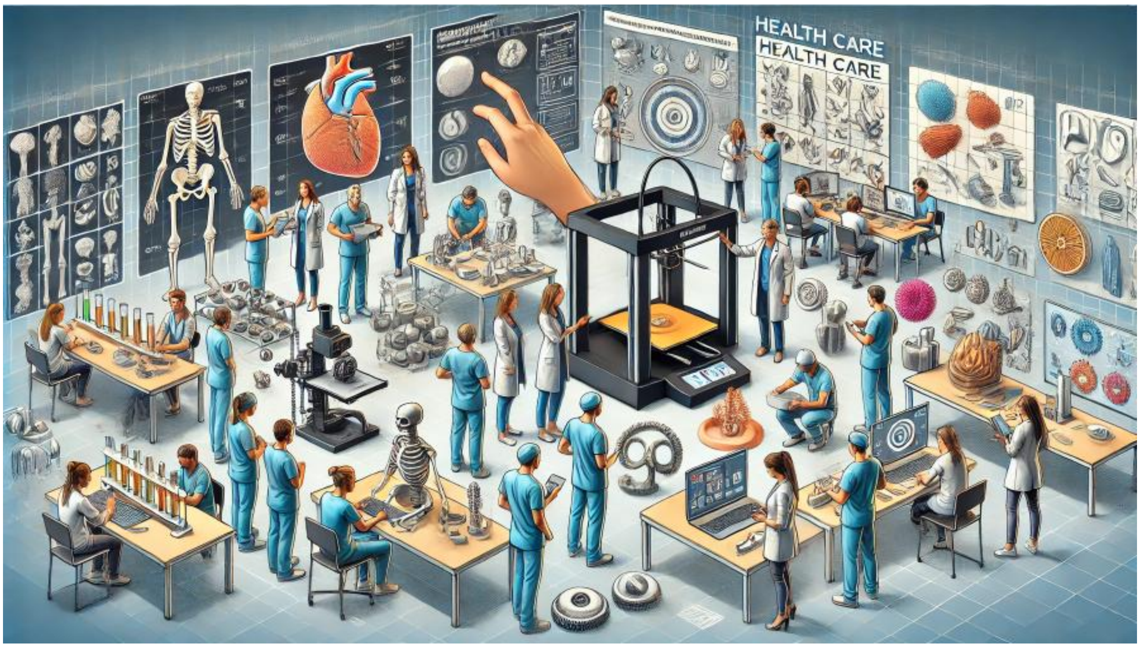
TECH-HEALTH Toolkit

Innovative 3D Printing Technologies for Healthcare Professionals

A Guide for Vocational Education and Training - VET



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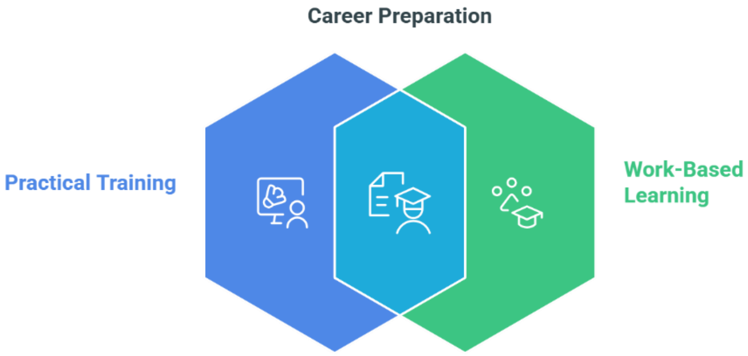
1. INTRODUCTION

1.1 Purpose of this document:

Vocational Educational Training provides individuals with the practical skills, knowledge, and competencies needed to succeed in specific trades or professions, focusing on **hands-on training and work-based learning**, often combining **classroom instruction with practical experiences in real work environments.**



Main goals

Building Skills

Align competencies to the evolving jobs and the digital transition.

Innovative Methodologies

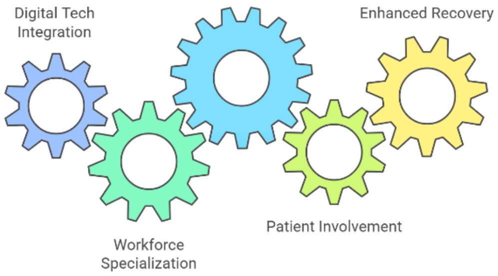
Encourage new methods in 3D printing for healthcare.

Good Practices Toolkit

Create a resource of best practices for 3D printing and participatory models in healthcare.

Target population

The increasing role of digital technologies in the medical field requires a higher specialization among the health workforces. The indirect target groups are patients in hospitals and healthcare centres.



1.2 Why 3D Printing is Transforming Healthcare

1.2.1 The Transformative Potential of 3D Printing

Three-dimensional (3D) printing, or additive manufacturing, has rapidly emerged as a revolutionary force in multiple industries, with healthcare being the prime beneficiary (1–3). This technology facilitates the precise fabrication of complex structures from digital models, enabling the customization of medical devices, implants, and even biological tissues (1–4). The ability to generate patient-specific solutions has led to widespread adoption in the medical field, addressing intricate clinical challenges with unprecedented precision (5–10).

Three-dimensional (3D) printing is redefining modern healthcare by offering unprecedented precision, customization, and efficiency in the development of medical solutions. This transformative technology enables rapid fabrication of complex structures from digital designs, facilitating the creation of patient-specific medical devices, prosthetics, implants, and even bioengineered tissues (*Figure 1*). The adaptability of 3D printing has revolutionised surgical planning, medical education, and regenerative medicine, making it an indispensable tool in contemporary healthcare (1–5,11). The ability to generate patient-specific solutions has led to widespread adoption in the medical field, addressing intricate clinical challenges with unprecedented precision (5–10).

Figure 1: benefits of 3D printing in Health Care

A significant advantage of 3D printing in healthcare is its capacity to accommodate the specific anatomical and physiological characteristics of each patient, marking a fundamental shift in personalized medicine (1,6,11). This individualized approach ensures that prosthetics, implants, and medical models provide an optimal fit, enhancing both function and patient comfort. Additionally, 3D printing facilitates rapid prototyping and iterative testing, allowing researchers and clinicians to refine designs in real time and expediting the innovation process (9,11–14).

As technological advancements continue, three-dimensional (3D) printing is expected to play an even greater role in healthcare. The integration of artificial intelligence (AI) and machine learning in 3D printing workflows will likely enhance automation, material optimisation, and predictive modeling, further refining patient-centred medical solutions. With ongoing research and collaborative efforts between engineers, biomedical scientists, and healthcare professionals, the adoption of 3D printing in medicine is set to accelerate, revolutionizing both treatment methodologies and patient care paradigms (9,11,11,12,14).

Another transformative aspect is the cost efficiency. Traditional manufacturing methods for custom medical devices involve expensive moulds and extensive production times, often limiting their accessibility. In contrast, 3D printing reduces material waste and enables localized production, significantly lowering overall costs. The speed of fabrication further enhances its appeal, with complex anatomical models and surgical tools being produced in a fraction of the time required for conventional techniques (9,11,11,12,14). This efficiency is particularly crucial in emergency medical scenarios where timely access to patient-specific medical devices can dramatically improve outcomes.

The ability to produce customized healthcare solutions on demand is a key advantage of 3D printing. Unlike traditional manufacturing methods, which often require extensive lead times and expensive molds, additive manufacturing streamlines the production process, allowing for rapid prototyping and real-time modifications. This flexibility enables healthcare professionals to develop tailored treatments that cater to the unique anatomical and physiological needs of individual patients, improve outcomes, and enhance patient satisfaction (11,12,14,15).

1.2.3 The Role of Digital Fabrication in Modern Medicine

Digital fabrication, which encompasses 3D printing and other advanced manufacturing techniques, is redefining modern medicine by introducing precision, flexibility, and innovation in patient care. Through the integration of digital workflows, medical professionals can design, simulate, and produce complex anatomical structures, customized implants, and even bioengineered tissues with unprecedented accuracy (5,6,8).

One of the most significant contributions of digital fabrication to medicine is its ability to enhance surgical planning. Surgeons can now use 3D-printed models of patient-specific anatomies to practice procedures before performing them, thereby reducing risks and improving outcomes. This application is particularly beneficial in complex surgeries, such as neurosurgery, orthopaedics, and reconstructive procedures, where high precision is essential (6,16,17).

