A Comprehensive Review of Advancements in Materials and Manufacturing for 3D Knee Implants

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REVIEW

A Comprehensive Review of Advancements in Materials and Manufacturing for 3D Knee Implants

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ABSTRACT

Over the past three decades, knee implant design has significantly advanced to address the challenges of replacing damaged knee joint bone with durable and efficient prosthetics. The aim of this review explore key developments in materials and manufacturing processes, focusing on biocompatible options such as zirconium, titanium alloys, UHMWP, and smart materials, as well as coatings designed for metal-sensitive patients. The study examines the mechanical forces acting on implants during daily activities, highlighting wear and infection risks, and evaluates the role of innovative manufacturing techniques in improving implant precision, cost-efficiency, and durability. Simulation methods, including Finite Element Analysis (FEA), are discussed for assessing implant behavior under static and dynamic loading conditions, ensuring stress distribution and wear reduction. By synthesizing advancements in material science, coating technologies, and simulation techniques, this review provides valuable insights into optimizing knee arthroplasty outcomes and identifying future opportunities for innovation.

Keywords: Knee implants, FEA, Advanced materials, Biomaterials, Polymer

1. Introduction

Intense physical activity, such as drop landing, may result in acute joint damage, particularly when coupled with increased height. Also, the knee joint is considered a complicated joint, strained, and the biggest articulation in the body. It connects the tibia and fibula via the thigh femur [1, 2]. The knee joint comprises the menisci, tibia, cartilage, fibula, femur, patella, muscles, and ligaments. This joint facilitates movement in both forward and backward directions during everyday activities such as climbing, walking, and running [3]. The compressive stresses experienced during daily activities can reach up to four times the body's weight [4], while during athletic training, these forces can escalate to ten times the body's weight [5]. Such significant stress, along with the strain on the joint's articular tissues, is a major contributor to knee discomfort [6]. Knee implants are surgically placed to replace damaged or worn-out biological components, allowing patients to walk more freely and with less discomfort. The first form of knee replacement surgery was the tibial plateau prosthesis, which McKeever invented during the early 1950s and 1960s [7].

Usually, metal and plastic components are used to encase the ends of bones and the patella that has undergone surgery, facilitating the creation of new joint surfaces into the bone. A thermoplastic polyethylene element is positioned between the tibial and femoral components to provide a smooth gliding surface. The traditional metallic materials increase weight, making the prosthesis cumbersome, non-ergonomic, and less economically feasible [1]. The polymers may address the problem as mentioned above [2, 3]. It is essential to use an appropriate design and optimize it to improve the performance and durability of the implants.

Over 140 kinds of implant models are now available globally. The earliest models comprised solely one

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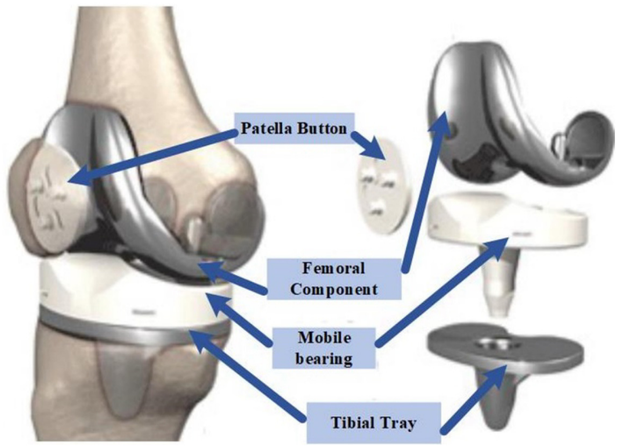

Fig. 1. The knee implant components.

metallic component; however, with advancements in design, contemporary implants are constructed from poly-ether-ketone (PEEK), cobalt, and alloys of titanium, and the ceramics that replicate the structure of the human knee and exhibit biocompatibility [7, 8]. Metal sensitivity among those persevering with knee replacement surgery and polyethylene wear particles is detrimental to the health of humans. Consequently, some manufacturers provide protected implant materials for individuals with metal sensitivities [9]. For example, the authors [10] investigated optimization and fabricating a tibial intramedullary implant for an 8-year-old kid with osteosarcoma using the suggested technique. Customization aims to align the implant's shape as closely as feasible with the patient's natural tibial anatomy. Structural design optimization is being investigated to enhance the intended implant. A computational topological optimization resulted in a 30% decrease in weight. The process chain was verified digitally using Abaqus/Tosca, and a proof of concept is shown by producing a stainless steel 316L prototype by the selective laser melting (SLM) technique. Fig. 1 illustrates a schematic of a standard knee replacement components.

The knee's cartilage is called the meniscus [13]. The partial knee replacement procedure involves substituting a tiny area of the knee with metal and plastic ingredients. The kneecap substitution, also known as patellofemoral substitution, is performed only to address a broken kneecap and alleviate discomfort. knee replacement is especially performed whenever a patient has serious arthritis. The production of implants requires specific machining techniques. The use of additive manufacturing (AM) to make biomaterials is growing quickly because it has many benefits, such as the ability to create complex shapes, high levels of accuracy, a clean work environment, the ability to make things that are exactly what you want, and the ability to use very little material in many biomedical applications [14]. Oil emulsions resulting from machining processes may lead to infections in implants, necessitating the use of biodegradable lubrication. Several approaches for minimal quantity lubrication (MQL) and CO_2 machining using cryogenics are currently developed globally. The attributes and performance of the component are evaluated prior to the implantation of the prosthesis in a human body to prevent the need for further surgery. Hundreds of mechanical investigations on knee implants, which require substantial time and financial resources, may be replicated by an analysis of finite elements [15].

