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REVIEW ARTICLE

Bone Plate Fabrication through 3D Printing: A Review of Methods and their Applications in Bone Regeneration

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ABSTRACT

There has been a lot of talk in recent times regarding the advantages of utilizing 3D printing as a novel approach to the production of implants, particularly customized ones. This technology has undergone significant advancements and enables the creation of intricate-shaped implants made of metal and polymer, which were previously challenging to produce using conventional techniques. Both metals and polymers have been utilized as biomaterials that can withstand pressure, making them suitable materials for producing such implants. This article aims to provide an overview of the 3D printing technique used to produce load-bearing implants made from metallic and polymeric materials.

Keywords: 3D Printing, Additive manufacturing, Bone Plate, Bone regeneration.

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INTRODUCTION

The inflexible bodily tissue known as bone is made up of cells that are encased in a lot of hard intercellular substances.[1] The two main components of bones are collagen and phosphate, calcium which distinguish bone from other hard tissues like enamel, shell and chitin. The composition of bone is 25% water, 40% hydroxyapatite (an inorganic component) and 35% organic material (proteins). Collagen type I accounts for 90% of the organic component, with non collagenous proteins making up the remaining 10%.[2] The periosteum is the term used to refer to the tough and thin outer membrane of bones that contain tunnels and canals where blood and lymphatic vessels pass through to provide nutrients to the bone. The periosteum also allows tendons, ligaments, and muscles to connect with it.[3]

The human skeleton comprises 206 bones, which support and shape the body while safeguarding various organs. Bones can also store minerals and produce the marrow vital for creating and preserving blood cells.[4] As living bone tissue regenerates and reforms over time, bone growth continues throughout life. Three cell types are present in bones: osteoclasts, which help shape and structure bones by breaking them down. Osteocytes are mature bone cells, and osteoblasts generate new bone and facilitate the healing of injuries.[5] The growth plates in children's and young adolescents' bones, which act as "growing zones," are smaller than those of adults. These plates are made up of lengthening, multiplying cartilage cells that later transform into hard, mineralized bone. On an X-ray, these growth plates are simple to identify. Girls' growth plates develop into hard bones earlier than boys' because they mature at an earlier age. When a bone experiences a force that exceeds its capacity, it may break or fracture. The categories of bone fractures are oblique, comminuted, stable, open, transverse, spiral, greenstick, stress, compression, impacted, segmental, and avulsion fractures. The tibia, a long bone in the lower limbs that bears most of the body's weight, is one of the routinely fractured long bones, accounting for up to 37% of lower limb fractures annually.[6] Available treatments for broken bones are external fixators, intramedullary nailing, internal fixation, and other therapies.[7] Internal fixation therapy, which has been used for over a decade, involves the use of plates and screws. These bone plates and the screws used for anchorage hold the broken bone segments together, minimizing tensile stress at the fracture site while allowing essential amounts of compressive stress at the fracture segments to optimize bone repair.[8] Simple tibia fractures as well as other lengthy fractured bones have been treated with this method.[9,10]

Bone Regeneration

The human bone has the inherent capacity to regenerate as a part of the natural healing process after an injury and during skeletal

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Table 1: Mechanical properties of Bone

Bone properties	*Trabecular*	*Cortical*
Porosity	50–90 %	1–20 %
Young's modulus	0.05–0.10 GPa	17.5–21 GPa
Compressive strength	5–10 MPa	130–225 MPa
Tensile strength	1.5–38 MPa	35–283 MPa
Elongation at break	0.5–3%	1.07–2.10 %

development or continuous remodelling in adulthood.[11,12] Bone regrowth necessitates a set of properly synchronized physiological activities called bone induction and conduction, comprising various types of cells and signaling molecules, both intracellularly and extracellularly. These processes work together to facilitate skeletal restoration and reinstate skeletal function.[12,13] For successful bone regeneration, three key components are required: an osteoinductive signal, an insoluble substrate to carry the signal and act as a scaffold for bone growth initiation, and host receiver cells that can differentiate into bone cells in response to the osteoinductive signals. However, bone regeneration can sometimes be impeded, resulting in delayed healing or failure to heal (non-union), which account for up to 13% of tibia fractures.[14] The first stage involved in successful tissue regeneration is the initial closure of the wound to promote continuous and seamless healing, followed by the recruitment of undifferentiated mesenchymal cells and angiogenesis to deliver vital blood flow, creating and maintaining space for bone ingrowth, and promoting wound stability to encourage the formation of blood clots and facilitate painless healing. The process of bone regeneration involves the formation of hematomas, fibrocartilaginous calluses, bony calluses, and bone remodeling.[15]