Additionally, digital fabrication supports the rapid production of personalized prosthetics and orthotic devices. Traditional manufacturing processes for these devices can be time consuming and costly, whereas digital fabrication enables the creation of custom-fitted solutions in significantly less time. This is especially advantageous for paediatric and trauma patients, who require frequent adjustments to their devices as they grow or heal (5,6,8).

Another groundbreaking application of digital fabrication is bioprinting, which is revolutionizing tissue engineering and regenerative medicine. Scientists are now capable of fabricating tissue scaffolds, organoids, and even functional human tissues using specialized bio-inks. These advances hold immense potential for drug testing, disease modelling, and, ultimately, the development of lab-grown organs for transplantation (5,6,8).

Furthermore, digital fabrication facilitates innovation in the development of smart medical devices. Wearable health monitors, drug delivery systems, and customized implants can be tailored to individual patient needs, improving treatment effectiveness and patient compliance. The ability to integrate electronics into 3D-printed structures further enhances the scope of medical applications, making real-time health monitoring and automated therapy adjustments a reality (5,6,8).

As digital fabrication technologies continue to evolve, they will bridge the gap between medical research and clinical practice. Standardising digital fabrication training in medical education and vocational programs is critical to ensuring that healthcare professionals are equipped with the necessary skills to effectively harness these innovations. By fostering interdisciplinary collaboration among engineers, medical practitioners, and material scientists, digital fabrication will continue to shape the future of modern medicine and improve patient outcomes globally.

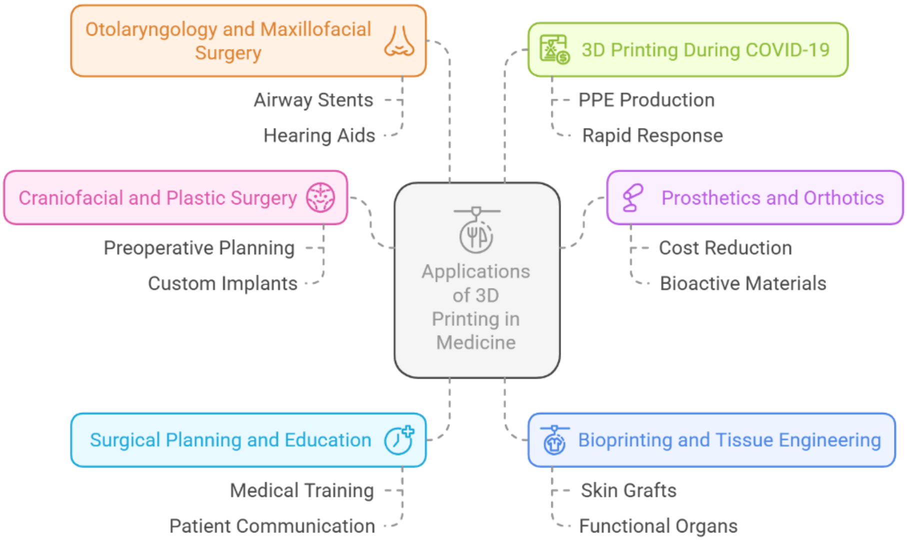


Figure 2: Applications of 3D printing in medicine

2. Technological Foundations: Principles and Key Advantages

Three-dimensional (3D) printing is an additive manufacturing technology that constructs physical objects by depositing materials in successive layers based on a digital blueprint. Unlike subtractive manufacturing methods, which remove material from a solid block, additive manufacturing builds geometry through controlled material addition (18–21).

The process typically begins with a three-dimensional digital model created using computer-aided design (CAD) software or generated from medical imaging data such as magnetic resonance imaging (MRI) or computed tomography (CT) scans. These digital models serve as the blueprint for fabrication (19).

2.1 Primary 3D Printing Techniques:

Several additive manufacturing technologies are currently used in technical and medical contexts:

- **Extrusion-based printing:** Thermoplastic or bio-based material is extruded through a nozzle and deposited layer by layer.
- **Sintering:** Powdered or liquid material is selectively fused using a high-energy source, such as a laser.
- **Stereolithography (SLA):** Laser or ultraviolet light solidifies liquid resins to create high-resolution structures.
- **Fused Deposition Modeling (FDM):** A thermoplastic filament is melted and precisely layered to construct objects.

Among these, Fused Deposition Modeling (FDM) is one of the most widely applied technologies in healthcare.

2.2 Fused Deposition Modeling (FDM): Principles and Functional Architecture (18,20,21)

Fused Deposition Modeling (FDM) is extensively applied in healthcare for producing anatomical models, orthoses, splints, surgical guides, and educational simulators. The process is based on the controlled extrusion of a thermoplastic filament that is heated to a semi-molten state and deposited layer by layer, forming a three-dimensional object from a digital model. Each newly deposited layer thermally bonds to the previous one, creating a cohesive structure.

Understanding the mechanical and thermal architecture of FDM systems is essential for ensuring dimensional accuracy, structural integrity, and reproducibility—especially in clinical applications.

2.2.1 Extrusion System

The extrusion system manages material transport, melting, and deposition. A continuous thermoplastic filament (e.g., PLA, ABS, PETG, TPU) is driven by an extruder motor into a thermally regulated hot end, where it melts and exits through a calibrated nozzle (commonly 0.4 mm diameter).

Nozzle diameter determines line width (X–Y resolution), maximum layer height, extrusion stability, and print speed. For adequate interlayer adhesion, layer height should generally not exceed 70–80% of nozzle diameter.

Two mechanical configurations are commonly used:

- **Direct Drive**: The motor is mounted directly on the print head. This configuration offers precise extrusion and retraction control and is advantageous for flexible polymers.
- **Bowden**: The motor is mounted remotely and directs the filament through a Bowden tube. This reduces moving mass and may increase speed but requires precise calibration to maintain extrusion consistency.

2.2.2 Kinematics and Mechanical Precision

FDM printers operate within a Cartesian coordinate system (X: lateral, Y: anterior–posterior, Z: vertical stacking). Stepper motors drive belts, pulleys, and lead screws to position the print head with discrete, incremental movements. Most systems use open-loop control, meaning that commanded positions are executed without real-time positional feedback. Mechanical irregularities such as loose belts or pulley slippage may cause cumulative errors (e.g., layer shifting), compromising dimensional accuracy. This is particularly critical in clinical applications such as surgical guides or patient-specific interfaces.

Routine calibration and mechanical maintenance are therefore essential quality-control measures.

2.2.3. Thermal Management

Thermoplastics expand during heating and contract during cooling. Proper temperature regulation is central to structural integrity and dimensional stability.

A heated build plate improves first-layer adhesion, reduces thermal gradients, and minimizes warping. Typical temperature ranges include:

- **PLA:** approximately 50–60°C
- **ABS:** up to 100–120°C

Active cooling systems regulates the solidification of deposited layers and prevent heat creep within the hot end. Appropriate balance between extrusion temperature and cooling rate optimizes interlayer bonding, surface finish, and dimensional stability.

2.3 Materials in FMD and Medical Applications (20)

Material selection is a critical determinant of both mechanical performance and clinical suitability.

- **Polylactic Acid (PLA):** A highly versatile thermoplastic used not only for standard prototyping but also in medical contexts such as surgical guides, orthopedic surgery applications, tissue regeneration matrices, and controlled-release drug coatings.
- **ABS:** A durable thermoplastic with higher temperature resistance.
- **PETG:** Offers improved mechanical resistance and chemical stability.
- **TPU:** A flexible polymer suitable for soft interfaces or orthotic components.
- **PVA:** A water-soluble material typically used for complex support structures in multi-material printing.

Selecting the appropriate material must consider mechanical demands, biological compatibility, structural resistance, and intended clinical function.