Joint prosthetic simulations often focus on stress studies between the implant and bones or inside the implant components to forecast the mechanical properties of the joint. Implant loadings may be analyzed from many angles under either static or dynamic loading conditions [16]. To enhance patient comfort during rehabilitation, a two-degree-of-freedom lower limb exoskeleton has been constructed for knee joint mobility. The controller employed the parasitic force in the exoskeleton-human body shank as a control signal, adjusting joint trajectories to reduce the force [17]. Although the exoskeleton-driven knee joint rotation enhanced patient comfort, it did not match the physiological rotation needed by the knee joint. Studies indicate that considerable efforts have been consistently made to identify appropriate procedures for implant materials, methods of production, and design. The study aims to provide an overview of current advancements in knee arthroplasty [18].

On the other hand, the biomedical manufacturing industry must consider an additional aspect to achieve effective procedures. The crucial factor is the entirely aseptic atmosphere that ensures the absolute cleanliness of the machined prosthetic components [19]. Currently, they are composed of plastic protective layers and disinfected using radiation methods [20–22]. Nonetheless, despite this sterilizing procedure, the incidence of prosthesis replacements necessitated by infections is around 10%. This number implies about 350–400 rejections every year only in Spain. The radiation procedures used do not entirely eradicate the contaminants produced during machining operations, necessitating a resolution [23].

Other studies highlight the effectiveness of Finite Element Analysis (FEA) and simulation techniques in evaluating knee joint performance, particularly in understanding stress distribution and material behavior under varying mechanical loads. Computer-aided engineering has become an indispensable software tool in recent years, forming the foundation of modern biomechanical analysis [24]. It enables the routine resolution of highly complex stress problems through FEA, a method so essential that even foundational topics in mechanics of materials, like those addressed in studies related to 3D knee implementation, must underscore its core principles [25].

The development of knee implants has seen remarkable advancements over recent decades, driven by the growing need for effective solutions to replace damaged knee joint bones and improve patient outcomes. These advancements have focused on enhancing implants' mechanical performance, biocompatibility, and longevity through innovative materials, manufacturing techniques, and design optimizations.

This article aims to evaluate and specific emphasis on smart materials and their role in advancing implant performance. A detailed comparison of the advantages and limitations of various materials, including zirconium, titanium alloys, and UHMWP, is conducted to assist researchers in selecting the most appropriate materials for specific applications. The study also highlights the critical role of implant coatings in addressing the needs of metal-sensitive patients, improving frictional properties, and preventing infections.

Furthermore, the article examines mechanical forces and boundary conditions affecting implant wear and stress distribution, providing insights for design improvements. It explores innovative, cost-effective manufacturing methods to enhance implant precision and biocompatibility. Also, FEA illustrates how well knee joints work under different loads so that future implant designs are better. The contributions of the article can be briefly outlined as follows:

1. An evaluation of the existing smart materials for 3D knee implants was conducted.
2. The paper compares several advantages and disadvantages metrics of different smart materials used by previous researchers. This comparative analysis supports the selection of smart materials used in 3D-printed knee implants, helping researchers identify the most suitable materials for enhancing implant performance in specific applications.
3. The paper emphasizes the use of implant coatings in knee arthroplasties for metal-sensitive patients, focusing on their role in reducing friction, preventing infections, and enhancing durability through advanced application methods.
4. The paper investigates the impact of mechanical forces and boundary conditions on knee joint performance while exploring innovative manufacturing methods that ensure cleanliness, cost-efficiency, and precision in producing high-quality, durable implants. These methods address wear, stress distribution, and dynamic loading conditions to enhance implant functionality.
5. The paper utilizes FEA and simulation techniques to evaluate knee joint performance, focusing on stress distribution, wear prediction, and the impact of dynamic loading conditions to enhance implant design and durability.

The structure of our review paper is as follows: Section 2 illustrates the advanced materials for 3D knee implants and presents their features; Section 3 presents the coating materials used in 3D knee implants; Section 4 describes mechanical forces in the knee joint; Section 5 presents additive manufacturing methods for clean and cost-effective 3D knee implants; and the finite element analysis and simulation techniques are presented in Section 6. Finally, the conclusion and future scope are discussed in Section 7.

2. Advanced materials for 3D knee implants

The development of knee implants has been profoundly impacted by advancements in intelligent materials, engineered to enhance strength, biocompatibility, and durability while reducing wear and the risk of implant failure. These materials address several facets of knee replacement, guaranteeing performance and longevity [26], facilitating superior customization, durability, and overall efficacy. This section illustrates the advantages and disadvantages of different intelligent materials in 3D printing for knee implants, along with a table that outlines the primary benefits and drawbacks of each material. These materials are designed to better withstand the mechanical stresses of the knee implant while minimizing wear and the risk of complications like inflammation, infection, or loosening. The material characteristics of human bones are intricate, and bone production is heterogeneous and anisotropic, complicating the application of a particular anisotropic material [27].

Materials known as biomaterials have the potential to replace any human body components or interact with human tissues and bodily fluids [8]. The objective of choosing the right material is to get the best mechanical properties while reducing corrosion and material degradation and making implant placement easier over time [11]. A wide range of materials is available to enhance the stability of implants, as shown in Fig. 2.

