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Additive Manufacturing of Knee Joint Implants: Design, Fabrication, and Performance Analysis

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Abstract

These days, the number of knee joint failures is rising daily due to factors like pollution, big accidents, poor diet, which weakens the bone, and lack of rest. One of the main joints in the human body is the knee. Metals are utilised to repair damaged surfaces in knee joint surgery. More than 800,000 knee implants are used worldwide, and now various advanced manufacturing methods are used for its production. One of the most common methods that is used for manufacturing knee implants is metal additive manufacturing. It is critical to understand the manufacturing and analysis of knee implants to improve its design and reduce cost. This literature reviews studies on additive manufacturing and analysis of knee joints. The number of knee replacement procedures is rising daily. As the number of knee replacement procedures rises and engineering technology advances, more models are being created to better suit patient needs. Artificial knee components composed of various materials are used to replace the failed knee joint.

Keywords: knee implants, finite element analysis, stress, additive manufacturing

INTRODUCTION

Artificial components take the substitution of malfunctioning real body parts, such as the knee and hip joints. Rheumatoid arthritis, osteoarthritis, and traumatic arthritis are frequent conditions affecting the knee joint that can cause the joint to fail. The first metal knee implant model for commercial use was created in the 1950s.

In orthopaedic surgery, joint replacement surgery is a difficult process that addresses pathological alterations and degenerations of human joints. It has been successful since the 1950s in restoring motion and reducing discomfort in joints that have been diseased, where traditional physiotherapy and medication have not shown much improvement. It is possible to replace nearly all movable joints with artificial ones. Revision surgery is frequently necessary due to persistent problems such wear and component fractures, recurring joint deformity, implant loosening, and loss of functional mobility. We are still waiting impatiently for the perfect implant system option.

When measured against human bone, the metals have higher Young's modulus and density. Wear and tear on the bones, misalignments in the knee joints, and stress mitigation in the knee joint result from this. Another crucial element is how the knee implant is made. The knee implants are made using industrial techniques including casting, machining, etc. These procedures cost more and take longer. In the world of medicine, quick prototyping innovation is becoming more and more popular as a means of producing biomedical implants quickly. This will cut down on the time, expense, and risk of surgery.

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The efficient fabrication of the anatomical pieces is made possible by the advancement of new technologies in RP. Such models can be created using laser-based techniques such as LENS. Similar capabilities are also being developed for arc-based models. To guarantee appropriate engineering and production, the study provides a review of the literature on knee implant failure modes. The research can also be utilised to create different knee implant-related solutions.

RELATED STUDIES

The goal of Shashishekar et al.'s study was to examine the distribution of pressures in a prosthetic knee joint made of polyethylene. The calculation of finite elements was performed using the Ansys 18.1 programme. The effects of external load, flexion angle, and sagittal radius on knee joint stresses were examined in experimental experiments. Using design modelling software, factors such as flexion angles and sagittal radius were used to generate a 2D model of the prosthetic knee joint [1]. The research conducted by Gibson et al. presented the development of an artificial finger joint [2].

Lee et al examined the femoral component of a knee prosthesis using multi-axis machining, rapid prototyping, and reverse engineering (RE). Each patient's femoral component is made specifically for them based on a prescription. By combining the CT medical pictures with the Mimics programme, a 3D geometric model of the knee joint is produced. First, the important dimensions and positioning analysis required for a total knee replacement are conformed under cases with varied specific knee skeleton characteristic shape and damage condition through the coordination of the specialised doctor's discussion [3].

The study conducted by Sivalingam et al. examined how the forming confines of stainless steel SS316 were affected by process variables such as tool rotation speed, feed rate, and tool path profile [4]. The titanium implant was constructed by the researchers using a three-dimensional printing technology, utilising data from magnetic resonance imaging [5]. Two distinct total knee prosthesis were examined by Ingrassia et al. The primary difference between them was the form of the polyethylene (PE) component that is put between the femoral and tibial plates [6]. Three bone structures—the tibia, femur, and patella—as well as their articular cartilage layers, medial and lateral menisci, and five major ligaments—the collaterals, cruciates, and patellar tendon—make up the Bendjaballah et al. model. The menisci are modelled as a non-homogeneous composite consisting of a solid matrix with collagen fibres extending in both directions [7]. The tribological effects of different materials used in biomedical applications were investigated by Sahoo et al. [8]. In order to improve the prosthetic pylon's longevity and user comfort, Abdalikhwa et al. demonstrated the latest inventions and advances of novel composite materials. Prosthetic pylons are often composed of lightweight metals like aluminium, titanium, stainless steel, or an alloy of these [9]. An experimental and numerical (FEM) investigation on buckling multilayer composite cylinders composed of carbon fibre reinforced plastics (CFRP) was carried out by Priyadarsini et al. [10].

