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Review

Historical development and emerging trends of biomaterials and structural design in total hip arthroplasty

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Abstract: Total hip arthroplasty (THA) has evolved tremendously over the last century due to technological innovations in materials engineering and femoral stem design. This paper explores the evolution of biomaterials from ivory and stainless steel used in the past to current biomaterials, such as titanium alloys, ceramics, polymers, and composites, in terms of mechanics and biocompatibility. This review gives particular attention to femoral stem materials and structural designs, highlighting fixation methods and emerging hybrid composites. The manufacturing of porous materials has been widely studied, but traditional processes can only provide limited control over internal architecture. This review sets out to understand the advances in additive manufacturing of various types of biomaterials and how they can be integrated with artificial intelligence (AI). Limitations such as wear, stress shielding, and immune responses are critically investigated. Additionally, this article provides a focused perspective through synthesizing past developments and current innovations on how advanced biomaterials and structural designs are shaping the future of THA.

Keywords: total hip arthroplasty; biomaterials; structural design; femoral stem; traditional stem design; non-traditional stem design

1. Introduction

Total hip joint replacement (THA) or total hip arthroplasty is one of the most revolutionary procedures to replace the injured or diseased hip joint with an artificial joint. It is performed mainly to relieve pain, restore function, and improve the quality of life of people with advanced disease of the hip joint, most commonly osteoarthritis (OA) [1,2]. The hip joint is a ball-and-socket joint with two main parts: the femoral head (femur) and the acetabulum. Friction is reduced, and shock is absorbed when moving, due to the articular cartilage that covers these parts. Muscles and ligaments surrounding them provide stability and permit a great deal of motion, which is required for daily activities such as walking and climbing stairs. Therefore, the current study critically reviews all aspects of THA through materials, structure design, and emerging technologies.

The historical development of hip arthroplasty reflects the progressive refinement of both biomaterials and implant concepts. Early efforts included the use of artificial ivory joints by Themistocles Glück in 1891; yet, due to the mechanical unreliability of such materials, they could not be used in the long run. Mold arthroplasty was invented by Marius Smith-Petersen in 1925 when a glass hollow mold was put around the head of the femur, creating a new articular surface [3]. While this procedure was a crucial step in hip replacement surgery, it should not be taken as equivalent to total hip arthroplasty because it did not include the replacement of both components of the hip joint. The first total hip arthroplasty done with stainless steel components was reported by Philip Wiles in 1938, and this marked a crucial step in the direction of hip joint replacement [4]. In 1940, Moore and Bohlman inserted a fabricated prosthesis using the metal Vitallium to replace the proximal portion of the femur following the resection of a giant cell tumor. This metallic prosthesis was a breakthrough in hip hemiarthroplasty but did not constitute a total hip arthroplasty, as it replaced only the femur and not the acetabulum. The fenestrated-stem design that Moore and Bohlman designed in 1952 aimed to facilitate bone growth. This particular design was then extensively produced in the form of the Austin Moore prosthesis to treat femoral neck fractures [5]. At the same time, Per-Ingvar Brånemark noticed direct bonding of titanium to live bone during his experiments in 1952; this process was later referred to as osseointegration. The first well-known application of Brånemark's titanium implants to human patients appeared in 1965. This discovery later became a basis for the biocompatibility of titanium and porous materials in cementless orthopedic implants [6].

In addition to material properties development, there have been improvements in the design of femoral stems; these include short stems, neck-saving stems, porous surfaces, lattice structures, functionally graded structures, and auxetics. The objective of these methods is to increase load transmission, minimize stress shielding, increase osseointegration, and maintain proper mechanical strength and fatigue resistance. The advent of additive manufacturing techniques has increased design possibilities for orthopedic implants by creating a variety of porous structures and lattice structures that have been customized with respect to pore size, porosity, unit cell structure, and gradients. Finite element analysis can assist in the examination and optimization of implant stresses, micromotion, structural performance, and bone remodeling response [7].

Two review papers have been published recently that considered the significance of materials in THA. Morano et al. reviewed the major groups of materials that have been employed in hip prostheses and provided an assessment of the mechanical, biological, chemical, and clinical properties of each class of these materials, while Garofalo et al. focused on the selection criteria of suitable materials for THA components [8]. However, the selection of the material is just one part of the process in making

a successful hip implant. The performance of a THA implant is also dependent on the effects of structural design, production method, surface properties, and patient-specific loading conditions. Therefore, a review is required that can incorporate all these aspects into a single approach to develop next-generation THA implants. While other review articles have covered each of these topics independently—THA biomaterials, femoral stem design, porous implants, additive manufacturing, and artificial intelligence (AI)—a systematic review that combines all of these related elements is still lacking. As such, the aim of this review article is to critically assess the history and future trends of biomaterials and femoral stem design for THA. The literature review includes both traditional and novel materials and structures, with a focus being on porous, lattice, auxetic, hybrid, and biodegradable scaffolds. In particular, attention is paid to design, finite element analysis, and artificial intelligence methods for preoperative planning and femoral stem optimization. This review integrates biomaterial evolution, structural design, and digital technology to give a unified view of strategies to optimize load transfer, osseointegration, and implant survival for personalized THA.

Figure 1 depicts a flowchart that outlines a map of the review, indicating the evolution of orthopedic biomaterials, progression from traditional to sophisticated stem structures, importance of manufacturing and digital technology, and future aspects of polyether ether ketone (PEEK)-based orthopaedic implants.