Current Clinical Approaches to Enhance Bone Regeneration

Treating complex clinical disorders associated with bone regeneration can be difficult and have medical and socioeconomic implications. However, several treatment

Figure 1: 3D Printed Metal Implants

Table 2: Comparison of Non Degradable and Degradable bone plate.

Non-Degradable Bone Plate	*Degradable Bone Plate*
Permanent implant	Not a permanent implant
Higher strength	Lower strength
Not suitable for children	Suitable for children
Suitable for elders	Not highly suitable for the elder, it gives holes in the bone
Mainly it is used in high-stress/load region eg, Femur bone	Mainly it is used in low-stress/ load region eg, finger bone
Re-surgery is needed for removal	Re-surgery is not needed for removing the implant
Sometimes gives a stress-shielding effect	Sometimes injuries due to degradation before healing.
Corrosive nature	Non-corrosive comparatively

options are currently available to surgeons, which can be used in isolation or combination to manage or heal these conditions. These treatment options include various bone augmentation techniques, such as allografts, autologous bone grafts, growth factors, and bone-graft replacements, which are commonly utilized in medical practice to enhance or promote bone regeneration.[16-19] Moreover, non-invasive biophysical therapies like low-frequency ultrasound and electromagnetic field stimulation are also employed as adjunct methods to promote bone regeneration.[20-22]

Bone Plate for Bone Regeneration

Bone plate AM is a popular form of the biomedical implant due to its design and eco-friendly manufacturing process. 3D printing or additive manufacturing is used to build these implants layer by layer using CAD models. Biomedical implants can be made from various materials like titanium, magnesium, stainless steel, polymers, and cobalt. The conventional manufacturing process for complicated implants is challenging, but additive manufacturing simplifies the process and produces implants with improved microstructure, mechanical properties, and design. Understanding additive manufacturing technology and materials is crucial for producing high-quality biomedical components.

Fabrication Methods of Bone Plate in AM

- *Selective laser melting (SLM)*

Additive manufacturing uses powder bed fusion, such as selective laser melting (SLM), to completely melt powders.[23,24] This method creates dense, strong metallic implants, such as Ti alloys, commercially pure Ti, stainless steel and cobalt–chromium.[25,26] The bone plate fabricated by this method has a bright metallic shine and meets the mechanical criteria of traditional titanium alloys with a maximum tensile strength of 1000–1100 MPa, elongation of 8–10%, as well as yield strength of 900 to 950 MPa. A personalized bone plate can

Table 3: Comparison between the different additive manufacturing methods.

Method	Material	Advantages	Disadvantages
SLA	Resin	•Liquid building materials with high resolution and accuracy. The complicated scaffold is also removed easily from the building platform.	•Limited selection of materials; possible need for UV postprocessing (e.g., for bioceramics) •High cost of materials •Sophisticated and Costly equipment
FDM	Filament	• No items were wasted •Low price	•During the procedure, materials may undergo heat degradation. •Unwanted porosity •Powder that is stuck and difficult to remove
Selective laser sintering	Polymers	•Good dimensional accuracy •Capability to process on various types of materials •Doing design changes is easy •Good less anisotropy and mechanical properties	•High dimensional precision • Materials that can be flexible • Easy modification as well as design changes • Removing all post-curing • Less anisotropy and the best mechanical qualities
Selective laser melting	Metal	•No melt phases and distinct binder •Producing high-dense parts •Eliminating some post-treatments	•There is no separate binder or melt phase •Directly producing completely dense pieces •Removal of a few post-treatments
Direct metal laser sintering	Metal	•High speed •Complex geometries •High resolution • Favorable mechanical characteristics under static conditions. •Medium surface roughness with better biological performance	•Faster pressing •Difficult geometries •High resolution • Strong static mechanical characteristics •Good biological performance with medium surface roughness