You can overview the main characteristics of FDM 3D Printing in Health Care in ***Table I.***

Table I. Overview of FDM 3D Printing in Health Care

FDM 3D Printing in HC	*Core Principle*	*Key Components / Variables*	*Technical Considerations*	*Clinical / Practical Relevance*
FDM Foundations	Additive manufacturing builds objects layer by layer from a digital model	CAD models, MRI/CT imaging, STL files	Model quality determines final accuracy	Enables patient-specific solutions and anatomical customization
3D Printing Techniques	Different energy/material deposition methods	Extrusion, Sintering, SLA, FDM	Resolution, material compatibility, equipment cost	Selection depends on precision needs and application context
Extrusion System	Thermoplastic filament is melted and deposited through a nozzle	Filament (PLA, ABS, PETG, TPU), Hot End, Nozzle (e.g., 0.4 mm), Direct Drive / Bowden	Nozzle diameter determines resolution and layer height (≤70–80% of nozzle size)	Determines structural integrity and suitability for orthoses, guides, simulators
Kinematics & Motion Control	Controlled movement in Cartesian coordinates	X–Y–Z axes, Stepper motors, Belts, Lead screws	Open-loop control; mechanical misalignment may cause layer shifting	Critical for dimensional accuracy in surgical guides and patient-specific devices
Thermal Management	Controlled heating and cooling ensures bonding	Heated bed (PLA: 50–60°C; ABS: 100–120°C), Cooling fans	Balance between extrusion temperature and cooling rate	Prevents warping and ensures structural stability
Materials in FDM	Mechanical and biological performance depends on material choice	PLA, ABS, PETG, TPU, PVA (supports)	Strength, flexibility, temperature resistance, support removal	Determines mechanical behavior and potential medical application
Digital Design & Optimization	Geometry created or modified before fabrication	CAD software, medical imaging, mesh inspection	Surface quality and model integrity essential	Prevents printing errors and improves clinical precision
Slicing & G-Code Generation	Digital model converted into machine instructions	STL file, Slicer software (e.g., Cura), G-Code	Correct printer selection prevents mechanical damage	Ensures safe and precise execution
Parameterization	Internal and external object characteristics are software-defined	Layer height, Speed, Infill density/pattern, Wall thickness	Trade-off between strength, time, and surface quality	Tailors’ device resistance and weight
Execution & Fabrication	Layer-by-layer physical construction	G-Code transfer, First-layer adhesion, Skirt	Calibration and maintenance essential	Determines reproducibility and reliability
Post-Processing	Final refinement of printed object	Support removal, Acetone vapor, UV curing, Mechanical polishing	Material-dependent finishing techniques	Enhances durability, aesthetics, and functional performance

2.4 Digital manufacturing and 3d printing workflow: from technical design to clinical application (18,20)

The transformation of a digital concept into a physical, high-fidelity object involves a structured workflow known as additive manufacturing. This process requires the seamless integration of specialized software and hardware to ensure precision, especially when applied to technical or medical fields.

2.4.1 Digital Design and Model Optimization

The workflow begins with the creation of a three-dimensional model. This can be achieved through Computer-Aided Design (CAD) software, downloading verified files from online repositories like *Thingiverse*, or utilizing reverse engineering through medical imaging such as CT scans or MRIs. Using CAD/CAM tools at this stage is essential, as it allows for the modification and optimization of the model's geometry before any material is consumed. Quality control is essential at this stage. Digital models must be inspected for surface facets and mesh quality. Low-quality digital files result in poor physical outcomes during printing (11,19).

2.4.2 File Export and Slicing Procedures

Once the design is finalized, it is exported as an STL file. This format translates the model's surface into a simplified mesh, removing additional data such as color or texture. The STL file is then imported into "slicing" software, such as Ultimaker Cura or Orca, which partitions the model into horizontal layers and generates the G-Code. During slicing, the specific printer model (e.g., Creality Ender 5) must be selected. Using G-Code intended for a different machine can lead to severe mechanical damage (22,23).

2.4.3 Material Selection and Hardware Configuration

Before printing, operators must ensure that the appropriate material is selected according to application requirements. That the printer is properly calibrated and that the nozzle size configured in the software matches the physical hardware. This alignment ensures extrusion consistency and dimensional accuracy (24).

2.4.4 Technical Parameterization (24)

The internal and external characteristics of the printed object are determined by several key parameters:

1. **Layer height (Z-axis resolution) and printing speed:** Balance surface quality and production time.
2. **Infill density and patterns:** The percentage and pattern (e.g., lines for efficiency, tri-hexagon for structural resistance) determine strength and weight.

3. **Wall thickness:** Influences resistance to external pressure and overall durability.

2.4.5 Execution and Layer-by-Layer Fabrication

The G-Code is transferred to the printer (commonly via memory card), and the object is fabricated layer by layer. Successful execution depends on a regular calibration and maintenance, and a proper first-layer adhesion.

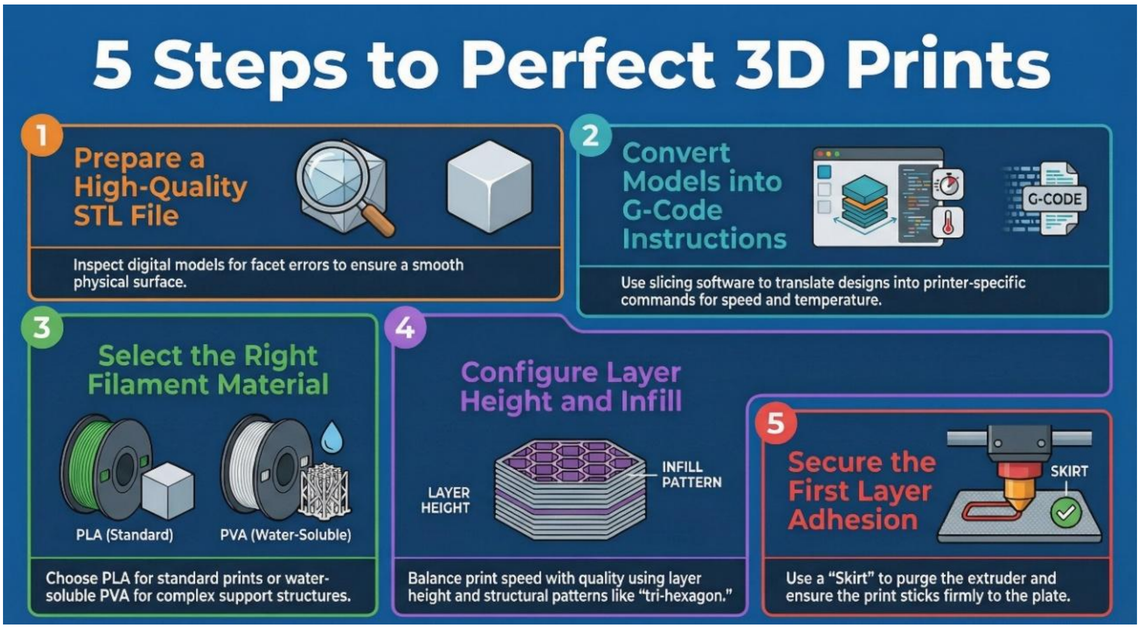
Techniques such as printing a “Skirt” (a perimeter line around the object) help purge air from the nozzle and ensure consistent material flow before deposition begins.

2.4.6 Post-Processing and Refinement (21)

The final stage involves physical adjustments to meet technical and clinical specifications. Depending on the material and technology used, post-processing may include:

- **Support removal:** Manual extraction of temporary structures.
- **Surface finishing:** Application of acetone vapor, ultraviolet curing, or mechanical polishing to improve durability and aesthetic quality

By adhering to this structured technical workflow—from digital design to post-processing—it is possible to produce customized, cost-effective solutions that meet the high standards required in industrial and clinical applications. Proper understanding of technological foundations, mechanical architecture, material properties, and process parameters is essential to ensure safety, precision, and reproducibility in healthcare-related additive manufacturing.



5 Steps to Perfect 3D Prints

1 Prepare a High-Quality STL File

Inspect digital models for facet errors to ensure a smooth physical surface.

2 Convert Models into G-Code Instructions

Use slicing software to translate designs into printer-specific commands for speed and temperature.

3 Select the Right Filament Material

Choose PLA for standard prints or water-soluble PVA for complex support structures.

4 Configure Layer Height and Infill

Balance print speed with quality using layer height and structural patterns like “tri-hexagon.”

5 Secure the First Layer Adhesion

Use a “Skirt” to purge the extruder and ensure the print sticks firmly to the plate.

Figure 3: 5 steps to perfect 3D prints

2.5 Major Advantages of 3D Printing in Healthcare.

- **Personalisation:** Fabrication of medical implants and devices tailored to the patient's anatomy (1,2,5,11,15).
- **Accelerated production:** Rapid prototyping and reduced time to market for novel medical solutions (1,3,5,11,15,16).
- **Cost efficiency:** Lower material waste and production costs compared with traditional manufacturing methods (2,11,14,15).
- **Enhanced precision:** Facilitates the creation of intricate, high-fidelity structures essential for medical applications (1–3).
- **Material versatility:** Compatibility with a broad spectrum of materials, including polymers, metals, ceramics, and bio-inks (1,2,11,25).