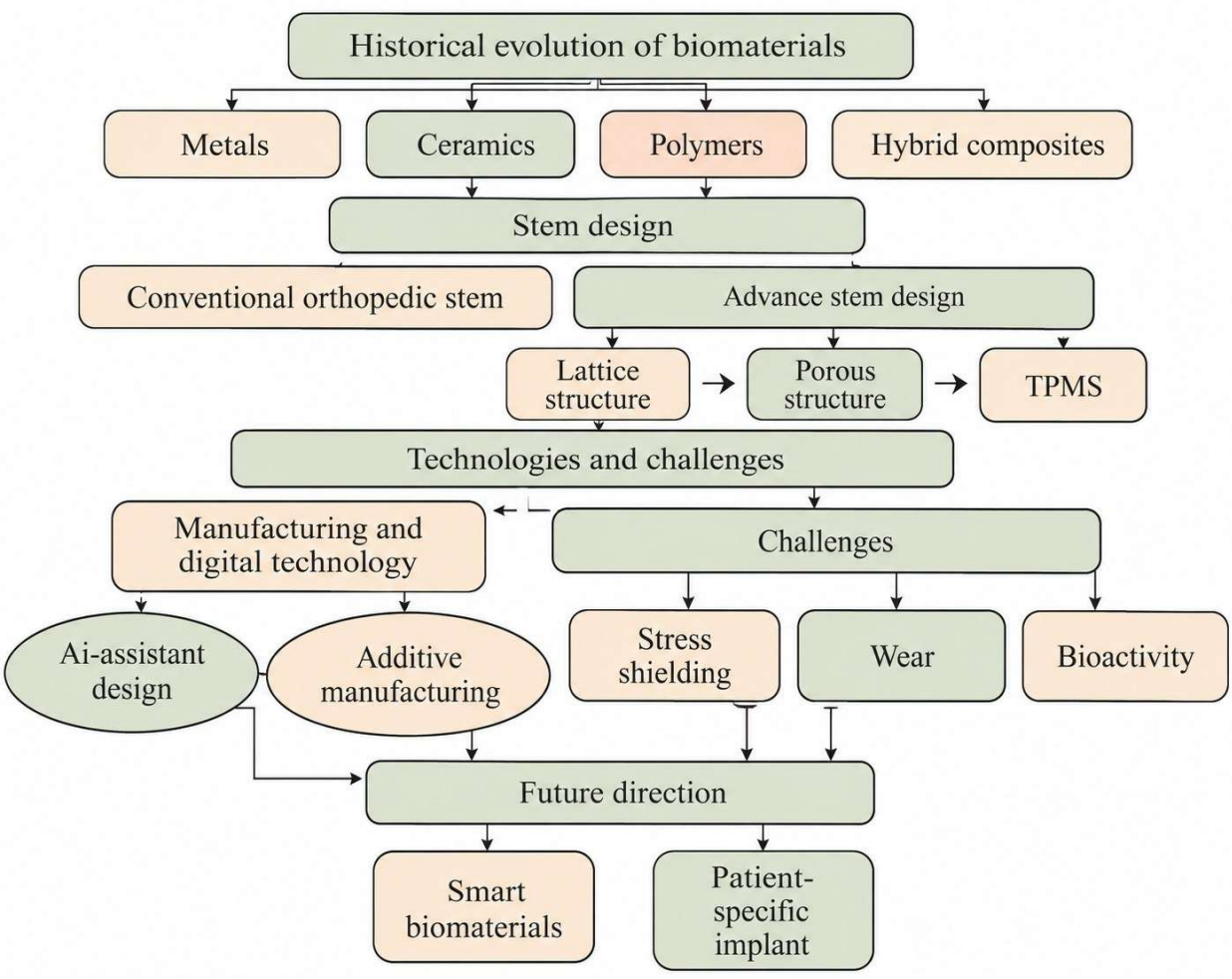


Figure 1. Review roadmap.

2. Review methodology and literature selection

2.1. Review scope and information sources

This article was conducted to examine the historical development and emerging trends of biomaterials and femoral-stem design in total hip arthroplasty (THA). The scope encompassed metallic, ceramic, polymeric, and composite materials; fixation strategies; conventional, short, porous, lattice, auxetic, and functionally graded stem designs; manufacturing methods; surface engineering; and engineering and clinical applications of artificial intelligence.

Literature searches were performed using the principal search, covering publications from 2010 to 2026. Earlier publications were considered separately when necessary to document historical developments or foundational implant concepts.

2.2. Methodological limitations

There was no formal analysis of quality and risk of bias among the included papers. This is the first drawback of the current review since the reliability of the studies was not measured with the help of any standards. Therefore, it is wrong to assume that the present synthesis presents any formal certainty of evidence and shows the superiority of any material, structure, or technology.

3. Biomaterials for total hip arthroplasty

3.1. Metals and alloys

Titanium alloys, particularly Ti-6Al-4V, are a common choice for the femoral stem because of their strength and biocompatibility [9]. However, tribocorrosion behavior is still a concern for some materials Co-Cr-Mo alloy, zirconia-toughened alumina (ZTA) ceramic, and zirconium-niobium (Zr-Nb) cermet [10]. Cobalt-chrome alloy (Co-Cr-Mo) remains a common choice for the articulating femoral head, owing to its durability against wear and ease of processing. The selection of a suitable material for stem implants, so that longevity and improved properties are achieved, is dependent on whether the implant is temporary or permanent. Temporary implants can be made with biodegradable materials, where secondary surgeries are eliminated. Permanent implants demand non-degradable materials with good mechanical and tribological stability and biocompatibility to prevent early failure and inflammation. Magnesium alloys are under consideration for long-term bioimplants due to their biodegradable properties. They can be employed for shoulder, knee, bone plate, cardiovascular stent, trauma, spinal disc, and fixation plate replacements [9,11].

The development of novel biodegradable metallic scaffolds such as those comprising iron-based metallic alloys with additions of manganese is a perfect illustration of the current trends in the field of orthopedic biomaterials. Fe-Mn alloys have excellent mechanical and biological properties; manganese doping might potentially overcome the issue of slow degradation rate and the inability to be used with magnetic resonance imaging of Fe-based metals. It is important, however, to regulate the process of degradation to prevent the local concentration of toxic manganese ions. These materials are currently better suited for bone scaffolding than for use in femoral stem prostheses [12].

3.2. Ceramics

By the 1970s, the French orthopedic surgeon Pierre Boutin introduced ceramic bearings, which offer greater hardness and scratch resistance with reduced wear debris compared to metal [13,14]. More common ceramics that are utilized in implants include hydroxyapatite (HA), β-tricalcium phosphate (β-TCP), alumina, zirconia, and ceramic composites [15–17].

Bioceramics are a class of ceramics used for the reconstruction and repair of damaged structures, increasingly used for the replacement of bone defects due to their biocompatibility and composition similarity to bone tissue [18,19]. Silicon nitride is another prospective orthopedic implant material owing to its wear resistance, mechanical properties, and biocompatibility. Its flexural strength, hardness, and fracture toughness are consequences of its chemical structure and composition [20].

However, ceramics also present certain disadvantages. Alumina, zirconia, and zirconia-toughened alumina are known for their high hardness, wear resistance, chemical stability, and compressive strength. Nevertheless, they have lower fracture toughness and more brittleness when compared to metallic alloys. It can thus be concluded that ceramics cannot be said to be stronger than metals in general; their main strengths include their tribological behavior and resistance to compressive loads, while their main weakness is their proneness to fracture under inappropriate tensile, impact, or defect-induced loading.

3.3. Polymers and composites

Polymers have also been used in biomedical applications, including hard and soft tissues, prosthetic implants, and dental applications. The man-made polymer era began in the early 1920s, when Hermann Staudinger established the premise of using macromolecules. Polymethyl methacrylate (PMMA) was established in dental procedures by 1937, later achieving importance after World War II due to its favorable biocompatibility and low rate of foreign body reaction observed in injured pilots [21]. John Charnley developed a cemented total hip prosthesis with PMMA in the 1960s, which became common in THA. Ultra-high molecular weight polyethylene (UHMWPE) was used as the bearing surface in the THA procedure, presenting better wear properties than other materials used before [22,23].

A polymer-based femoral stem prosthesis could work well since the elastic modulus of the polymer is closer to that of the bone compared to metallic materials, ensuring even stress distribution without micromotion and stress shielding. When PEEK is reinforced with fibers, it is able to emulate the biomechanical behavior of cortical bone tissue and potentially prevent bone resorption and promote osseointegration [24]. As an alternative to the permanent implant, some biodegradable polymers that have been used include polylactic-co-glycolic acid (PLGA), although this may lead to local irritation [25].

Biocomposites made of polymers have been increasing in popularity because of their cheapness, high tensile strength, and easy manufacturing, despite poor mechanical properties like wear rate, hardness, and Young's modulus [26–28]. The design of a matrix-based prosthesis composed of a biopolymer, i.e., castor oil–derived polyurethane (PU) reinforced with fiberglass, can prove beneficial in terms of osseointegration [26]. Carbon fiber–reinforced PEEK composites (CFRPC) have been utilized to enhance the proximal load transfer and minimize the stress shielding effect. Moreover, CFRPC offers high tensile strength and is light and flexible [29].

Shape-memory polymers (SMPs) are adaptive materials with the capacity to dynamically alter their dimensions, form, hardness, and stress due to stimulation from outside, including physiological

parameters such as ion concentration, pH, and body temperature. SMPs can also remember their pre-damage state and post-deformation state, presenting the ability to recover their former shape without a stimulus. Biomedical applications of SMP nanofibers (SMPNs) are increasing because of their high surface area per unit of volume, porosity, and nanoarchitecture that mimics the native extracellular matrix (ECM), as well as their low density, small diameter, and necessary orientation of fibers. SMPNs' benefits in some biomedical applications have been reported and reviewed in [30].