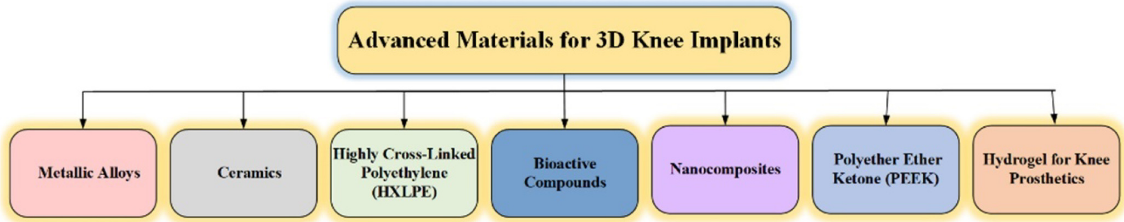

Fig. 2. Illustration of advanced materials for 3D knee implants.

2.1. Metallic alloys material

Recent research has shown titanium alloys enhanced implant fit and individualized designs, improving load distribution and minimizing wear. Vertullo et al. [28] evaluated and analyzed a large dataset of 17,577 total knee arthroplasties conducted in Australia. This study explicitly analyzes the efficacy of oxygen and CoCr femoral components within the same knee replacement design, emphasizing revision rates across various age groups. The findings demonstrate that oxygen femoral components did not significantly reduce revision rates compared to CoCr components, even when infections were excluded as a reason for revision. This conclusion is consistent across all age demographics, including those under 55. The research emphasizes that the prosthesis design significantly influences long-term results more than the material used for the bearing surface. Dion et al. [29] evaluated the fixation stability of an innovative 3D-printed titanium augment in revision total knee arthroplasty (TKA), demonstrating markedly reduced micromotion relative to the traditional cemented technique, while Kumar et al. [30] demonstrate Co-Cr-Mo-4Ti alloys improved durability and suitability for knee implants owing to their homogeneous porosity, elevated strength, ductility, and abrasion resistance, making them preferable to alternative compositions.

2.2. Ceramic materials

Ceramic materials, like zirconia and alumina, get advantages from 3D printing, which facilitates the creation of exceptionally smooth surfaces that enhance wear resistance and diminish friction. Ahmed et al. (2020) showed that 3D-printed zirconia exhibited decreased wear rates, whereas Patel and Jones indicated that 3D-printed alumina knee implants mitigated inflammation owing to its smoother surface. Morozova et al. [31] proposed that using composite materials derived from zirconium dioxide might mitigate some problems, hence augmenting the service life and dependability of orthopedic implants via enhanced fracture toughness and mechanical strength. The findings of the study highlight the crucial importance of zirconium dioxide in bioengineering, especially in 3D knee implants, dental, and orthopedic applications, while also identifying the limitations and future research prospects in this domain. Ueyama et al. [32] performed a retrospective cohort analysis with 135 consecutive patients who had primary alumina medial rotation surgery. The average follow-up duration was 11.8 years, with 7.4% of patients unaccounted for. Substantial improvements were seen in the implant knee and functional ratings after surgery. The alumina-based medial pivoting complete knee arthroplasty exhibited favorable clinical results and survival rates for a minimum further investigation period of 10 years, signifying its efficacy and safety for clinical use. Mödinger et al. [33] discussed the evaluation of a new type of 3D knee implant made from a ceramic material, specifically an alumina matrix composite (AMC), in the context of magnetic resonance imaging (MRI) safety. The MR image artifacts generated by the AMC knee were markedly reduced (7 mm) compared to those from a cobalt-chromium knee implant (88 mm).

2.3. Highly cross-linked polyethylene (HXLPE) material

A HXLPE is a widely used material in 3D knee implants due to its superior wear resistance and mechanical properties. Its enhanced cross-linking structure reduces wear particles, minimizing the risk of implant loosening over time. HXLPE also offers excellent biocompatibility, making it a reliable choice for long-term orthopedic applications. For example, Kim et al. [34] analyzed 1,217 patients who received NexGen LPS-Flex prostheses with traditional tibial inserts in one knee and HXLPE tibial inserts in the contralateral knee. The two groups did not significantly differ in clinical and radiographic results. At 17 years, the predicted survival rate for the HXLPE group was 97.7%, and for the standard polyethylene group it was 97.9%. This showed that the clinical and radiological outcomes were the same.. Remily et al. [35] conducted a study on 139 patients with (TKA) using second-generation HXLPE and showed that periprosthetic linear radiolucency was common in 19.9% of cases. However, only 0.6% of TKAs required revision due to polyethylene wear. The study found a 99.4% survival rate for polyethylene revision for wear, indicating excellent results in polyethylene wear characteristics and strength. In addition, UHMWPE is a type of polyethylene characterized by extremely long molecular chains, which provide exceptional strength, low friction, and high wear resistance. UHMWPE is commonly used in medical implants, including joint replacements, due to its durability and biocompatibility.

Gao et al. [36] investigated the utilization of highly crosslinked ultra-high molecular weight HXLPE, particularly concerning joint implants, including knee implants, examining the chemical events associated in crosslinking UHMWPE, the creation of crosslinked structures by high-energy radiation, and techniques for identifying leftover free radicals This work employs several strategies to comprehend and enhance the features of strongly crosslinked UHMWPE in 3D knee and other joint implants.