You can access a comparative overview of 3D printing technologies in healthcare in ***annex II.***

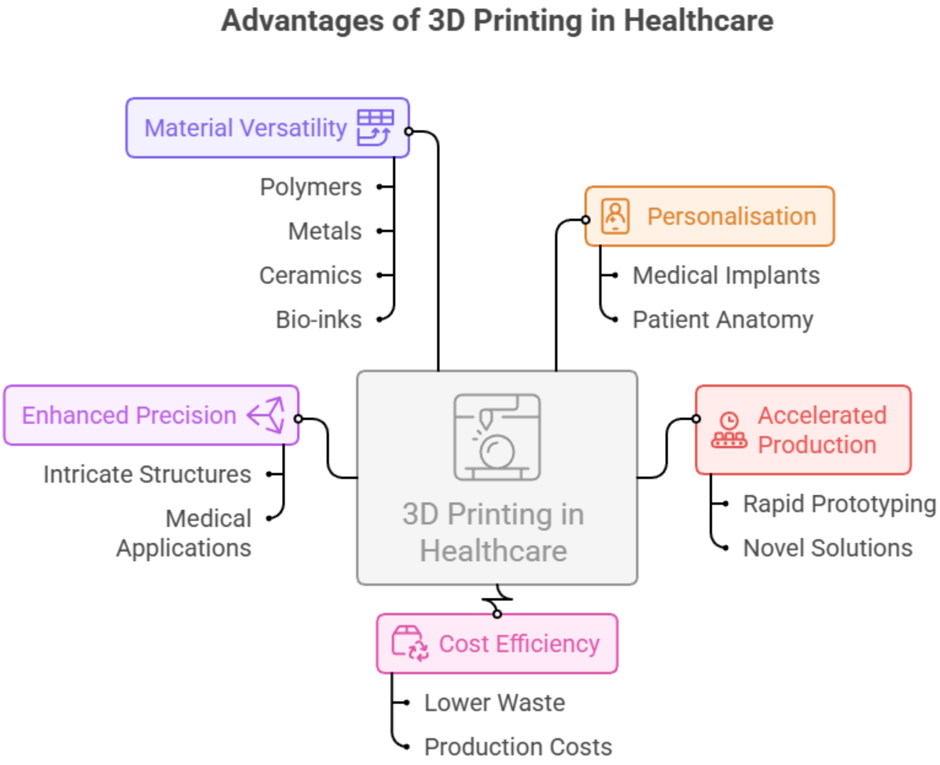


Figure 4: Advantages of 3D printing in Health Care.

3. Clinical Applications of 3D Printing.

The integration of 3D printing technologies into healthcare has significantly advanced clinical practice, surgical planning, patient recovery, and personalized treatment delivery (17,19,26,27). By enabling the creation of complex, customizable, and cost-effective medical solutions, 3D printing is reshaping how care is conceptualized and delivered across multiple healthcare disciplines. Applications span prosthetics, anatomical models, implants, and patient-specific medical devices, as well as transforming areas, such as medical training, public health response, and pharmacological innovation.

3.1 Prosthetics and Orthotics

3D printing facilitates rapid and affordable production of patient-specific prosthetic limbs and orthotic devices. These personalized solutions are designed to match the individual’s anatomy, resulting in improved mobility, enhanced physical comfort, and better usability. Advanced materials such as carbon-fibre composites and thermoplastic elastomers allow for lightweight yet durable components that support natural movement.

The impact is especially significant for paediatric patients, trauma survivors, and individuals in resource-limited settings, where access to traditional prosthetics is often restricted. Additionally, the aesthetic personalization of prosthetic devices helps patients gain confidence and supports emotional well-being. 3D printing also allows for on-demand manufacturing, reducing wait times and increasing accessibility (28–30).

3.2 Anatomical Models and Surgical Guides

Anatomical models derived from high-resolution imaging, such as CT or MRI resonance imaging, provide clinicians with detailed tactile visualisations of complex anatomical structures. These 3D-printed models are used to enhance preoperative planning, facilitate surgical rehabilitation, and improve patient education and consent processes. Surgeons can practice replicas, reduce intraoperative time, and minimise risks (31).

The use of 3D-printed medical devices in the direct treatment of patients has increased considerably since 2015. Metal and nonmetal 3D printing in orthopedics and orthopedic oncology are the most common applications. With an emerging trend toward the use of nonmetal 3D printing in medicine for patient-specific and precision devices in neurosurgery and oncology (30).

Surgical guides customized to a patient’s unique anatomy further increase procedural precision. These devices help direct cutting instruments and implant placement with high accuracy, reducing variability and improving outcomes. Applications extend across craniofacial surgery, orthopaedics, oncology, and cardiovascular interventions.

3.3 Personalized Implants

Custom 3D-printed implants offer unparalleled anatomical conformity and structural compatibility. They are fabricated from biocompatible materials, such as titanium alloys, PEEK, or bioresorbable polymers. These implants are especially valuable in cases where off-the-shelf solutions are inadequate, such as in complex skeletal reconstructions, tumour resections, or congenital malformations (4,32).

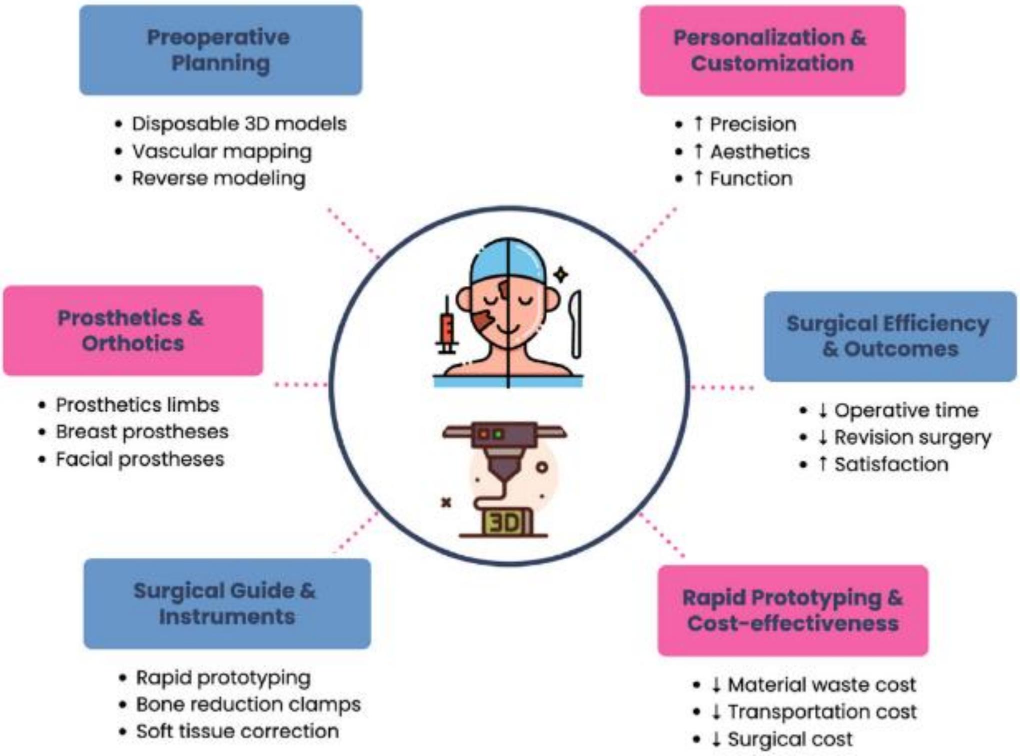


Figure 5: Advantages of 3D printing in Health Care (4).

The ability to plan and fabricate these implants preoperatively using CAD software enables shorter surgery, fewer complications, and faster recovery. Surgeons increasingly rely on this approach to deliver bespoke care, which improves both functional and aesthetic results.

3.4 Custom Medical Devices

The versatility of 3D printing supports the production of a wide array of customized medical devices. Examples include ergonomic surgical instruments, orthopaedic braces, wearable health trackers, hearing aids, dental appliances, and drug delivery implants. These devices are tailored not only to fit the patient's body but also to integrate into specific clinical workflows (11).

This adaptability allows iterative improvements based on real-time clinical feedback. It also enhances patient adherence to treatment regimens by improving the device comfort, usability, and performance. In postsurgical rehabilitation or chronic care settings, such personalised devices can be transformative.

Figure 6: Assistive devices made in SOUL Fab Lab, FSJD, Madrid.

3.5 Cost-Effective, Decentralized Manufacturing

3D printing supports the rapid, localised production of small- or single-use medical items. This is especially advantageous in scenarios where traditional supply chains are disrupted or insufficient, such as during global health emergencies. During the COVID-19 pandemic, 3D printing was widely adopted to produce nasal swabs, and ventilator components, demonstrating its role in public health resilience.