be created with an orthopedic surgeon's help. Its lightweight, porous structure allows for bone ingrowth and integration, making the implant more stable and reducing the risk of rejection. SLS is a precise and flexible method for creating customized bone implants that match the patient's anatomy, which can result in better outcomes and faster recovery times. The bone plate's orientation is critical and must be positioned with spatial orientation and minimal surface roughness for optimal performance.[27]

- *Fused deposition modeling (FDM)*

Fused deposition modeling (FDM) is an additive manufacturing technique that employs filament extrusion to produce objects from CAD models.[28] It's known for its cost effectiveness, lack of solvents, ability to make complex structures, and small size.[29,30] FDM converts a virtual model into G-code and builds the object layer by layer using molten filament. The quality of the implant depends on various factors, including layer thickness, build orientation, and nozzle diameter.[31,32] Biodegradable composites such as polylactic acid/hydroxyapatite can be optimized for 3D printing parameters to produce an implant with optimum bending strength and low porosity. Factors such as cross-sectional dimension, printing pressure, and heating can affect specimen porosity and bonding. Research has shown that the optimised bone plate has improved mechanical characteristics and roughness affects bending strength.[33]

FDM is a relatively straightforward and economical 3D printing process that can produce robust, long-lasting bone implants with excellent mechanical properties. However, the printed implants may have a smooth surface and lack the desired level of porosity needed for optimal bone ingrowth and integration. To address this limitation, postprocessing techniques, such as surface texturing or coating with a biocompatible material, can be used to enhance the implant's biocompatibility and osseointegration.

- *Selective laser sintering (SLS)*

Selective laser sintering (SLS) uses a laser to combine powder particles into objects layer by layer based on a predefined design. The powder is distributed by a sled, preheated, and then scanned by a blue diode laser. The process works best with amorphous polymers like semi-crystalline polymers and polycarbonate powders like nylons. The implants are detached from the build platform, and any surplus powder is brushed away. SLS can process high-performance thermoplastic materials like PEEK, but has limitations such as surface porosity and long production times due to heating and cooling requirements.[34]

CAD software is used to create templates that are stored as STL files and sent to the printer. A sled distributes the powder to create a flat, preheated layer before the blue diode laser scans and sinters the powder components to build up the object layer by layer.[35] Using amorphous or semi-crystalline polymers, SLS can produce high-quality implants with excellent dimensional precision, surface quality, and mechanical qualities.[36] SLS can also process high-performance thermoplastic materials

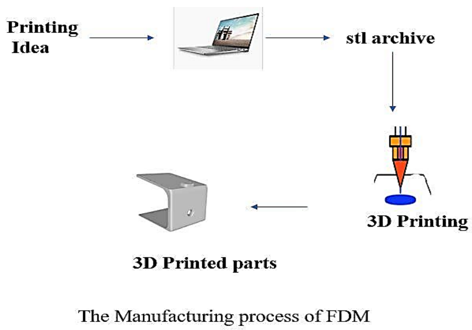

Figure 2: 3D Printing process

like PEEK, but there are challenges in controlling the high temperature and waste.[37,38] Despite experimental examination of various polymers, only polystyrene (PS), PEEK polyamide (PA12 and PA11), polycarbonate (PC), and their variations are used in practical applications.[39] However, the production time is prolonged due to the necessary heating and cooling time, and there are limitations in surface porosity.[40,41]

In several studies, researchers have investigated the usage of selective laser sintering (SLS) technology to produce customized bone plates for medical applications. They found that SLS-produced bone plates have excellent biocompatibility and mechanical properties, and can be customized to match individual patients' anatomies. Additionally, SLS-produced porous bone plates have been found to exhibit excellent mechanical properties under physiologically relevant loads. Compared to traditional bone plates, 3D-printed bone plates using SLS technology have been found to have superior mechanical properties, suggesting they may provide a new option for mandibular reconstruction surgery.