2.4. Bioactive material

Bioactive material has become fundamental in orthopedic implant technology, especially in the creation of 3D-printed knee implants. These materials favorably engage with biological systems, facilitating osseointegration, tissue regeneration, and implant durability. In 3D knee implant applications, bioactive materials provide superior mechanical performance, greater biocompatibility, and extended implant longevity. For example, Lauck et al. [37] focused on the importance of bioactive materials in 3D knee implants, which stimulate beneficial body responses upon implantation. The most common applications are knee procedures, shoulder, and ankle surgeries. Bioactive polymers like Polyether Ether Ketone (PEEK) are preferred for their lightweight, biocompatibility, and mechanical robustness. Recent improvements include incorporating bioactive additives for improved osseointegration. Zhou et al. [38] investigated the integration of bioactive herbal components into biomaterials, which may improve the characteristics of scaffolding employed as 3D knee implants for the regeneration of tissue. Herbal compounds are generally inexpensive and easily obtainable compared to traditional bioactive molecules like growth factors and cytokines. This makes them a more accessible option for regenerative therapies.

2.5. Nanocomposites material

Nanocomposites provide better performance in 3D knee implants by including nanoparticles that spread out load better and lower friction. These materials also enhance biocompatibility, promoting better integration with surrounding tissues and reducing the risk of implant failure. The study by Yildirim et al. [39] discusses the uses of polymer nanocomposites in biomedical implants, emphasizing their biodegradability, biocompatibility, and adaptability. It highlights their growing use in diverse implant categories, such as dental, knee, bone, and vascular grafts, corroborated by current in vitro and in vivo research. Kumar et al. [40] conducted a thorough study on the function of nanoparticles as composite materials in the progress of orthopedic implants. A review of several nanomaterial-based reinforcements has been conducted, focusing on diverse matrix materials such as metals, alloys, ceramics, composites, and polymers for biomedical implant applications. Moreover, the enhanced biological characteristics and mechanical qualities.

Recent studies focus on the FEA of polymeric-based knee implants with a nanodiamond nanocomposite spacer. The authors in [41] created a spacer made of high-density-polyethylene (HDPE), known as hybrid nanocomposite, augmented with nanodiamond as a filler at 0.1 wt %, used in 3D knee implants. When a nanodiamond nanocomposite spacer serves as a prosthetic material, the maximum Corresponding Von-Mises stress remains below the yield strain of 33 MPa [5]. This makes it a safe and ideal choice for implant design in total knee replacement.

2.6. Polyether ether ketone (PEEK) material

PEEK is a semi-crystalline thermoplastic polymer characterized by its polyaromatic structure and favorable mechanical properties for biomedical applications. The medical profession has used its mechanical qualities to create bone implants and models for surgical planning using 3D printing, officially known as AM technique. 3D-printed implants exhibit improved biocompatibility and mechanical stability. Meng et al. [42] introduced model using a PEEK-on-HXLPE knee implant that was developed for in vivo MRI monitoring of the area around the implant, free from metal artifacts, which may enhance the diagnostic precision of clinical postoperative problems after TKA. Caraan et al. [43] presented a brief analysis of PEEK and its evolution for orthopedic applications, addressing the issues and potential associated with 3D printing this material, particularly in enhancing PEEK's biocompatibility and printability for Knee.

2.7. Hydrogel material

Hydrogels engineered to replicate cartilage can be 3D-printed for partial knee arthroplasties. Chitosan hydrogels are distinguished by their sticky matrix, exhibiting biocompatibility, antibacterial and osteogenic qualities, biodegradability, and non-toxicity, while effectively holding, releasing, and dispersing therapeutic ingredients at the application sites. Nepomuceno et al. [44] proposed an antibacterial hydrogel using chitosan and vancomycin for use in TKA to avert bacterial infections. The study successfully created a novel hydrogel, designated H5Q1GV, which exhibited significant antibacterial activity. The hydrogel's good viscosity and adherence made it suitable for syringe administration during knee surgery. The hydrogel demonstrated efficient drug release during the first four hours after implantation and had remarkable biocompatibility. Li et al. [45] introduced a vancomycin delivery method using chitosan as a thermosensitive hydrogel, intended for implants to avert surgical site infections, potentially applicable in knee prostheses by offering localized antibacterial effects during surgery. The authors developed an antibacterial hydrogel based on vancomycin and chitosan for implementation in TKA and to prevent bacterial infections.

This study improved recovery from knee misalignment, also addressing the critical social factors that may limit its accessibility and effectiveness in diverse populations.

Table 1 presents a summary overview of each material's features that have been applied through 3D printing over the years, helping to assess its suitability for various patient needs and surgical applications. Moreover, Table 2 presents a comparative analysis of the advantages and disadvantages of intelligent materials used in 3D knee implant materials.

3. Coating materials used in 3D knee implants

The use of coatings in knee implants is a notable innovation intended to improve their functionality and durability. Coatings enhance wear resistance, diminish metal ion release, and facilitate osseointegration, consequently mitigating prevalent issues linked to knee implants. The following sections elucidate the essential elements of coatings in knee implants [46]. Surface coatings enhance radiation resistance, reduce friction, and increase temperature tolerance. Metal components are coated with anti-corrosive substances to avert oxidation and moisture exposure. The antibacterial coating guards against joint infections.