The ability to decentralise manufacturing reduces transportation costs, shortens delivery times, and supports just-in-time inventory systems in healthcare settings. This decentralisation can also foster innovation in rural or underserved regions by enabling point-of-care fabrication (8,14,33,34).

To conclude, beyond the major application areas, the impact of 3D printing has expanded into a wide range of additional medical specialties, including ophthalmology, where it enables the fabrication of customised intraocular lenses and corneal scaffolds; ENT (otolaryngology), through the printing of sinus models, auditory implants, and airway splints; vascular surgery, with the development of personalised stents, vascular grafts, and anatomical models for aneurysm repair planning; dentistry, via the production of crowns, bridges, dentures, surgical guides, and orthodontic aligners; oncology, through the design of radiation-shielding devices and patient-specific surgical guides; and paediatrics, where it supports the creation of adjustable prostheses, airway models, and tailored educational tools. This diversity highlights the transversal and increasingly integrated role of 3D printing across contemporary healthcare practice (33).

4. Innovations and Future Trends: Bioprinting and Regenerative Medicine

As 3D printing continues to evolve, it is increasingly entering the biological and cellular domains. Bioprinting represents the convergence of additive manufacturing with regenerative medicine, using bioinks composed of cells, growth factors, and biomaterials to fabricate functional living tissues and potentially even complete organs in the future.

4.1 Tissue and Organ Engineering

Bioprinting enables the construction of viable tissues such as dermal layers, cartilage, bone, corneal implants, and vascular conduits. These bioprinted tissues are used in both research and clinical applications and offer alternatives to donor grafts and synthetic substitutes. Scientists are also progressing toward printing organ components, including liver lobules, kidney tubules, and cardiac patches (2).

By utilising patient-derived stem cells in the bioprinting process, the risk of immune rejection can be minimised. Such advancements may eliminate organ waitlists for one day, allowing for autologous organ replacement.

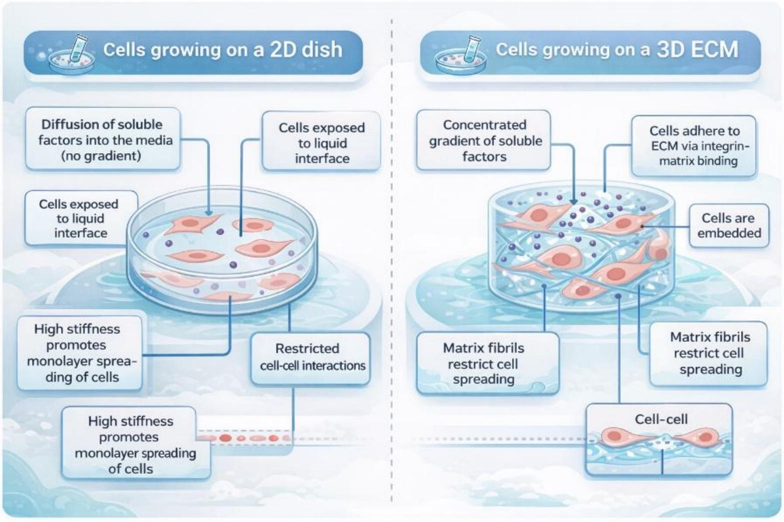


Figure 7: Advantages of 3D printing in Health Care (2)

4.2 Disease Modeling and Drug Testing

3D-bioprinted tissue platforms simulate the complex microenvironment of diseases, such as cancer, Alzheimer's disease, and fibrotic conditions. These platforms serve as models for studying disease mechanisms and screening pharmaceuticals under physiologically relevant conditions.

Using patient-specific cell lines, these bioprinted systems also support personalized pharmacology by testing how individual patients may respond to various treatments. This approach streamlines drug development pipelines and reduces dependence on animal testing (35).

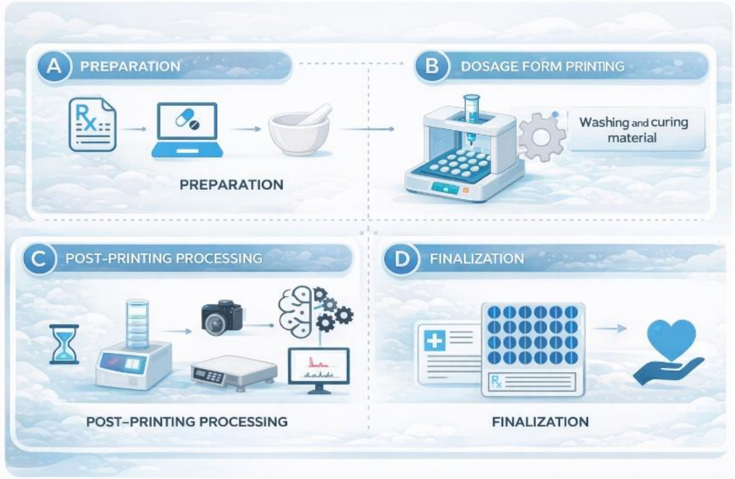


Figure 8: Personalised pharmacology process (35)

4.3 Regenerative Medicine and Scaffold Engineering

Scaffold engineering with 3D printing enables the precise spatial organization of cells and biomaterials to regenerate damaged or diseased tissues. These scaffolds are often infused with growth factors or extracellular matrix (ECM) proteins that promote cell attachment and proliferation. Applications include musculoskeletal repair, skin regeneration of burns, cardiac tissue reconstruction, and neural tissue engineering. Scaffolds can be designed to degrade in tandem with tissue regeneration, eliminating the need for secondary surgery (36,37).

4.4 Smart Therapeutics and Micro-Robotics

Cutting-edge research is combining 3D printing with sensors, actuators, and wireless communication modules to produce intelligent therapeutic devices. These include smart orthopaedic implants that monitor mechanical stress, biosensors that detect infections, and neurostimulators for managing pain or tremors. In parallel, the development of microscale robotic devices such as "micro swimmers" offers promise for precision-targeted interventions, including site-specific drug delivery, clot disruption, and minimally invasive diagnostics (38,39).

These innovations align with the broader shift toward predictive, preventative, and personalized medicine, supporting the delivery of treatments that are more responsive to patient-specific physiological data.

5. Educational and Training Implications

3D printing has emerged as a game changer in medical education. Printed anatomical models provide tactile 1:1-scale replicas for students to explore human anatomy and practice surgical techniques. These models overcome the limitations of cadaver availability, costs, and ethical concerns (7,40).

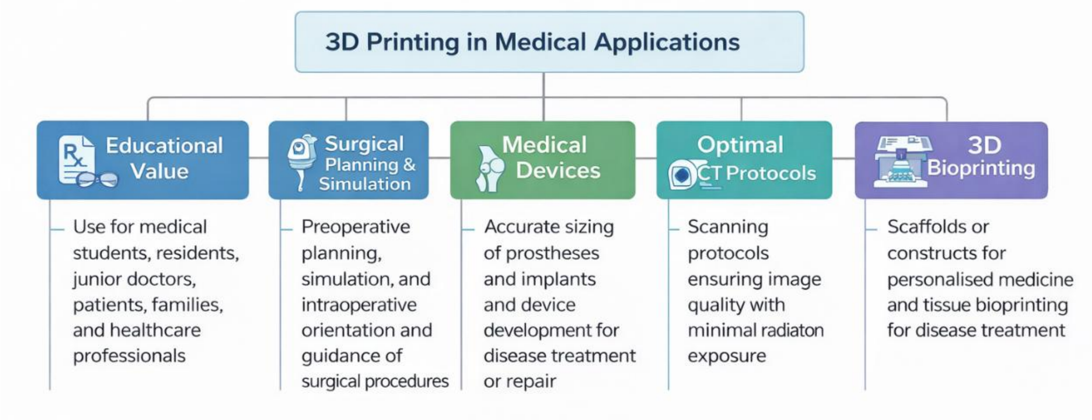


Figure 9: Educational and training implications (7)

Simulated pathological models allow trainees to rehearse procedures under rare or complex conditions. Institutions integrate 3D printing into simulation laboratories and curricula, offering learners a low-risk environment to build technical and decision-making skills. In addition, printed tools support interprofessional training and foster collaborative practice in real-world scenarios (7).