3.4. Hybrid materials

Hybrid composites aim to leverage the benefits of multiple materials to improve overall performance. These composites often combine a matrix material with reinforcing fibers to achieve specific mechanical and biological properties [31]. Several studies have examined the use of hybrid materials, such as Ti-6Al-4V/silk fibroin scaffolds [32], hemp/sisal-green epoxy composites [33], and polymer/TiO_2/Al_2O_3 hybrids [34]. These materials offer a balance of mechanical properties with biological compatibility, a reduction in stress shielding, and improved bone integration. Modern analytical approaches emphasize meticulous surgical techniques for both modes of fixation (a cemented femoral component with an uncemented acetabular component) as well as innovative material designs that attempt to optimize long-term outcomes by maximizing biomechanical compatibility between implants and host tissues [35]. Hybrid composite hip replacements improve biomechanical performance and patient outcomes, thus becoming increasingly popular in modern orthopedic surgery, which reduces stress shielding, increases load transfer, conserves bone stock, improves stability, and is cost-effective [36–38].

The critical analysis of the materials mentioned above has to be separated into the performance of each component and the overall implant performance. Information on the bearing surface, the fixation surface, and the load-bearing stem cannot be considered similar. Positive results on the mechanical or biological properties obtained in laboratories do not indicate that the implant will have a higher survival rate in clinics. Therefore, any comparison should contain the description of the specific application of the THA, the reference material or the implant, and the type of result. Especially in the case of polymeric and hybrid materials, one has to interpret their biomechanical advantages in terms of experimental validation and clinical follow-up data. The material selection problem is not about choosing the material with the most favorable properties, but rather selecting an appropriate combination of them.

The selection of biomaterials for total hip arthroplasty requires a balance between mechanical properties, elastic modulus, wear, corrosion resistance, biocompatibility, and osseointegrative properties, among others. Table 1 shows some commonly used biomaterials in THA.

As shown in Table 1, no single biomaterial is ideal for all THA components or patient groups. The titanium alloys and porous metal play an important role in cementless fixation and osseointegration, while cobalt-chromium alloys and ceramics have excellent tribological properties in bearing surfaces. Polyethene is still the most commonly employed lining material, whereas materials made out of PEEK and fiber composite can offer reduced stiffness mismatch. Therefore, material selection should be linked to implant location, fixation method, bearing combination, structural design, and patient-specific biomechanical requirements.

Table 1. Comparison of important biomaterials used for total hip replacement.

Main limitations	Main advantages of the biomaterials	Biomaterial typical application in THA main advantages	Elastic modulus (GPa)	Types of THA biomaterials
The elastic modulus is still greater than that of the bone, stress shielding can happen, low wear resistance compared to Co-Cr alloys	High strength-to-weight ratio, corrosion resistance, biocompatibility and osseointegration possibilities	Cementless femoral stems, acetabular shells, and porous coatings	~55–130	Titanium alloys, particularly Ti-6Al-4V
Stiffness, potential metal ion release and negative reaction of local tissues, especially metal-on-metal articulations	High hardness, strength, and wear resistance, good corrosion resistance	Femoral heads and selected bearing or stem components	~190–280	Co-Cr-Mo alloys
Brittleness, lower fracture toughness than metals, risk of fracture or squeaking, and relatively high cost	Hardness, low frictional coefficient, wear resistance, chemical stability, and less debris formation	Femoral heads and acetabular liners	~200–210	Alumina, and zirconia-toughened alumina ceramics
Debris can cause inflammation and osteolysis; oxidation and degradation can have an impact on performance	Less friction, long clinical use history, good biocompatibility, and better resistance to wear in highly cross-linked versions	Acetabular liners	~0.7–1.5	UHMWPE and highly cross-linked polyethylene
Biocompatibility surface, minimal integration, complicated production process, and lack of THA evidence	Similar elastic modulus to that of the bone, radiolucency, corrosion resistance, and minimization of stiffness mismatch	Emerging femoral stems and structural orthopedic components	Approximately 12–150, depending on reinforcement	PEEK and carbon fiber–reinforced PEEK
Increased manufacturing costs, fatigue design considerations, and lack of long-term data on some patient-specific porous geometries	Interconnected porosity, enhanced bone ingrowth, improved fixation, and potential local stiffness tailoring	Porous coatings, acetabular augments, fixation surfaces, and bone-defect reconstruction	Bulk ~186; substantially lower effective modulus in porous form	Porous titanium and tantalum
Material limitations in terms of carrying capability; potential risks of dissolution and coating delamination	Enhancement of osteoconductivity, better bone apposition, and superior implant	Bioactive coatings on metallic or polymeric implant surfaces	35 to 120	nHydroxyapatite and β-tricalcium phosphate coatings

4. Design of femoral stem implants

The structural design of femoral stem implants is critical because it is the central load-bearing part of THA. Over the decades, the design of the femoral stem has improved from simple models to advanced and hybrid structures. This section reviews the development of the structural design of the femoral stem, fixation techniques, and emerging advanced methods.

4.1. Traditional designs (design principles and fixation philosophies)

Standard designs encompass two different methods of fixation of the femoral stem into the femur: cemented and cementless.

4.1.1. Cemented femoral stems

Cemented fixation was introduced in the mid-last decade and uses PMMA cement to secure the femoral stem inside the femur. The cement hardens to form a mechanical interlock between the bone and the implant, providing immediate stability [39], which is beneficial for patients with poor bone quality or osteoporosis. This also results in lower periprosthetic fracture rates compared to cementless stems [39].

Bone preparation attempts to provide a stable interlock in the bone-cement and cement–implant interfaces. Routine broaching aims at using an implant that is smaller than the broach to achieve a cement mantle of 2 mm or more. Fragmentation and increased strain may threaten a thin mantle of cement. The line-to-line broaching method entails the use of an implant equal in size to the final broach, resulting in a very thin cement mantle [40]. A femoral cemented stem design aims to produce a prosthesis capable of transmitting axial stresses across the cement [41].

Femoral stem implants may be categorized based on their method of fixation into either taper slip design or composite beam design. The taper slip design is mostly polished and tapered, thereby permitting subsidence in the cement mantle. This mechanism induces compressive stress in the cement and could help with stability over the long term. In comparison, the composite beam concept relies on creating a stiff structure along with the cement mantle and the bone itself, thus preventing subsidence and allowing loads to be transferred via the stem–cement–bone complex. The choice between these concepts' hinges on the stem design, cementing procedure, bone density, and the necessary stability-load transfer balance [42].

4.1.2. Cementless femoral stems

Cementless fixation achieves primary press-fit stability, followed by long-term stability, through bone ingrowth or ongrowth onto the implant surface [39]. It promotes bone growth and integration with the implant, potentially leading to a more durable fixation over time. Cementless fixation is considered the preferred choice in the USA [43]. Several types of cementless stems are described below:

1. Short stems have shown better outcomes with reduced revision rates than traditional stems. Younger patients find them useful because of their bone-conserving architecture [43].

2. Neck-preserving femoral stems allow the neck excision to be made more proximal than with conventional stems. Maintaining the natural trabecular arrangement of the bone helps to preserve the femoral neck, therefore supporting functional loading [44].

3. The short-stem prosthesis is anchored on the femoral neck without damaging it, while the stem is implanted in the diaphysis-metaphysis region, leaving the trabecular architecture intact [45].

4. Femoral components that fit the metaphyseal regions do not require diaphyseal fixation and thereby prevent resorption of bone in the calcar region, as shown in Figure 2 [46,47].