The spraying procedure, vapor deposition procedure, and roll-state-to-roll process of important stages for coating material technique [47]. The buildup on the surface depends on the flexibility of the coating materials and the surface itself. In knee arthroplasty, implant coating is utilized for metal-sensitive individuals [12].

Table 3 presents the most famous coating materials in the 3D knee with current advantages and disadvantages.

Despite significant advancements in materials used for knee implants, each material has some limitations that may be addressed.

4. Mechanical forces in the knee joint and associated boundary conditions

Parasitic forces in the knee show that the exoskeleton and human body are interacting in a way that badly, which could affect comfort and function. Using these forces as a control signal to change the paths of the exoskeleton shows an effort to lessen the damage to the knee joint. Therefore, the authors in [17] developed a knee joint prosthesis including an adjustable rotation center to facilitate biomimetic motion therapy for people with knee joint mobility impairments. A revolute-prismatic-revolute model is designed to emulate the biomimetic movement of the knee joint, subsequently leading to the development of a similar system for the repetitive flexion-extension motion of the knee joint, largely. During the design phase, the equipment's weight was reduced from 1.96 kg to 1.16 kg, achieving the goal of lightweight equipment. A prototype of the proposed orthosis with the desired biomimetic rotating functionality has been created and verified. The findings suggest that the prototype's axis of rotation might behave biomedically like the axis of an active knee joint. This could help with rehabilitation for knee joint flexion-extension movements.

For example, Adouni et al. [48] utilized a hybrid molecular dynamics-finite element-musculoskeletal model to ascertain the load thresholds the knee may endure while descending from various heights from 20 to 60 cm, including the height at which cartilage injury transpires. the obtained data indicated that a rise in landing height corresponded with elevated stresses on the knee joint, especially affecting the vastus muscles and medial gastrocnemius. Mostly, cartilage-cartilage contact conveyed the load, which escalated with landing height. The crucial height of 126 cm, at which cartilage degradation began, was established by extrapolating the gathered data using an iterative method. Damage starts

Table 1. Features of advanced materials for 3D printing in knee implants.

Material	Author	year	Features
Metallic Alloys	Vertullo et al. [28]	2016	Cobalt-chromium alloys have exceptional endurance in knee implants, showing reduced wear rates and advantageous results relative to other materials such as oxonium in complete knee replacements
	Dion et al. [29]	2020	A 3D printed titanium enhancement provides superior early fixation stability in revision TKA compared to conventional techniques, potentially enhancing patient outcomes throughout this treatment.
	Kumar et al. [30]	2022	Co-Cr-Mo-4Ti alloys demonstrate improved durability and suitability for knee implants owing to their homogeneous porosity, elevated strength, ductility, and abrasion resistance, making them preferable to alternative compositions.
Ceramics	Morozova et al. [31]	2020	Zirconia ceramics have enhanced wear resistance and decreased friction, resulting in fewer long-term issues, hence making them preferable for knee implants over conventional materials.
	Ueyama et al. [32]	2023	Alumina ceramic implants exhibited less polyethylene formation wear and enhanced clinical results, resulting in greater mobility for patients and lifespan, with a 10-year survival rate about of 95%
	Mödinger et al. [33]	2023	The AMC ceramic knee implant, constructed from BIOLOX delta, is a metal-free alternative that reduces MRI artifacts and safety risks, proving its appropriateness for 3D knee implant applications.
Highly Cross-Linked Polyethylene (HXLPE)	Kim et al. [34]	2023	The research revealed no occurrences of osteolysis in either the HXLPE or regular polyethylene cohorts, suggesting that HXLPE did not elevate the risk of osteolysis in knee implants.
	Remily et al. [35]	2023	The research revealed that successively irradiation and annealing HXLPE in TKA had superior results in wear characteristics and implant survival over a decade, accompanied by a minimal incidence of problems and revisions.
	Gao et al. [36]	2018	Annealed highly cross-linked HXLPE improves wear resistance in knee implants, decreasing in vivo wear and enhancing durability relative to traditional UHMWPE components.
Bioactive Compounds	Lauck el al. [37]	2024	Bioactive compounds in knee implants facilitate recovery by enhancing autoinduction, osteointegration, vascularization, and especially cartilage repair, and meniscus surgeries.
	Zhou et al. [38]	2024	The integration of bioactive herbal compounds with biomaterials augments regenerative medicine by enhancing scaffold mechanical strength and stability, fostering tissue regeneration via anti-inflammatory, antibacterial, and antioxidative properties, and promoting stem cell differentiation, presenting a promising avenue for future applications.
Nanocomposites	Yildirim et al. [39]	2023	Polymer nanocomposites are becoming more prevalent in knee implants owing to their biodegradability, biocompatibility, and improved healing properties, making them the perfect candidates for regeneration of tissues.
	Kumar et al. [40]	2022	Nanomaterial-reinforced composites augment knee implants by enhancing mechanical characteristics, biocompatibility, and infection resistance, making them viable alternatives to traditional materials in orthopedic applications.
Polyether Ether Ketone (PEEK)	Meng et al. [42]	2018	The radiolucency of PEEK improves postmortem imaging quality, and its physiological compatibility and endurance make it a viable option for knee implants.
	Caraan et al. [43]	2023	PEEK's mechanical characteristics and the biocompatibility render it appropriate for knee implants, improving postoperative imaging owing to its high radioactivity and long-lasting durability.
Hydrogel for Knee Prosthetics	Nepomuceno et al. [44]	2022	Chitosan/vancomycin antibacterial hydrogels are emerging as effective treatments for infection prevention in 3D knee prostheses. These hydrogels use the biocompatibility and antibacterial characteristics of chitosan, in conjunction with the powerful antibiotic vancomycin, to provide an efficient barrier against microbial colonization during and post-surgical treatments.
	Li et al. [45]	2020	The innovative approach of using a responsive hydrogel could pave the way for future advancements in infection prevention strategies. develop and evaluate the intelligent vancomycin release system aimed at preventing surgical site infections (SSIs) in bone tissues. Here are the main methods described.