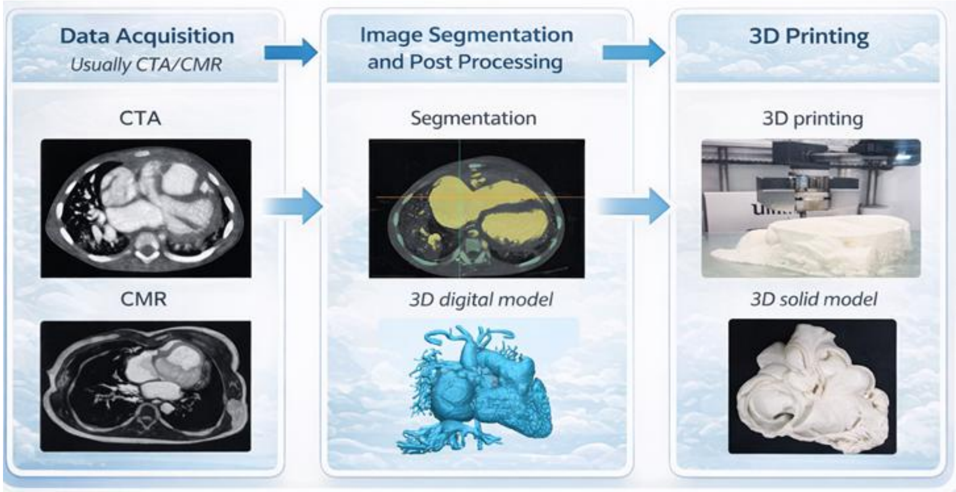


Figure 10: Educational and training implications (7)

The future of healthcare education lies in experiential, technology-enhanced learning environments; 3D printing is at the heart of this transformation.

6. Challenges, Strategic Considerations, and the Future of 3D Printing in Medicine

While 3D printing is reshaping the healthcare landscape by offering innovative solutions that enhance clinical precision, improve patient care, and reduce procedural risks (1,2,5,6,11,14–16,19,21,25), its safe and sustainable integration into routine practice requires careful attention to several critical challenges.

- Regulatory compliance remains essential, demanding rigorous quality standards and clearly defined approval pathways for 3D-printed medical products to ensure patient safety (1,6,7,11,15,41).
- Ethical considerations must also be addressed, particularly regarding transparency in patient-specific applications and robust data security protocols (42,43).
- From an environmental perspective, sustainability requires evaluation of material consumption, energy use, and waste production to minimise ecological impact (44).
- Economic accessibility continues to present a barrier, as high-precision printing systems and certified biocompatible materials can limit widespread implementation (17,45). In addition, scalability of production will be crucial to meet increasing clinical demand and enable broader adoption across healthcare systems.

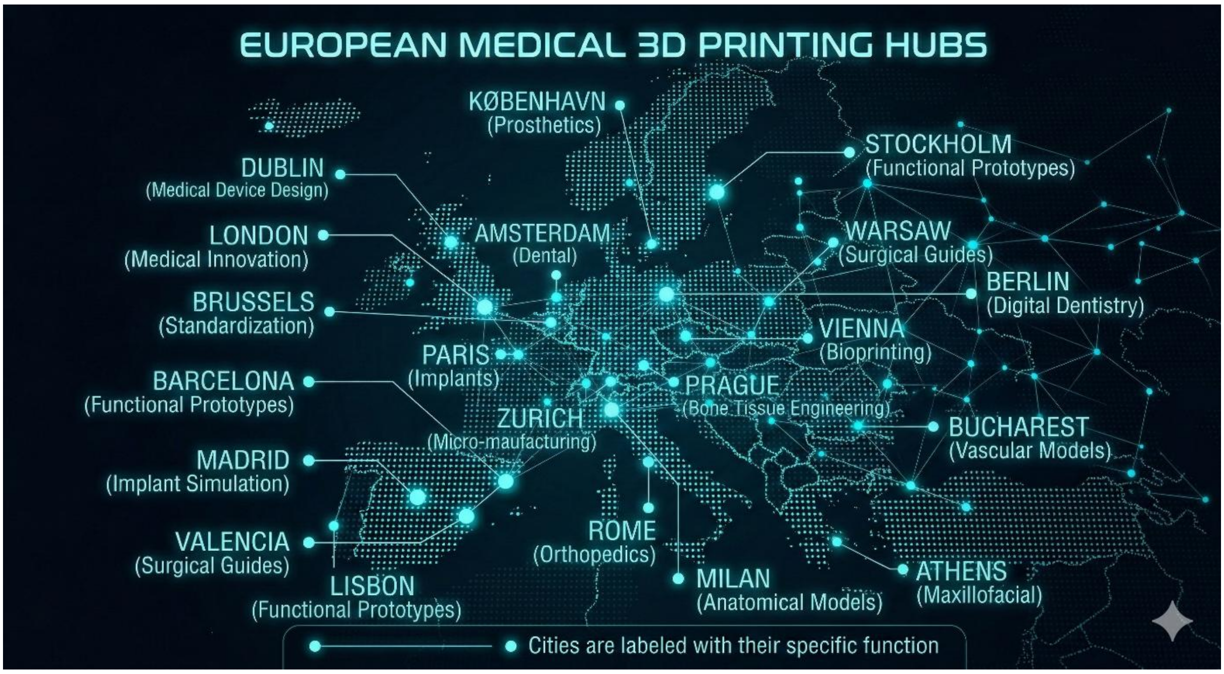
To fully capitalise on the transformative potential of 3D printing, healthcare professionals should:

- Develop in-depth expertise in its clinical applications.
- Engage in cross-disciplinary collaboration with engineers, material scientists, and regulatory specialists to drive responsible innovation.
- Support rigorous research initiatives that strengthen the scientific evidence base , and foster education and awareness through structured training programs for current and future professionals.

As the field continues to evolve, addressing these regulatory, ethical, economic, and sustainability considerations will be fundamental to ensuring that 3D printing fulfils its promise of delivering personalised treatments, improved clinical outcomes, and truly patient-centred care.

Figure 11: Assistive devices made in SOUL Fab Lab, FSJD, Madrid.

7. Mapping of the European Health Innovation Hubs



The landscape of healthcare innovation in Europe is undergoing structural transformation, driven by the convergence of additive manufacturing, digital twin technologies, and robotic assistive systems. This transition from standardised, mass-produced medical devices toward patient-specific interventions is catalysed by a distributed network of excellence centres that bridge the gap between academic engineering and clinical practice. Within the European Union, the regulatory framework—most notably the Medical Device Regulation (MDR 2017/745)—has redefined the parameters for " point-of-care " (POC) manufacturing, enabling hospitals to transition from mere consumers of technology to active designers and manufacturers of customised clinical solutions.

7.1 The Strategic Architecture of 3D Biomodeling and Medical Bioprinting

The development of 3D biomodels serves as a primary gateway for hospital-based technological integration. By converting complex radiological data into physical or high-fidelity virtual representations, clinical teams can significantly improve preoperative planning, intraoperative accuracy, and patient communication.

7.1.1 The Catalan Ecosystem: Barcelona as a Global Leader in Pediatric 3D Innovation

Barcelona has established itself as a premier global hub for paediatric 3D applications, primarily through the leadership of the SJD Barcelona Children's Hospital and the Vall d'Hebron University Hospital. The 3D Unit at SJD Barcelona, known as 3DForHealth (3D4H), exemplifies the multidisciplinary nature of modern medical engineering. Established formally in 2016 but operational since 2013, the unit integrates radiologists, surgeons, and innovation engineers to support over 500 projects annually.

Image: Anatomical education (40)

A critical component of the SJD model is the integration of the 3D unit directly within the hospital's clinical workflow. This " point-of-care " approach allows for real-time collaboration between the surgical team and engineering staff. For instance, in complex oncological cases, such as neuroblastomas, surgeons utilise life-size 3D-printed models of tumours and surrounding vascular structures to practice the resection process and identify potential complications before the patient enters the operating room. This practice has been credited with reducing surgical duration by more than 50% in specific complex procedures, thereby decreasing the duration of anaesthesia and the risk of postoperative infection.

Regulatory compliance of the Barcelona hub is a significant indicator of its maturity. SJD was among the first centres in Europe to obtain the EU MDR license5 licence to produce custom-made medical devices, a process governed by the ISO 13485:2016 quality management system. This certification ensures that the 3D-printed guides and implants meet the same safety standards as those produced by large-scale industrial manufacturers.