- *Direct metal laser sintering (DMLS)*

DMLS is an additive manufacturing technology developed by EOS GmbH in Munich, Germany,[42] that builds 3D components layer by layer using fused metal powder. It is derived from the SLS approach but uses high laser power and uncoated pre-alloyed metal particles for sintering. In contrast, SLS uses coated metal powders or polymers as the sintering medium.[43,44] Table 1 provides a list of advantages and disadvantages for SLS, SLM, and DMLS.

DMLS can use various powder-form metallic materials, including stainless steel, Co-Cr, Ti, Al alloys, nickel (Ni) alloys, and Ti alloys.[45] The technique involves melting the powder partially using a CO_2 or Ytterbium fiber laser in a temperature-controlled chamber, as part of the liquid-phase sintering process.[46] When the laser is directed at the powder, its energy is absorbed by the surface of the powder, which causes the underlying solidified powder to meld together and create a 3D object. The process, called sintering, is capable of producing highly accurate and detailed objects. DMLS can create metal implants with a porous structure that closely mimics the structure of natural bone, with similar mechanical properties and interconnected pore network. The size, shape, and distribution of these pores can be adjusted as per the design requirement, providing a high level of flexibility in the implant's customization.[47]

DMLS, which is similar to SLM and SLS, is an effective technique for creating complex and functional metal objects with intricate geometries. It is considered the most cost-effective L-PBF technology for producing a wide range of metal parts with fast production speed.[48,49] The texture, mechanical characteristics, and dimensional precision of the finished products are influenced by the type of material, laser process parameters, and powder characteristics, which also affect the manufacturing time.[50] Sanjairaj Vijayavenkataraman designed a new bone plate made of stainless steel AISI 316L by incorporating auxetic structures suggested in the study to address two issues. The auxetic structure would provide a flexible portion for intraoperative bending and adequate bending strength and stiffness, which would reduce stiffness and stress-shielding effect. The bone plate was tested using direct metal laser sintering, and the findings indicated that the re-entrant honeycomb structure-integrated bone plate was an effective bone design in terms of stress shielding and intra-operative bending, while providing mechanical and bending strength comparable to that of the standard bone plate design.[51]

- *Stereolithography (SLA)*

The SLA technique is the most commonly used and has been in existence for the longest time among all 3D printing methods.. It was patented by Charles Hull in 1986 and is used in large industrial photocuring 3D printers. SLA machines use 355 nm laser beams to solidify liquid resin in a resin tank, generating a solid 3D implant layer by layer.[52] The resin used in SLA is formulated based on either cationic

Table 4: Parameters considered for different AM techniques

Technique	*Material*	*Price*	*Accuracy*	*Use of Energy*	*Several Materials*	*Temp*
SLS	Metal	Excellent	High	Excellent	Poor	Excellent
EBM	Metal	Excellent	High	Excellent	Poor	High
SLS	Polymer, ceramics and metal	Excellent	Limited	Excellent	Poor	Low
FDM	Polymer	Excellent	Good	Low	Poor	low
SLA	Resin	Excellent	Excellent	Very low	Good	Very low

or hybrid photopolymerization. The laser beams used in SLA allow radical and cationic photopolymerization, but volume shrinkage is a challenge that reduces printing model precision.[53] However, cationic photopolymerization is known to have minimal volume shrinkage. SLA has a stable, mature printing process and can manufacture large models with high printing resolution, which is directly influenced by the laser beam size.[54] Olivier Guillaume proposes an implant that is customized to fit a patient's needs and made using stereolithography (SLA). This implant offers greater control over its shape and design and can be used instead of titanium mesh implants for restoring the orbital floor.[55]