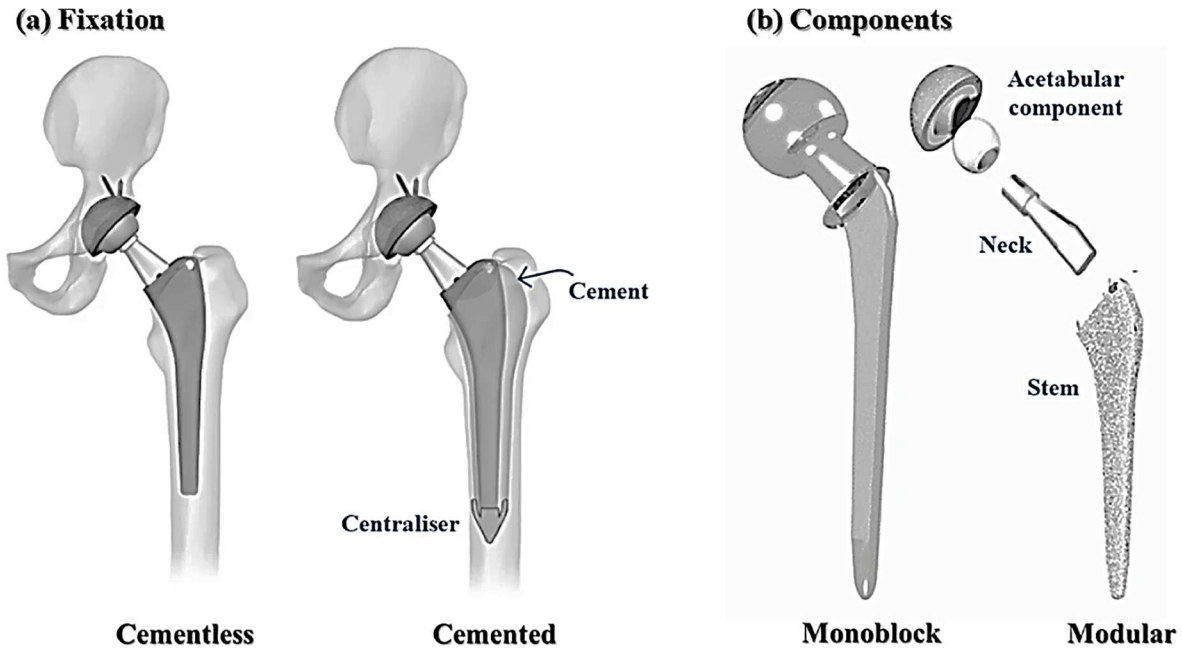


Figure 2. (a) Fixation type of implants, reflected in the stems. (b) Types of components and naming of the different elements of a hip implant (Reproduced from Ref. [47] with permission).

Short-stem total hip arthroplasty (SHA) is considered a choice in revision total hip arthroplasty (rTHA) due to its capacity for saving bone stock in the femur and short femoral stems. However, no research is available to determine the efficacy of the short stem in revision THA as far as primary stability is concerned [48]. Reconstruction of the femur with long stems is widely accepted as the gold standard for rTHA. Long stems are troublesome to implant and will destabilize bone stock for eventual revision.

A non-inferior primary stem was identified with respect to long-stem rTHA with Paprocki type 1-3B femoral bone defects. The primary stem offers an easy approach to ensure that the distal bone stock is left behind for later revisions, especially among young patients. Older patients who are less active and whose needs are not high will require a more cemented stem [49].

Advanced porous implants hold the potential to revolutionize orthopedic treatment. By closely mimicking the shape of the bone and diminishing the issues associated with traditional solid implants, they can potentially maximize osseointegration, load transmission, and long-term fixation. Further research and development must be conducted to unlock the full promise of these innovative solutions and maximize patient outcomes in orthopedic surgery [50].

The fixation of cementless femoral stems is accomplished through press-fit fixation and biological fixation using bone ingrowth or ongrowth on modified surfaces. The taper-wedge type of stem gets its stability from cortical interdigitation, preventing overloading distally. Stems that engage the metaphysis are intended to spare the proximal bone and promote more physiological load transfer, whereas stems that fixate the diaphysis offer greater stability in patients with metaphyseal bone deficiency, but they can cause proximal stress shielding [51].

4.1.3. Key geometrical and surface-design parameters

Femoral stem performance is highly affected by stem length, cross-section geometry, taper angle, neck geometry, femoral offset, neck-shaft angle, surface roughness, and porous coating distribution. Geometry and tapering affect the stability of press-fit and rotation resistance, while stem length and fixation position affect load distribution between the proximal femur and the shaft. The purpose of proximal porous coating is metaphyseal bone ingrowth and preservation of proximal loading, although distal or distant coatings may benefit some fixations but lead to increased loading at distal levels and increased risk of proximal stress shielding. Femoral offset and neck-shaft angles must be restored to maintain abductor muscle tone [52].

4.2. Non-traditional designs

Auxetic materials that have a negative Poisson's ratio have been investigated for their biomedical uses, such as the use of femoral stem implants in THA. Auxetics have the ability to expand sideways when subjected to axial tensile stress, thereby reducing the risk of stress shielding that causes the implant to become loose [53]. Stiffness grading in functionally graded porous stems is possible using lattice variation. In [54], a hybrid gyroid-diamond Ti-6Al-4V stem was reported, which has graded sheet thickness and resulted in reduced axial stiffness when compared to its solid counterpart (2.15 vs. 2.76 kN/mm), with almost 70% reduced simulated stress shielding when loaded by 2300 N.

The efficiency of the grading will also be affected by the way it is distributed; the proximal–medial load transfer was enhanced by the use of axial grading. On the other hand, the radial-gradient technique using an outer dense shell failed to prevent stress shielding. Hence, grading does not necessarily guarantee better performance [55]. Therefore, it is not just a question of decreasing the stiffness of the stem, but rather achieving a balance between modulus matching, interfacial stability, osseointegration, and safety factors.

4.2.1. Benefits of auxetic structures

1. Decreased stress shielding: in some scientific studies, it has been found that auxetic femoral stems lead to decreased stress shielding when compared with conventional solid designs. This is due to the fact that there is decreased stress shielding with auxetic femoral stems, as shown in Figure 3 [56].

2. Better stress distribution: since auxetics are characterized by unique mechanical properties, they make it possible to evenly distribute stress between the implant and bone tissue. Thus, the implant becomes better integrated and stabilized inside the medullary cavity [57].

3. Enhanced bone ingrowth: auxetic designs have the potential to improve the bone ingrowth process because of their capability to emulate the bone's mechanical characteristics to a greater extent compared to solid implants [57].

4.2.2. Design considerations

Various design parameters have an influence on the performance of auxetics in femoral stems:

- Geometric profile: the geometry of the auxetic material is very important for the mechanical properties of the material. Various re-entrant angles have been investigated, such as 60°, 70°, and 80°.
- Location of auxetic structures: positioning auxetic components in the right places on the tensile face of the stem will help to achieve this goal.

The research related to auxetic structures is ongoing, with researchers concentrating on the optimization of their design with regard to different applications in orthopedic surgery. The use of auxetic materials may not be restricted to femoral stems but also apply to other kinds of implants [56,57].

The concept of auxetics is an emerging field of study in the design of biomedical implants, especially for reducing stress shielding and bone integration. Additional research is needed to optimize these designs and evaluate the long-term implications in clinical settings [58].

The mechanical performance of the porous stem design is based on the geometry, porosity, dimensions, and location of the porous region. Stiffness reduction has to occur while considering sufficient structural and interface stability. Stress shielding, interface micromotion, fatigue strength, and bone ingrowth have been listed by Liu et al. as interrelated factors in optimizing porous stems. The article also presented topology-based porosity limits due to micromotion analysis at the interface, which suggested that a porosity limit valid for one topology cannot be applied to all topologies [55].

Comparison among various lattice topologies is also possible only when their geometry and loadings are precisely known. In fact, assigning superiority to either gyroid, diamond, or Schwarz primitive topology is not appropriate, as one should consider the performance of each architecture as well as the stem as a whole; for instance, by comparing the performance of a hybrid structure consisting of both gyroid and diamond sections as a stem to that of a solid stem [59].

Another advanced design structure for stems is the lattice structure, as shown in Figure 3. Femoral stems with porous lattice constructions have become easy to fabricate due to advances in additive manufacturing (AM) technology, also called 3D printing. Using porous metal reduces stiffness compared to solid implants, and modifying the number, size, and location of the pores will determine the flexibility of the femoral stem and reduce stress shielding on the proximal femur. Open pores in an implant allow for the transportation of nutrients and bone ingrowth, hence increasing the stability of the implant. The use of porous lattice structures in femoral stems offers several advantages, including reduced stress shielding and improved implant stability. These benefits are achieved through the design and material properties of the porous structures, which can be fabricated using the technique of AM [55].