The I3PT Parc Taulí 3D Lab in Sabadell is another pillar of the Catalan ecosystem. Initially focused on orthopaedic trauma, the lab has expanded into a multidisciplinary facility that serves as a meeting point between medicine and engineering. The lab collaborates with external SMEs, such as Tailor Surgery, to provide patient-specific implants and surgical guides, effectively bridging the gap between hospital research and industrial production.

Center	*Focus Area*	*Technology Implementation*	*Regulatory Standing*
SJD Barcelona Children's Hospital	Pediatrics, Oncology, Orthopedics	FDM, SLA, MJ, Virtual Reality	EU MDR 2017/745, ISO 13485
Vall d'Hebron University Hospital	Multi-specialty, Trauma	Mixed (In-house and Outsourced)	Hospital QMS Art. 5(5) Compliant
I3PT Parc Taulí 3D Lab	Orthopedic Trauma, Maxillofacial	FDM, SLA, MJ, Metal Printing	Manufacturer License EU MDR

7.1.2 The Madrid Healthcare Corridor: Advanced Research and Public Hospital Units

The Madrid ecosystem is characterised by a high density of public hospital-based 3D units that are deeply integrated into the national research network. The UPAM3D unit at the Hospital General Universitario Gregorio Marañón and the 3D Management Laboratory at the Hospital Universitario La Paz represent the leading edge of this development.

The Gregorio Marañón unit, established in 2015, functions as a hospital hub for a wide range of specialties, with a heavy emphasis on orthopaedic trauma. It utilises a diverse array of technologies, including fused deposition modelling (FDM), stereolithography (SLA), and powder bed fusion (PBF), as well as metal printing capabilities, to create permanent titanium implants. This facility has been pivotal in establishing the cost-effectiveness of hospital-based 3D printing, demonstrating that reductions in surgical time and improved patient outcomes can offset the initial capital investment in printing hardware and personnel.

The Hospital Universitario La Paz, through its IdiPAZ research institute, operates a 3D Management Laboratory founded in 2021. Its focus includes the creation of custom orthoses for paediatric patients with mobility issues and the development of prototypes for new medical devices. These units are also members of the Carlos III Health Institute (ISCIII) Biobanks and Biomodels Platform, a nationwide network that facilitates the exchange of biomodels and bioprinting services across 15 units throughout Spain.

7.3 Precision Surgery and the Development of Surgical Guides

Surgical guides represent one of the most practical and immediate applications of 3D technology in operating theatres. These patient-specific templates allow surgeons to translate preoperative plans with submillimetre precision, particularly in complex trauma and reconstructive cases.

7.3.1 The Trauma3D Project: Seville and Cádiz Inter-hospital Collaboration

The southern region of Spain, specifically the axis between Seville and Cádiz, has developed a specialised model for orthopaedic trauma through the "Hospital 3D" project. This initiative is a collaborative effort between the University of Cádiz (UCA), the Hospital Universitario Puerta del Mar in Cádiz, and the Hospital Universitario Virgen del Rocío in Seville.

The Hospital Puerta del Mar in Cádiz has established a dedicated 3D laboratory that produces replicas of organs and bone fractures. This allows for a "dry run" of the surgery, enabling the clinical team to select and pre-contour osteosynthesis plates before the patient enters the operating room. The inter-hospital nature of this collaboration ensures that specialised engineering resources at the university level are directly accessible to clinicians in different public hospitals, creating a shared knowledge base and optimising resource utilisation.

7.3.2 IRCAD and the Integration of AI and Augmented Reality

In France, the Research Institute against Digestive Cancer (IRCAD) redefined the role of 3D modelling through its Surgical Data Science (SDS) department. Under the leadership of Dr. Alexandre Hostettler, the SDS team is developing AI-based software systems that provide "transparent" visualisation of the patient's anatomy during surgery.

IRCAD's research centres on the superimposition of 3D medical images (computed tomography or MRI) onto live laparoscopic video feeds, a technique known as augmented reality (AR) surgery. This allows surgeons to see internal structures, such as deep-seated tumours or hidden blood vessels, in real-time. To support this research, IRCAD has developed "Sight" (surgical image guidance and healthcare toolkit), an open-source C++ framework designed to facilitate the creation of medical imaging software.

Software Component	***Functionality***	***Primary Application***
Sight Framework	Modular medical imaging toolkit	Navigation systems, planning software
SightViewer	2D/3D medical image viewer	Diagnostic review of DICOM/VTK data
SightCalibrator	Camera calibration tool	AR synchronization for mono/stereo cameras

7.5 Dental and Maxillofacial Applications: UMCG and 2INGIS

The field of dental implantology has rapidly adopted 3D-printed surgical guides. At the University Medical Centre Groningen (UMCG) in the Netherlands, research has focused on comparing digital and conventional fabrication methods for surgical guides. Their findings indicate that digital methods significantly improve the effectiveness of surgical guide placement, particularly for less experienced practitioners.

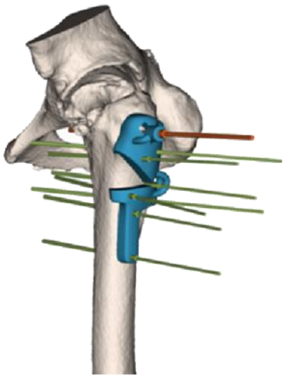


Image: 3D printed cut guides (orthopaediatrics)

7.6 Rehabilitation Robotics: The University-Engineering Interface

The development of robotic exoskeletons and neurorehabilitation systems represents one of the most complex areas of medical innovation, requiring the seamless integration of mechanical engineering, sensor technology, and neuroscience.

7.6 .1 The Alicante Hub: UMH and the University of Alicante

The province of Alicante in Spain has emerged as a major centre for rehabilitation robotics, characterized by a strong "University-Engineering Interface." Researchers at the Miguel Hernández University (UMH) in Elche and the University of Alicante (AU) are at the forefront of this research.

The Brain-Machine Interface Systems Lab at UMH, led by specialised researchers such as Dr. Marisol Rodríguez-Ugarte, focuses on the control of lower-limb exoskeletons using motor imagery (MI) and electroencephalography (EEG) signals. Their research explores the use of deep learning algorithms to decode a user's intention to start walking or change speed, thereby enabling more natural and intuitive control of robotic assistants.

Research Topic	*Institution*	*Key Finding/Focus*
Brain-Machine Interfaces (BMI)	UMH Elche	Deep learning for exoskeleton gait control
Transcranial Stimulation (tDCS)	UMH Elche	Boosting accuracy of intention detection
Myoelectric Control	Univ. of Alicante	Low-cost non-intrusive gesture recognition
Neurorehabilitation Centers	NeuroVital (Alicante)	Clinical implementation of robotic gait training

At the University of Alicante, the Robotics and Vision group (founded in 1996) focuses on neurorobotics and myoelectric control. This includes the development of sensor systems that use electromyographic (EMG) signals to control prosthetic hands or robotic arms. These academic efforts are translated into clinical reality at facilities like NeuroVital, a technological centre located in the UMH Science Park that is equipped with robotic exoskeletons and virtual reality environments for the rehabilitation of patients with neurological damage.

Image: 3D printed had (youbionic)

7.6.2 Exoskeletons for Pediatric and SCI Rehabilitation: Marsi Bionics and ABLE

The commercial and clinical applications of exoskeletons in Spain are further bolstered by companies such as Marsi Bionics and ABLE Human Motion. Marsi Bionics, a Madrid-based SME, has developed the "EXPLORER," the world's first pediatric exoskeleton designed for children with spinal muscular atrophy and cerebral palsy. The device is unique in its ability to adapt to children as young as two years old, providing them with the opportunity for upright mobility during their critical developmental years.

7.6.3 Aalborg University: Interdisciplinary Rehabilitation Robotics

In Denmark, Aalborg University operates the Center for Rehabilitation Robotics, an interdisciplinary facility that brings together researchers from health science, material production, and electronic systems. The centre's work is characterised by the involvement of end-users in the design process, ensuring that robotic solutions are practical for both clinical therapy and domestic use.

One of their flagship projects is the development of a lightweight intelligent tendon-based arm exoskeleton. This device utilises a hybrid control system that can adapt from myoelectric signals to tongue-based control or even full brain–computer interfaces, depending on the severity of the patient's disability. The centre maintains a robust network of collaborators, including the Danish Rehabilitation Centre for Neuromuscular Diseases and industrial partners, such as Life Science Robotics and Assistive Innovations.

7.7 Orthoprosthetics: Industrial Scale and Local Manufacturing Hubs

The orthoprosthetic sector in Europe is a blend of large-scale industrial manufacturing and specialised local workshops that provide custom fitting and fabrication.