Materials for 3D Printing

Ceramics

Porous ceramics created through 3D printing can produce lightweight, versatile, and customized materials to fit the patient's needs. In comparison to conventionally produced implants, 3D-printed porous ceramic scaffolds perform better. Biodegrading ceramics, such as calcium phosphates (CaPs) and calcium silicates, as well as non-biodegradable ceramics, such as zirconia and alumina are used in 3D printing procedures.[56-58] Depending on the application area, these ceramics can be functionalized with growth factors,drugs, and dopants or structurally altered to serve a specific function. CaPs are commonly used in bone regeneration and can achieve high structural resolution when made using powder bed 3D printing processes. Their high hardness and outstanding mechanical strength make alumina and zirconia ideal for bone regeneration. Liu W. studied alumina pieces made using stereolithography with in-situ precipitation of liquid-phase zirconium.[59]

Polymer

In contrast to metals, the selection of materials suitable for Additive Manufacturing of high-strength implants is restricted when it comes to using polymers. polycaprolactone (PCL), polyvinyl alcohol (PVA), polyetheretherketone (PEEK), Polypropylene (PP), ultra-high molecular weight polyethylene (UHMWPE), poly lactic acid (PLA), polymethyl methacrylate (PMMA), and polyamide (PA) are the polymers most frequently used in AM for load-bearing applications. The particle size, molecular structure and crystallinity are the most critical factors that directly affect the final product (implants) produced by AM.[60] Semi-crystalline polymers like PEEK, PA, PE, and PP have a well-structured high melting points and molecular structure, making them preferable for 3D printing due to their low viscosities above their melting point.[61,62] The rapid change from solid to low viscosity liquid after absorbing heat in these polymers leads to fast consolidation and full density implants, resulting in comparable density and mechanical properties to those made using conventional methods.[63] However, the crystallization rate should be moderate to avoid component distortion.[64-66] Various methods, including SEM, density measurement, XRD analysis, thermal analysis, and hot-stage microscopy, are necessary to assess the characteristics of the laser sintering powder.

Metals and Alloys

Metallic biomaterials are frequently used in orthopedic implants because of their high strength, toughness, fatigue resistance, and ductility.[67,68] Over the past few years, the usage of metal powders in the additive manufacturing of biomaterials has witnessed significant expansion.[69] The characteristics of metal powders such as shape, chemistry, and size are crucial for a successful AM process.[70] Metal powders with lower absorption and higher heat conductivity, such as copper and aluminum, can be challenging to melt, requiring more powerful lasers with various wavelengths.[71] Selective laser melting (SLM) has easily melted Ti and Co-Cr-Mo alloys to near full density. Co-Cr alloys, stainless steels and titanium-based alloys are the widely employed metallic biomaterials for weight-bearing applications.[72] Ti is a popular implant material owing to its strength, corrosion resistance, and biocompatibility. Different AM processes can significantly alter metal parts' mechanical properties from similar alloys. Co-Cr-Mo alloys are more fatigue resistant and less immunologically reactive than Ti alloys and 316L stainless steels.[73] SLM has been used to produce various Ti alloys, composites, and other metals for load-bearing biomaterials, including NiTi shape memory alloys, magnesium alloys, zinc alloys, Ta, and high-entropy alloys of TiNbTaZrHf.[74-78]

CONCLUSION

The capacity to create freely, customize components, and print complicated parts on demand are all features offered to the end user via 3D printing. Here is a discussion of the key methodologies, materials, and 3D printing processes used in bone regeneration. There is also a discussion of some of the difficulties associated with certain 3D printing procedures. The development of biological materials with personalized architectures and patient uniqueness has been aided by 3D printing. It is essential for load-bearing implants produced using these methods to imitate the structural properties of bone and enhance osseointegration to achieve rapid and enduring implant anchorage, which is critical for their efficacy. Three-dimensional printing has several technological limitations. The complexity of composite material manufacturing limits the range of metallic and polymeric materials that can be processed using this technology. Furthermore, the manufacturing process is currently not straightforward. However, with advancements in 3D printing technology, future improvements are anticipated to overcome current challenges such as production costs, size constraints, and product quality consistency and enhance the final product's physical characteristics and surface appearance.

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