Table 2. Comparative analysis of advantages and disadvantages of intelligent materials used in 3D knee implant materials.

Material Type	Advantages	Disadvantages
Metallic Alloys	Accurate customization, enhanced osseointegration, superior load distribution, and decreased wear.	Increased expenses and the possibility of enduring fatigue or fracture complications with intricate designs.
Ceramics (Zirconia, Alumina)	Polished surfaces have less friction, enhanced wear resistance, and decreased irritation	The brittle nature of ceramics may result in fractures and exhibit limited flexibility under severe stress conditions.
HXLPE (Highly Cross-Linked Polyethylene)	Reduced wear particle emission, enhanced implant durability, and decreased osteolysis.	Restricted flexibility relative to metals increased production costs.
Bioactive Material	Bioactive elements in 3D-printed knee implants facilitate osteointegration, improving implant stability and durability. They enable enhanced tissue regeneration and reduce the likelihood of implant loosening. Customizable designs provide enhanced fit and weight distribution for each patient. Furthermore, these materials reduce wear, inflammation, and rejection, enhancing therapeutic results.	Bioactive materials may exhibit restricted long-term durability, with some types deteriorating over time when subjected to stress. They often need intricate and expensive production procedures, limiting accessibility. Some bioactive ceramics exhibit brittleness, presenting a fracture risk under high-stress conditions. Furthermore, wear particles and inflammatory reactions may sometimes contribute to implant failure.
Nanocomposites	Superior wear resistance, increased strength, and lightweight characteristics.	Currently under review, elevated production costs.
PEEK (Polyether Ether Ketone)	Improved biocompatibility, radiolucency, robust mechanical qualities, customizable design possibilities.	Inferior strength relative to metals, susceptibility to wear at elevated loads.
Shape Memory Alloys (Nitinol)	Elevated flexibility, capacity to adapt to temperature variations, and resistance.	increased material costs and intricate manufacturing procedures
Hydrogels	Enhanced wear resistance, cartilage-replicating characteristics, and decreased friction in articulations.	Inferior in durability compared to metallic or ceramic implants, now in testing phases.

Table 3. Coating materials used in 3D knee implants.

Coating Material Type	Advantages	Disadvantages
Ta	Protects bacterial components by little ion release.	Elevated expense; restricted accessibility
TiN	It enhances wear resistance, strengthens the surface, is resistant to scratches, and has a relatively small frictional coefficient.	Can be cracked under high stress; limited biocompatibility in some cases
GLC	Enables substantial load-bearing capability	May deteriorate under cyclic loads
TiO_2	Nanotube coatings enhance adhesion with implant surfaces.	May deteriorate under acidic conditions;
DLC	Prevents corrosion caused by carbon molecules.	Costly to manufacture; susceptible to delamination
ZrN	Enhances mechanical and tribological characteristics, superior biocompatibility	Susceptible to brittleness; may deteriorate under extreme circumstances

and propagation mostly occurs in the superficial layers of the tibiofemoral and patellofemoral cartilage.

The proposed hybrid model illustrated important details about the processes that cause cartilage to break down during landing, which could help prevent joint injuries and make training better. The implemented approach incorporates a 3D finite element model of the knee as shown in Fig. 3.

Furthermore, progress in knee joint modeling has used many methodologies, including a FEA and musculoskeletal modeling, to forecast joint forces and replicate the impact of mechanical stress on cartilage and other soft tissues. These models provide the evaluation of how various factors, including muscular activity and gravity loads, influence knee joint strains and the risk of injury.

Recent literature further investigates the influence of mechanical loading on the pathophysiology of knee disorders [49], offering an enhanced understanding of how joint forces impact cartilage degradation, bone remodeling, and synovial inflammation, all of which are essential in the management of knee osteoarthritis.

Also, Jahn et al. [50] analyzed the significant impact of mechanical variables on knee osteoarthritis (KOA), particularly post-traumatic osteoarthritis (PTOA). It underscores the need for balanced mechanical loads for preserving knee joint health and averting joint deterioration. The research investigates the use of mechanical transmission, the mechanism via which cells react to mechanical stimuli, for rehabilitation and therapeutic approaches for osteoarthritis.

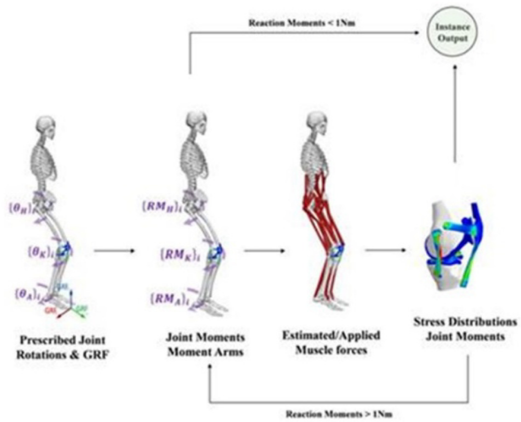

Fig. 3. A workflow for a 3D finite element simulation of the knee seen anteriorly [48].