The pursuit of improved femoral stem designs for total hip arthroplasty has led to creative production methods, including new geometries, structures, and materials. The goal is to better understand the mechanical properties of healthy femurs, enhance hip prosthesis implantation, promote osseointegration, extend implant lifespan, and enhance patient quality of life. Both models implanted with a commercial prosthesis and an engineered lattice structure prosthesis showed similar results. Therefore, tests with alternative lattice structures of 500 microns or less, preferably nanoscale, must continue. To avoid significant stress shielding, bone resorption, and implant loosening, the femoral

stem behaves like femoral osseous tissue. Future work aims to build lattice systems, which use artificial trabeculae to efficiently convey and guide loads through the femoral shaft walls [60,61].

Additionally, a previous study used Ti-6Al-4V to produce graded lattice structures for orthopedic implants, as shown in Figure 3. The goal was to create a graded lattice unit cell design that mimics human bone, with high surface curvature and adaptability for enhanced mechanical and biological qualities. The focus was on osseointegration and stress shielding.

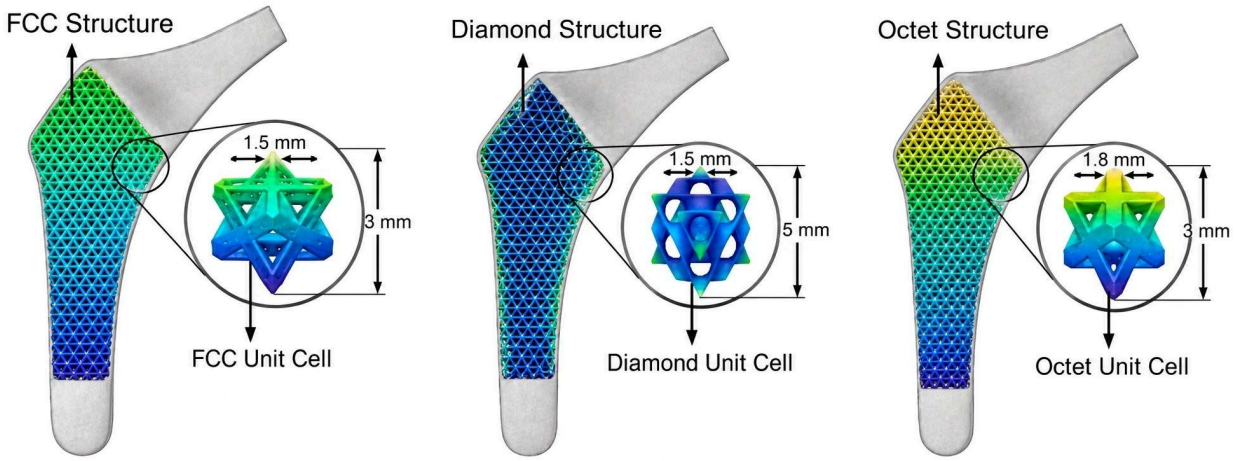


Figure 3. Lattice cells in hip implant struts.

That research modeled and evaluated simple cubic (SC) and body-centered cubic (BCC) lattice structures with various geometries and graded characteristics, conducting compressive testing to determine the ideal configuration, as shown in Figure 4. The results suggested that filleting improved mechanical strength. BCC lattice structure performed better than the SC structure. The optimized construction had a higher elastic modulus, yield strength, and compressive strength [62,63].

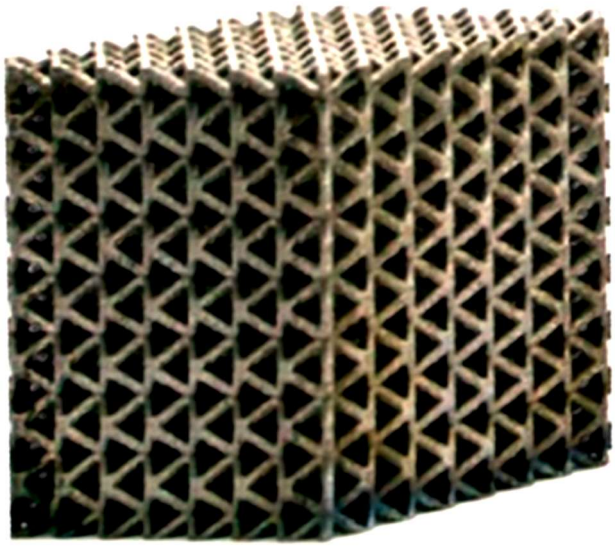


Figure 4. Ti-6Al-4V lattice with fabricated body-centered cubic structure subjected to compression testing (Reproduced from Ref. [63] with permission).

In summary, advancements in the design structure of the femoral stem, from traditional and non-traditional to hybrid designs, result in improved patient outcomes. Additionally, the gradual development helped improve load distribution and biological incorporation. Even though such new methods, such as porous surfaces, belong to the future, the validation of these processes is a must.

5. Manufacturing processes and AI in THA

The femoral stem implant has evolved significantly in terms of engineering and design, with the emphasis being placed on achieving an optimum balance between material properties and geometry [64]. Alongside these developments, AI has gained prominence as a significant tool in enhancing the planning of preoperative procedures, implant design, and the success of surgeries. Therefore, this section analyses the role of manufacturing and AI integration and emphasizes the significance of additive manufacturing, computational modeling, and machine learning in THA.

5.1. Design considerations and selection of materials

Custom femoral stems aim at achieving the best fit and fill in the metaphyseal area; this is of value to patients with variant proximal femoral anatomy. Computer-aided design (CAD/CAM) and manufacturing technologies allow these stems to be produced with greater accuracy and customization [65]. Porous lattice implants, which mimic cancellous bone, are being explored to enhance bone integration and stability. Fused deposition modeling (FDM)-made porous hip bone implants replicate natural bone with varied homogenization lattice architectures and outstanding characteristics. Five isotropic lattice structures with homogenization control methods are printed using PEEK and composite PEEK with decreased graphene oxide (rGO) and calcium hydroxyapatite (cHAp). The new design reduces small defects, making it more stable [61].

Researchers are creating hip implants made with porous lattice and functionally graded material (FGM) stems, femoral head resurfacing, short-stem, and collared stems to provide uniform stress distribution, promote adequate bone remodeling, and reduce stress shielding [66].

The technique of laser powder bed fusion (LPBF), alternatively called selective laser melting, allowed Naghavi et al. to fabricate a functionally graded Ti-6Al-4V hip stem that is a combination of gyroid and diamond elements. Yet, one needs to differentiate the planned design of the lattice from potential defects that may occur in the manufacturing process, as they may affect the fatigue properties of the material.

Correlations between LPBF processing parameters, internal defects, surface roughness, and four-point bending fatigue of Ti-6Al-4V have been examined. These investigations indicated that variations in the laser power, scanning velocity, and scanning path affected defect formation and surface condition. In particular, varying the scanning path without altering laser power and scanning velocity caused a reduction in the average surface roughness (aS) from 15 to 7 μm. However, the research highlights the need for process qualification to consider the surface condition and defect characteristics apart from the process parameters, instead of considering the density of the object alone. These results were achieved using rectangular-shaped materials and not porous femoral stems; hence, there is a need for component-specific studies [59].