7.7.1 Global Industrial Leaders: Ottobock, Proteor, and Blatchford

Germany and France are home to the largest manufacturers of prosthetic and orthotic components, respectively. Ottobock (Germany) and Proteor (France) dominate the market through extensive R&D investments and global distribution networks.

Proteor, for instance, maintains a central manufacturing facility in Burgundy, France, capable of producing 22,000 custom-made items per year. Their R&D unit, staffed by over 20 engineers and physicians, collaborates with 24 university hospitals to test and refine new designs. This scale is essential for the production of components, such as microprocessor-controlled knees and high-performance carbon-fiber feet.

Manufacturer	*Headquarters*	*Key Technologies*	*Manufacturing Capabilities*
Ottobock	Germany	Microprocessor knees, myoelectric hands	Global distribution, digital workflows
Proteor	France	Custom spinal orthoses, CAD-CAM	22k items/year, 24 university partnerships
Blatchford	Germany/UK	Biomimetic ankles, high-end prosthetics	Central manufacturing in Raunheim/Basingstoke
Ortho Europe	UK	Bespoke devices, modular components	Seven production facilities across EU

Blatchford, with a European head office in Raunheim, Germany, focuses on biomimetic design, aiming to replicate the natural movement of the human ankle and foot. These large firms are increasingly adopting digital workflows and using 3D scanning and CAD software to design sockets and orthoses that are then fabricated using CNC milling or 3D printing.

Image: 3d-printed-orthothics (Formlabs)

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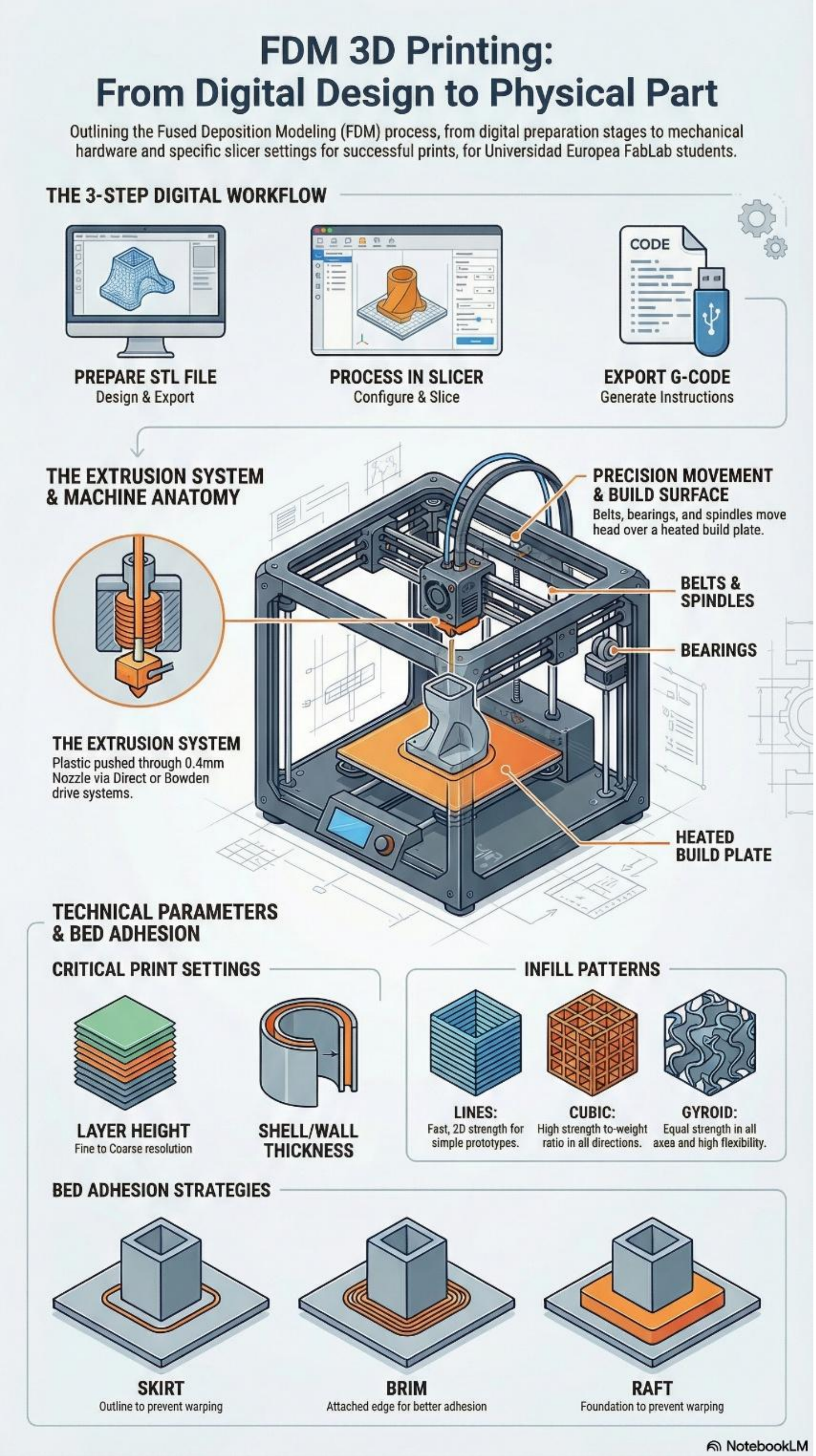
Annex I: 3D Printing principles.



FDM 3D Printing: From Digital Design to Physical Part

Outlining the Fused Deposition Modeling (FDM) process, from digital preparation stages to mechanical hardware and specific slicer settings for successful prints, for Universidad Europea FabLab students.

THE 3-STEP DIGITAL WORKFLOW

PREPARE STL FILE
Design & Export

PROCESS IN SLICER
Configure & Slice

EXPORT G-CODE
Generate Instructions

THE EXTRUSION SYSTEM & MACHINE ANATOMY

PRECISION MOVEMENT & BUILD SURFACE
Belts, bearings, and spindles move head over a heated build plate.

BELTS & SPINDLES

BEARINGS

THE EXTRUSION SYSTEM
Plastic pushed through 0.4mm Nozzle via Direct or Bowden drive systems.

HEATED BUILD PLATE

TECHNICAL PARAMETERS & BED ADHESION

CRITICAL PRINT SETTINGS

LAYER HEIGHT
Fine to Coarse resolution

SHELL/WALL THICKNESS

INFILL PATTERNS

LINES:
Fast, 2D strength for simple prototypes.

CUBIC:
High strength to-weight ratio in all directions.

GYROID:
Equal strength in all axea and high flexibility.

BED ADHESION STRATEGIES

SKIRT
Outline to prevent warping

BRIM
Attached edge for better adhesion

RAFT
Foundation to prevent warping

Annex II. Comparative Overview of 3D Printing Technologies in Healthcare.

3D Process Type	*Working Principle*	*Healthcare Applications*	*Advantages*	*Limitations*
Powder Bed Fusion (SLS / SLM)	Thermal energy selectively fuses powdered material inside a chamber	Medical implants, fixation devices, lattice-structured models	Small-scale technology, economical, wide range of materials	Low speed, limited size, material properties depend on powder grain
Material Jetting (PolyJet / NJP)	Inkjet-like deposition of material (continuous or drop-on-demand)	Anatomical models, customized dental guides and implants	High precision, low waste, multi-material and multi-color capability	Limited to polymers and waxes, requires support material
Sheet Lamination	Bonding of layered sheets (typically metal) via ultrasonic welding	Surgical and orthopedic models	Fast, economical, easy material handling	Limited material range, requires post-processing
Directed Energy Deposition (DED, LMD, LENS)	Heat source melts material during deposition, often for repair	Limited healthcare applications; repair of specific components	Rapid layer deposition, dense parts, no supports required	Limited materials, lower surface finish quality
Vat Photopolymerization (SLA / DLP)	Liquid photopolymer resin cured by UV or laser light	Bone structures, dental models, implant guides, hearing aids	High resolution and surface finish, complex geometries	Limited durability, UV sensitivity, not suitable for intensive use
Material Extrusion (FDM / FFF)	Thermoplastic extruded through heated nozzle layer by layer	Medical devices, surgical tools, prostheses	Economical, widely accessible, good structural properties (ABS)	Lower precision, nozzle-dependent quality, low speed
Binder Jetting	Powder layers bonded by liquid binder	Educational anatomical models, colored models	Fast fabrication, wide color range	Not ideal for structural parts, extensive cleaning/post-processing required

Fundación
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