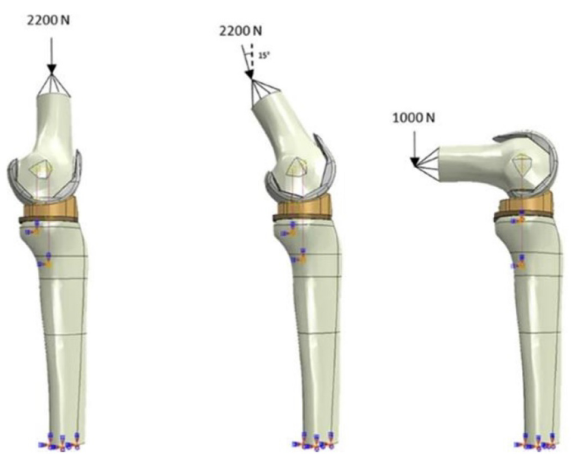

Fig. 4. Forces analysis of the proposed models in the three analyzed configurations.

Castellarin et al. [51] analyzes knee joint forces through finite element modeling for various prosthesis designs. It includes boundary conditions like ligament pre-strain and material properties such as cobalt-chromium for femoral components. The study offers insight into forces during daily activities and their implications for knee arthroplasty.

Different levels of constraint in TKA prostheses, from the least to the most constrained (from left to right), as shown in Fig. 4.

5. Additive manufacturing methods for clean and cost-effective 3D knee implants

The most important factor in prosthetic manufacturing is its implantation into the human body; thus, the purity of the machining procedure is important [52]. One of the manufacturing techniques that has gained prominence in the previous decade is AM technique. The additive manufacturing process fabricates components progressively from various materials, including plastic, concrete, and metal, with the potential for body tissue in the future.

The process involves the heating and extrusion of thermoplastic filament [53]. Various AM techniques exist, contingent upon the materials and stacking processes used according to certain specifications.

Fig. 5 illustrates many AM processes. The authors in [54] conducted an experiment on complete knee balancing by using two mechanical balancers, called a Pistol Grip and In-Line. 3D printing designs were created on the Stratasys F120 with ABS plastic material. In stereolithography, photopolymers are polymerized utilizing a light source that facilitates the bonding of tiny molecules to create a cross-link. The first layer and resin layer adhere to one another, initiating a curing process that results in enhanced layered manufacturing [35].

The authors in [55] aimed to design a cost-effective manufacturing process chain for all ceramic knee implants. The operation of aided manufacturing (CAM) software was verified using CO_2 as the internal coolant and without any lubrication as cutting fluid. The use of CO_2 is an innovative clean performance approach that eliminates oils, as shown by the findings.

6. Finite element analysis and simulation techniques for evaluating knee joint performance

A viable technique is necessary for simulating the real-time functioning of the knee joint under constraints and conditions [56]. FEA performs the multiplication of the contact forces and their distribution

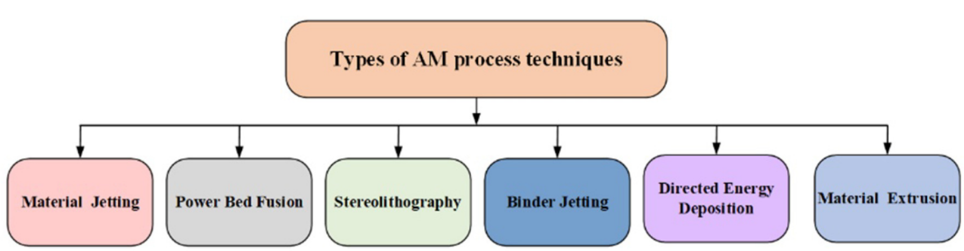

Fig. 5. Types of AM techniques [53].

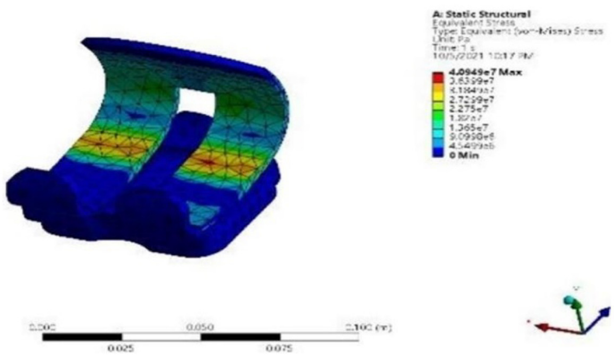

Fig. 6. Von misses stress distribution ANSYS Workbench techniques [25].

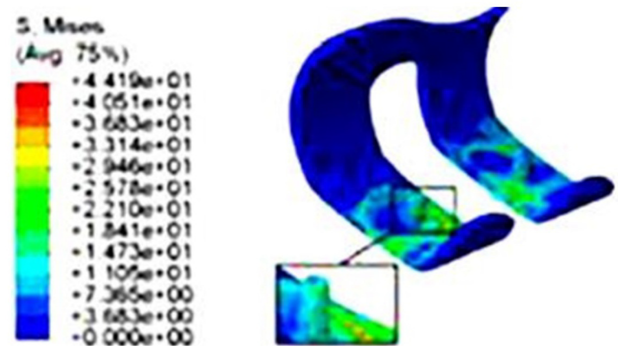

Fig. 7. The distribution of von Mises stress [3].

on the joints of the knee [57], analyzes knee biomechanics affected by ligament degenerative diseases [30], and evaluates the transmission of load on the fixed-bearing tibial module [58].