5.2. Manufacturing techniques and optimization

Finite element analysis (FEA) is employed to optimize the shape of femoral stems and analyze the developed designs. For example, Ansys R2023 was used to model the mechanical behavior of the distal part of the femoral stem fabricated from either CFRPC or Ti-6Al-4V [67]. Structural optimization and process optimization must be treated independently, using the stress field from finite element analysis to determine the variation of sheet thickness for the lattice structure of a porous hip stem. This is an example of structural optimization toward a specific biomechanical goal. The choice of LPBF parameters and scanning strategy influenced defects in the manufacturing process, surface roughness, and fatigue behavior of Ti-6Al-4V implants. The first paper deals with the issue of implant design that should be created, while the second deals with the quality and behavior of the created material. Neither of those results guarantees cost efficiency or clinical effectiveness of the manufacturing process [55].

5.3. AI in THA

Hip replacement procedures are becoming more and more reliant on AI, which is used for surgical planning and implant identification. Artificial intelligence technologies used in femoral-stem research can be distinguished by their application. With regard to implant design and manufacture, artificial intelligence models can be used to optimize the material composition, such as lattice parameters, porosity distributions, LPBF processing parameters, and mechanical properties, which will aid in creating structurally sound and stiffness-matched implants [68]. On the other hand, artificial intelligence can be utilized in clinical applications before a THA surgery to help with anatomical reconstruction, component sizing, and implant placement. Recent studies have suggested that use of AI for THA planning improves component fitting in the acetabulum and femur, decreases postoperative leg length difference, and may help reduce operating time and blood loss during surgery. However, care must be taken while interpreting these findings due to the differences between studies in terms of imaging modality, the AI model used, the population studied, and the endpoints measured [69]. The following are major applications and results of AI in hip replacement.

5.3.1. AI-assisted preoperative planning

- 3D planning technology: 3D preoperative planning by use of artificial intelligence technology has proven to be more beneficial than traditional 2D X-ray technology. A study done on 61 patients with Developmental Dysplasia of the Hip (DDH) showed that planning assisted by AI produced better accuracy for prosthesis size prediction and acetabular cup positioning. In that research, 91.2% of the acetabular cups were located in the safe zone through AI, while the traditional method achieved only 66.7%. Deep learning algorithms were deployed by the artificial intelligence hip system (AIHIP) software for the analysis of computed tomography (CT) data and quick reconstruction of the anatomy models, essential for complicated scenarios [70].
- Automatic detection: one of the most innovative applications of artificial intelligence in hip arthroplasty is the automatic detection of hip implants using deep learning algorithms. A previous work created a convolutional neural network (CNN) model, which proved highly accurate in distinguishing between different types of hip replacement designs through radiographs. The model was trained using

a dataset comprising 714 images and was able to classify the design of implants with a success rate higher than 99%. The model not only helps in recognizing implants in revision surgeries but can also help reduce surgical procedures and their related complications [71].

The implementation of AI in hip replacement surgery brings about many advantages, as follows:

- Increased accuracy: AI provides more accurate placement and measurement of the implants.
- Cost efficiency: by reducing the amount of time spent on surgical preparations and human errors, AI has the potential to reduce surgery costs [70].
- Potential for broader applications: the evolving nature of AI technology could enable its utilization at different levels of hip replacement, from diagnosis through postoperative care [72,73].

The fast development of AI technology has made great breakthroughs in different medical specialties. Research has aimed to compare perioperative factors and postoperative functional recovery of hips after the first THA using traditional two-dimensional X-rays in planning versus an AI preoperative planning system [74]. A related earlier study was based on the design of patient-specific prosthetic implants using the combination of multi-body dynamics, machine learning, and finite element method (FEM) simulations. Through joint angle estimation by OpenPose, vector construction from hip, knee, and ankle joints, as well as the use of human multi-body modeling, the proposed algorithm intends to increase the functionality and lifespan of the prosthetics used by individuals suffering from joint arthritis [75].

5.3.2. Surgical results of AI-based implants

1. Improved accuracy and efficiency: studies have shown that the use of AI for planning results in higher precision in terms of component positioning. This is essential for reducing any complications like dislocation and limb-length inequalities after surgery. For example, one study found that 91.2% of the acetabular components could be accurately placed in the Lewinski safe zone using AI-assisted planning, while only 66.7% were accurately placed using the traditional approach [76].

2. Short-term results: according to a retrospective study of patients with DDH, the patients undergoing AI-based THA demonstrated significantly better results concerning reestablishment of the lower limb length and the overall score for hip functions than those who had undergone conventional therapy [76].

The precision of artificial intelligence planning has also been proven to surpass conventional techniques in terms of prosthetic position and size. Use of AI algorithms, especially deep learning algorithms, allows for automatic segmentation of anatomical structures and three-dimensional reconstruction of the hip joint, which can help surgeons make the right decisions with regard to the design and measurements of implants. A virtual surgery simulation based on AI can help surgeons in the analysis of various situations prior to entering the operating room. Although some flaws have been found with respect to geographical bias and language barriers, it is clear that the use of AI in presurgical planning has greatly improved the accuracy of femoral alignment, hence becoming an important component of THA success [76].

In hip implant surgery, Triply Periodic Minimal Surfaces (TPMS) are used in order to solve some problems like stress shielding, bone resorption, and malfunctioning of the implants. With the use of FEA, the performance of gyroid and split-P TPMS-based hip implants was compared with that of solid hip implants using a 3D model of a femur bone generated from CT data. Results showed that stress levels were very low in the gyroid implant compared to its critical values, along with a 28% weight

reduction compared to the solid implant. Deep learning was also employed in the analysis of X-rays for total hip replacement (THR) patients [77].

An evaluation of loads on prosthetic implants through FEM simulation revealed a very significant enhancement of the lifespan of the prosthetic system. Past research can indeed be considered a great achievement in prosthetics, aided by a better treatment method for patients who have joint arthritis. Research can contribute significantly to the improvement of quality of life and performance of prostheses [75].

Another previous study demonstrated that vibrometers have the potential to diagnose acetabular cup loosening early in total hip replacements. The study determined the minimum level of acetabular cup loosening that can be detected by vibrometers in a reliable way, as well as the optimal frequency range to detect it [78].

To conclude, the integration of advanced manufacturing processes and AI is a promising technology in THA. Optimization of stem geometry and materials behavior can be investigated through manufacturing innovations, such as 3D printing and FEA. AI improves preoperative planning, detection of implants, and surgical precision. The improvement of patient outcomes, reduced complications, and long-term implants are promised through these technologies. However, long-term clinical validation is still important and essential before adoption.

6. Surface engineering and bone–implant interface biology

The bone–implant interface is a key factor in determining femoral stem fixation, as the surface of the implant will influence protein adsorption, cell adhesion, bacterial colonization, and the osseointegration process. Surface engineering thus complements bulk material selection and lattice design through surface modifications such as chemistry, topography, wettability, and corrosion properties. Hydroxyapatite and other bioactive coatings based on calcium phosphate could improve osteoconductivity. Porous titanium surfaces offer a network structure into which bone can grow and lock into place. Optimizing surface roughness is more important than maximizing it because suitable micro/nanoscale surface roughness can enhance cell attachment, whereas excessive roughness can lead to contaminant retention, bacterial attachment, and even mechanical damage to the surface [79].

Additionally, antibacterial surface techniques such as ion release coating, drug delivery layering, and contact active coating can be used to decrease early microbial colonization and periprosthetic infections. However, their biological effect against microbes should be weighed against their cytocompatibility, since a surface that is bactericidal could equally reduce osteoblasts' viability and hinder osseointegration. The same applies for corrosion and tribocorrosion at the interface, as ion and particulate release due to degradation can affect local tissue responses, leading to inflammation and interface instability. Therefore, a successful femoral stem surface should have multiple functions; requirements for a metallic biomaterial include promoting bone integration by osteoblasts, inhibition of bacterial adherence, corrosion resistance, and the maintenance of chemical and mechanical properties [80].

The biological usefulness of any surface treatment should always be evaluated alongside its physical and chemical resistance. For instance, in the case of hydroxyapatite coatings, the process of dissolution, cracking, and detachment may result in the loss of interface activity. Therefore, the effectiveness of the coating is influenced not only by its composition but also by defects caused by deposition and resistance to physiological media. In other words, although the coating promotes

biological activity initially, it does not necessarily remain biologically useful for the duration of its operation. Therefore, surface analysis should include the assessment of coating degradation and biological activity. This is especially important when experimental evidence is provided to support claims of osseointegration [81].

Moreover, the threats associated with corrosion processes have to be separated from stress-shielding issues. Mechanically induced corrosion at modular hip–implant interfaces may lead to a release of metal debris and ions into the surroundings of the implant. Though such products of degradation may trigger an adverse tissue reaction, the biological consequences will depend on the particular type of the released products and the conditions of their exposure. Therefore, any positive outcome achieved in terms of cellular responses or degradation testing conducted under a specific laboratory condition cannot be considered evidence of a safe interface [82].

7. Main challenges in THA

The main challenges associated with hip joint implants, particularly THA, encompass a range of mechanical, biological, and surgical factors. The challenges, such as stress shielding, implant longevity and wear, surgical complications, and patient-specific factors, can significantly affect the longevity and functionality of the implants. Thus, structure design, materials selection, and clinical validation are required to address these challenges. All these mechanisms should not be considered independent problems. While stress shielding might decrease the density of bone in the vicinity of the prosthesis, micro-motion might prevent osseointegration. In parallel, fretting and tribocorrosion at the interface of the modular components can release metal ions and wear particles that can lead to inflammation due to macrophages, osteolysis, and eventually aseptic loosening. Loss of bone and instability of the prosthesis can predispose patients to periprosthetic fractures. Thus, the outcome of femoral stems is influenced by the interplay between implant biomechanics, surface/interfacial behavior, positioning, and patient-specific bone and systemic factors [83].

7.1. Stress shielding

Stress shielding is a mechanobiological response in which a relatively stiff femoral stem carries an excessive proportion of the physiological load, reducing mechanical stimulation of the surrounding bone. This altered load transfer may cause proximal bone remodeling, bone resorption, and reduced bone mineral density. However, excessive implant flexibility may increase interfacial micromotion and compromise fixation.

Stress shielding is influenced not only by implant elastic modulus but also by stem geometry and length, fixation method, porous or lattice distribution, implant alignment, and patient-specific femoral anatomy. Lower-stiffness materials, short stems, carbon fibre-reinforced (CFR) PEEK composites, porous surfaces, and graded lattice structures may improve proximal load transfer; nevertheless, their design must retain sufficient strength, fatigue resistance, and primary stability.

Therefore, femoral stem optimization should balance physiological load transfer, rotational stability, osseointegration, and long-term fixation. Material and design selection should also consider bone mineral density, cortical thickness, femoral morphology, age, body mass, activity level, and comorbidities [84].

The concept of stress shielding must be analyzed based on its design and biological aspects rather than simply based on the stiffness of the implant. Standard, long, dense stems can offer excellent support but might actually shift the loads from the proximal femur to a considerable extent, especially when the rigidity of the stem greatly exceeds the rigidity of the bone. Short stems try to maintain the proximal loads while minimizing the distal fixation and preserving the bone stock of the femur; meta-analysis shows that short-term preservation of Bone Mineral Density (BMD) in selected proximal Gruen zones is better than with conventional stems. However, such improvements are related to stem design, since new short-stem designs provided better bone mineral density maintenance compared with classical tapered short stems; there is currently no evidence to show a definite reduction in aseptic loosening or revision rate [83].

The ideas behind porous, auxetic, and functionally graded stems lie in the local design of stiffness, load distribution, and interface performance by variations in porosity, lattice structure, or material content. A porous or graded structure may provide better modulus matching and provide conditions conducive to bone growth, while an auxetic structure provides unique deformation characteristics, which could help achieve conformal contact. However, their benefits are mainly attributed to computational modeling, mechanical testing, and initial translation studies; the issues related to fatigue resistance, manufacturing flaws, pore clogging, micromotion at interfaces, and reproducibility persist. Therefore, despite the strong mechanobiology possibilities associated with these advanced designs, their clinical superiority compared to proven standard or short stem designs needs to be established by standardized clinical and registry studies [69].

It is imperative to make a distinction between the clinical results of stress shielding mitigation techniques and computational biomechanical analyses when comparing them quantitatively. Table 2 provides numerical data for traditional, short, porous, auxetic, and graded femoral stems. This table provides numerical data relative to its comparators and anatomical location, not to compare different groups of stems directly.

These results underscore disparities both in the outcome measure and the setting for validating the stems. While the short stem analysis showed design-specific retention of proximal bone mineral density, the other three designs were associated with computational changes either in bone loss predictions or in stress shielding measurements. Hence, a 75% decrease in bone loss prediction, a 96% decrease in stress shielding in regions, and a 70% decrease in the whole femoral stress shielding index do not equate to each other. Further research on the matter would be warranted, but no particular stem design is better than the rest.

Table 2. Examples of quantitative data on stress shielding and bone maintenance for different femoral stems.

Interpretation and principal limitation	Numerical finding	Representative comparison and evidence type	Stem category
Serves as a study-specific baseline value rather than a universal value for regular stems. Depends on the model and the stress-shielding definition used in the particular study.	The reported proximal stress-shielding increase was 68%, compared with 37% for the porous graded stem in Gruen zones 1 and 7.	Solid Ti-6Al-4V comparator in computational context.	Conventional solid
Indicates design-dependent, short-term BMD preservation. Standardized Mean Difference (SMD) is dimensionless and must not be interpreted as a percentage reduction in stress shielding [84].	At 12 months, bone mineral density maintenance in zone 1 for Gruen favoured short stems: SMD = 0.59, probability value (p) = 0.002. Novel design subgroup had SMD = 0.94, $p < 0.00001$, while traditional tapered short stems did not show any significant effects.	Short stems vs. straight stems; clinical meta-analysis.	Short
This is a prediction of bone loss, not a reduction of 75% of clinical stress shielding. This finding has been provided via a secondary review [50].	Bone loss resulting from the stress shielding effect was reduced by about 75%.	Fully porous Ti stem with optimized structure vs. solid stem; computational bone loss prediction.	Porous
Shows regional and design-specific computations; values do not refer to whole femur computations or clinical results [56].	The stress shielding for Gruen zone 1 is reduced by 76%, 96%, and 71% in (model) M1, M2, and M3, respectively.	M-type auxetic stems compared to solid stems; finite element analysis.	Auxetic
Supports the studied graded arrangement under the simulated circumstances, without proving the lower clinical revision risk. The traditional and graded rows represent the same research, not separate evidence [9].	The overall stress shielding ratio for Gruen zones 1 to 7 was reduced by roughly 70%.	Comparing hybrid graded gyroid-diamond Ti-6Al-4V stem to a solid stem; computational.	Graded porous

The following are the primary effects and factors of stress shielding of stem implants:

7.1.1. Effects of stress shielding

• Bone resorption: stress shielding can lead to bone resorption, as the bone adapts to the reduced stress by decreasing its mass. This can weaken the bone and potentially lead to fractures or implant loosening [85].

• Reduced bone density: the reduction in stress can result in decreased bone density, which may compromise the long-term stability of the implant [85].

• Implant loosening: increased interface stresses due to flexible stems can cause debonding and micromotion at the implant–bone interface, potentially leading to implant loosening [86].

7.1.2. Considerations for reducing stress shielding

• Stem design and stiffness: reducing the stiffness of the stem can minimize stress shielding. Anatomical short stems with low stiffness have been shown to provide a more physiological strain-loading effect on the bone [87].

• Material properties: using materials with lower elastic moduli can reduce stress shielding but may also increase interface stresses [84].

• Anatomical variability: stress shielding is influenced by anatomical variability, such as bone density and stem orientation. Evaluating new implant designs across diverse populations is crucial [88].