FEA and simulation are conducted using software such as ABAQUS [59], LS-Dyna [59], ANSYS [23, 60], Comsol, and Mentat [59]. The study [59] delineated three separate stages for FEA simulation. The first step included the virtual implantation of the femoral component, followed by investigational loading of the rebuilt implant in the second phase, and the third phase entailed the removal of knee-implant contact to assess permanent joint deformation. Utilizing the FE software's interference-suitable option, the joint surface nodes that originally penetrated the implant were compelled toward the implant's surface. The stress responses of the femoral component under the effect of triaxial combined forces produce von Mises stress.

Study [25] utilized ANSYS Workbench to analyze geometric models of the tibial and spacer components in the knee joint. Three-dimensional models, measuring 55 mm, were subjected to various load conditions. PEEK material properties were assigned to the femur component, and the models were meshed with a 5 mm mesh size. Fixed support was applied to the spacer component's surface. The analysis revealed a direct correlation between increasing loads and stress levels, with shear stress ranging from (2.4372eˆ62.1934eˆ7 Pa), and Von Mises stress varied from (4.5499eˆ6 4.094eˆ7 Pa) as shown in Fig. 6. Contact stress on the femur component also rose significantly as the load increased.

One study [3] indicates that the loading scenario produces a significant stress of (44.12) MPa on the top region of the posterior femoral component surface near the fixation rod, as shown in Fig. 7. The tibial element had a peak stress intensity of (52.7) MPa. Stresses were identified in a tiny region at the lateral posterior connection of this element with the tibial tray. As a result of the triaxial combined forces, a notable correspondent stress of (15.59) MPa is seen on the spacer at the upper contact zone with the femoral component.

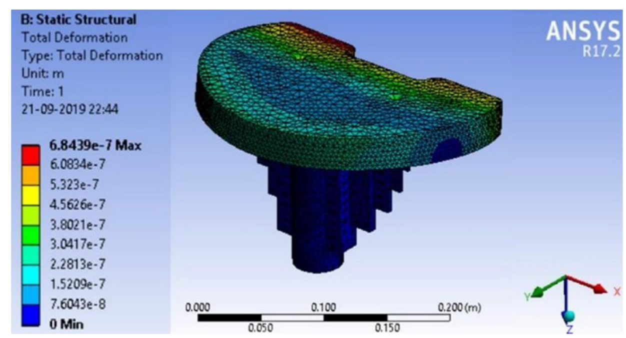

Fig. 8. Total deformation predicted by FEA for the tibial tray composed of Co-Cr-Mo-4Ti alloy [30].

Kumar et al. [30] investigated the development of Co-Cr-Mo alloys with 2%, 4%, and 6% Ti using a μ-plasma-based AM process for knee implants. The study examines microstructure, aspect ratio, mechanical properties, and abrasion resistance, complemented by FEA of a tibial tray made from these alloys. Optimal deposition conditions were achieved at 264 W μ-plasma power, 2.5 g/min powder flow rate, and 50 mm/min head speed, yielding a least aspect ratio of about 1.11. The Co-Cr-Mo-4Ti alloy exhibited a uniform absorbent structure, finer grain size, and enhanced mechanical properties, including higher tensile and compressive strengths, ductility, and abrasion resistance as shown in Fig. 8. These improvements are attributed to the occurrence of lamellar chromium carbides and intermetallic phases. FEA showed that the alloy's Von Mises stress and deformation were higher when it had more Ti in it. This showed that it is a good choice for knee implants because it can handle stress well and doesn't wear down easily.

7. Conclusion and future scope

This article comprehensively provides a comprehensive review of advancements in the many advanced materials used in 3D knee implants, emphasizing the evaluation of smart materials, their comparative advantages and disadvantages, and their role in improving implant performance. It highlights the importance of specialized coatings for metal-sensitive patients and examines mechanical forces and manufacturing innovations that influence implant durability and cost-effectiveness. Furthermore, it explores simulation techniques like FEA are critical in optimizing implant design by ensuring proper stress distribution and minimizing wear under various loading conditions. These advancements collectively contribute to improving knee arthroplasty outcomes by increasing implant longevity and patient safety.

In the future, researchers can focus on adding nanotechnology to smart materials to make them stronger and more biocompatible, look into new coating methods to make them less likely to get infections and create real-time simulation models for custom implant design. Additionally, the development of real-time simulation models tailored for custom implant design can revolutionize patient-specific knee replacements. Additionally, scaling up cost-effective manufacturing techniques and investigating the long-term effects of dynamic loading conditions will be crucial in optimizing knee implant performance and durability. These future directions pave the way for more reliable, long-lasting, and patient-centered knee arthroplasty solutions. Moreover, emerging trends in AI-driven design optimization are transforming implant development by utilizing machine learning algorithms to forecast stress distribution, enhance material selection, and customize implant geometry according to patient anatomy, thereby minimizing complications and improving long-term outcomes. Translating these advancements into clinical practice necessitates overcoming difficulties like regulatory clearances, integration with current surgical processes, and long-term validation via clinical studies.

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Conflict of interest

The authors declare no conflict of interest to any party.

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