• Optimization strategies: optimized stem designs aim to balance rotational stability with reduced stress shielding. Finite element analysis is often used to predict and minimize stress shielding effects [89].

While stress shielding leads to adverse effects, such as bone resorption and implant loosening, careful design and material selection can mitigate these issues.

7.2. Implant longevity and wear

• Wear and tear: hip prostheses can wear out during daily use over time, resulting in loosening or failure of the implant. This wear is often exacerbated by biological processes such as osteolysis, whereby bone is resorbed due to inflammatory responses to wear debris from the implant [5].

• Metal-on-metal (MoM) implants: MoM implants have been associated with higher failure rates, predisposed to failing within five years due to loosening and metal debris-induced adverse tissue reactions. The implants can release toxic metal ions that have the potential to lead to serious health issues, including inflammation and potential systemic effects [90].

7.3. Surgical complications

• Infection: postoperative infections remain a significant danger, with further surgery a possibility if they are serious, if there is an infection at the wound level or at a deeper level in the tissues around the implant. Following THR, a multidisciplinary approach and a clear protocol will increase the chances of infection elimination [91].

• Dislocation: this is a frequent problem that often occurs in the initial weeks or months after surgery. This may result from incorrect tension of the surrounding soft tissue or incorrect positioning of the implant parts [90].

• Fracture and nerve injury: it poses a danger of causing fractures in unharmed parts of the hip joint or nerve damage that leads to problems like pain or disability. There is a need for site-specific risk assessment because of variations in risk levels among different sexes, ages, or health conditions and changes in morphology and functions [92].

7.4. Revision surgery challenges

• Aseptic loosening: one of the most frequent causes of revision surgery, due to improper cementing in the first place or non-integration of bone in the case of uncemented prostheses. Chronicity of the problem usually makes it more difficult to diagnose and treat [93].

• Bone loss: revision surgery is more challenging since there is the likelihood of having lost some bone after previous surgeries or bone loosening, which makes it hard to anchor the implant [94].

7.5. Patient-specific factors

• Age and activity level: younger and more active patients are more likely to face problems of prosthesis longevity because their lifestyle may speed up prosthesis wear [95].

• Health conditions: current conditions such as obesity or diabetes can complicate recovery and increase the risk of post-surgery complications.

Based on this section, the main challenges in THA highlight the need for further development in the design of implants and surgical validation. The selection of materials, geometry optimization of the stem, and patient-specific planning can reduce these issues. Therefore, the next research direction should plan to address these challenges comprehensively through integrating computational modeling, biomaterials, and AI support.

8. Clinical translation and manufacturing reliability

Even though there is a lot to be said about the mechanical and biological benefits of optimizing the lattice structures using computational methods, there is still much to be done before their application in the clinical setting. Additive manufacturing can produce some process-based issues, such as lack-of-fusion problems, undesired porosity, surface roughness, dimensional errors, partially melted grains, and local strut thickness differences. Such defects may affect the effective stiffness, stress distribution, fatigue properties, and ultimate strength of the porous implants used in orthopedic surgery. Moreover, the fast temperature changes that take place during additive manufacturing may lead to residual stress formation and geometrical distortions, therefore requiring adequate post-processing, heat treatment, and verification of size. Hence, a lattice structure that performs well in a finite element simulation will not necessarily exhibit the same behavior after processing, sterilization, and exposure to physiological loads [96].

The result is that reliable clinical application also demands manufacturing reproducibility, validated cleaning and sterilization, non-destructive inspection, quality assurance, and material confirmation regarding its composition, shape, surface state, and mechanical properties. In addition,

regulatory approval also requires demonstration of biocompatibility, mechanical/fatigue durability, and corrosion/degradation resistance (when necessary). While recent progress in orthopedic additive manufacturing has made it possible to develop highly complex and even multifunctional implants, a considerable difference exists between optimized computing models and solid evidence from a long-term clinical trial. Future work should therefore combine computer optimization with validation, fatigue testing, biological studies, and follow-up trials in order to verify the safety and efficacy of modern orthopedic implants [97].

9. Integration of femoral stem design and clinical implementation

Development of femoral stems should involve a holistic evaluation of material, geometry, fabrication process, and surface characteristics, as opposed to optimizing each one separately. Table 3 presents their interactions with the desired advantage, main disadvantage, available evidence, and clinical maturity. The description of the evidence indicates the nature of the research that supports it, and not its quality, since there was no systematic assessment of study quality carried out. Clinical maturity is evaluated for the particular stem design and use, not for the material or fabrication method as a whole.

Table 3. Integrated framework connecting femoral stem material, design, fabrication, interface approach, scientific evidence, and clinical development.

Material	Stem architecture	Manufacturing	Interface strategy	Main benefit	Main limitation	Evidence type	Clinical maturity
Metallic alloys	Solid cemented	Conventional processing	PMMA fixation	Immediate stability	Cement-related failure	Clinical/registry	Established
Titanium alloys	Solid cementless	Conventional processing; surface modification	Press-fit and bone ingrowth/ongrowth	Biological fixation	Stress shielding	Clinical/registry	Established
Stem alloys	Short	Conventional processing	Proximal fixation	Bone preservation	Design-dependent outcomes	Comparative clinical	In clinical use
Titanium alloys	Porous/lattice	AM	Press-fit and intended ingrowth	Reduced stiffness	Fatigue and manufacturing defects	Computational/ experimental	Design-specific
Ti-6Al-4V	Graded lattice	LPBF	Intended porous fixation	Tailored load transfer	Limited clinical validation	Computational/ experimental	Investigational
Design-dependent	Auxetic	Architecture-dependent	Intended adaptive contact	Reduced predicted stress shielding	Manufacturing and fatigue validation	Computational	Investigational
CFR-PEEK	Composite	Composite processing	Modified surface/coating	Reduced stiffness mismatch	Fixation and durability validation	Computational/ preclinical	Emerging

In this synthesis, it becomes apparent that different priorities must be met during the validation of each discussed strategy. In the case of cemented and cementless stems that are already used, the primary goal will be finding an appropriate stem design and fixation technique for a particular patient, rather than proving their superiority in comparison with another technique. The same goes for porous, graded, auxetic, and composite stems; the prediction of certain mechanical benefits must be related to the reproducibility of production, fatigue resistance, interface stability, and clinical significance.

10. Conclusions

From the analysis carried out above, it is clear that there is a need for the development of orthopedic implants integrating material–design–manufacture methods rather optimizing one factor alone. Traditional implant materials and current fixation techniques offer the most robust clinical basis for use. Porous and lattice structures, graded and auxetic materials, bioactive surface treatments, and patient-specific computational optimization have demonstrated promising mechanical and biological outcomes mainly in computational contexts. However, their long-term clinical superiority has yet to be conclusively demonstrated. Future work will require solving issues related to reproducibility in manufacturing, fabrication defects, fatigue resistance, coating stability, sterilization of porous materials, and clinical validation.

11. Recommendations for future research

- Consider manufacturing constraints and quality control during the optimization of the implant design.
- Consider the influence of any manufacturing defects, surface finish, and stress on the mechanical properties of the implant.
- Subject the fully processed and sterilized implants to physiological cyclic loading.
- Evaluate osseointegration, implant-bone micromotion, coating stability, and biocompatibility in appropriate animal studies.
- Establish standard reporting for material characteristics, structure, fabrication process, post-treatment process, and testing methods for fatigue tests.
- Conduct long-term comparative clinical studies to prove the advantages of advanced implants over existing orthopedic implants.

Use of AI tools declaration

The authors declare they have not used Artificial Intelligence (AI) tools in the creation of this article.

Author contributions

Anwer contributed to formulating the article concept and structuring the article, carried out the analysis and synthesis of the literature data, and was responsible for drafting and editing the manuscript. Hala and Kadhum provided a critical review of the manuscript and approved the final version for publication.

Conflict of interest

The authors declare no conflict of interest.

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