MATERIALS USED IN COMPOSITION

Knee implants, or artificial knee joints, are generally made of the following materials:

- *Metal:* Metal alloys like cobalt-chromium or titanium are frequently used to make the femoral component, which is attached to the thigh bone, and the tibial component, which is joined to the shin bone. These materials are robust and long-lasting, able to bear the pressures applied to the knee during regular exercises.
- *Plastic:* Ultra-high molecular weight polyethylene (UHMWPE) is frequently used as the plastic insert for the tibial component. This plastic creates a smooth gliding surface akin to real cartilage by acting as a cushion between the metal components. In artificial knee joints, ultra-high molecular weight polyethylene (UHMWPE) is essential. It is frequently employed in place of the natural cartilage that covers the ends of bones in a healthy knee joint as the bearing surface in the tibial component of knee implants. The plastic tibial component and the metal femoral component can move smoothly and with little wear thanks to UHMWPE's extremely

low coefficient of friction. UHMWPE has a cushioning function that absorbs impact during exercises like jogging, walking, and jumping.

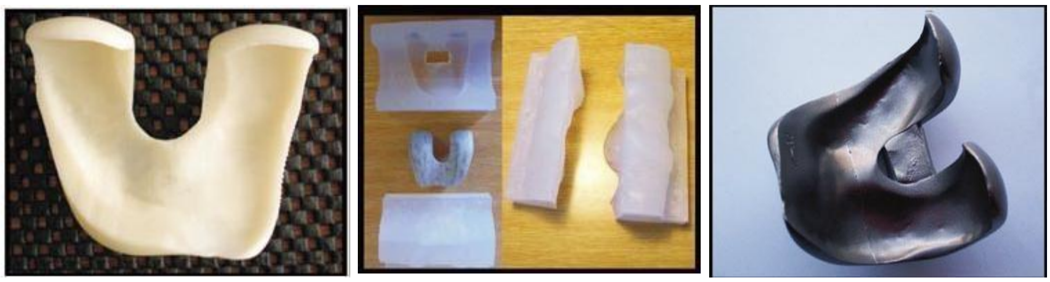
- *Ceramic:* The femoral component of certain knee implants is made of ceramic material, such as zirconia or aluminium oxide. Because ceramic materials can be quite smooth, the plastic insert will not deteriorate as quickly over time.
- *Bone Cement:* Polymethylmethacrylate, or "bone cement," is sometimes used to attach metal parts to the bone. This contributes to the stability and securing of the implant.
- *Parts for Patellofemoral Joint:* An implant may have a patellar component, which is often composed of plastic or a polymer blend, if the patellofemoral joint which connects the thigh bone to the kneecap is impacted. These materials were used because they are strong, biocompatible, and can replicate the functionality of a real knee joint.

DESIGNING OF ARTIFICIAL KNEE JOINT

From initial idea development through final manufacture and clinical evaluation, there are multiple processes involved in designing an artificial knee joint. The following are the main stages in creating an artificial knee joint:

Recognise the patient's needs as well as the clinical requirements for the prosthetic knee joint, considering anatomical features, biomechanics, and disease pathology. Choose a variety of design ideas for the prosthetic knee joint while taking fixation techniques, geometry, and material choices into account. Consider factors including wear resistance, biomechanical performance, manufacturing feasibility, and surgical procedure compatibility while assessing the design concepts. Create comprehensive engineering drawings and specifications, including exact measurements, tolerances, and material requirements, for the selected design concept. Develop prototypes of the artificial knee joint design to evaluate how well it functions in realistic scenarios. This includes mechanical testing to determine the knee joint's strength and longevity. To validate the design, carry out a thorough testing process that includes wear testing, biomechanical testing, and testing for compatibility with biological tissues. Get regulatory approval (e.g., from the US FDA) for the prosthetic knee joint by providing clinical data and testing that demonstrates its efficacy and safety. To construct the artificial knee joint at scale while maintaining uniformity and quality control, manufacturing procedures must be established. Run clinical trials to evaluate how well patients respond to the prosthetic knee joint while collecting information on patient outcomes, safety, and effectiveness. Through post-market surveillance programmes, track the performance of the artificial knee joint on the market and resolve any concerns that may occur.

To make sure that the prosthetic knee joint satisfies the needs of patients and healthcare professionals, engineers, surgeons, materials scientists, and other experts must work together throughout the design process.



a) Femoral model using b) Silicon mould c) Fabricated by casting

Figure 1. Manufacturing process of Femoral component of knee joint [1].

A ripped or damaged knee implant may occasionally need to be replaced. Every knee replacement is not made equally. Every surgeon has various objectives, and every implant is unique. Surgeons' individual tasks often involve pushing implants into different shapes rather than creating new ones.

Selecting the appropriate knee implant is the first step in replacing one. A new implant usually requires multiple operations to create. This page contains information that can assist you in choosing the best implant. A new development in manufacturing, additive manufacturing allows for the creation of intricate shapes and the manipulation of material properties that are not achievable with conventional manufacturing techniques.

Table 1. Metal with characteristics.

Metal	**Characteristics**	**Major parts**
Cobalt-Chromium	High strength, corrosion resistance	Femoral and Tibial Components
Titanium	Lightweight, biocompatible	Femoral and Tibial Components, sometimes Patellar Component
Stainless Steel	Good strength and corrosion resistance	Older Implant Designs
Tantalum	Biocompatible, high corrosion resistance	Tibial Components
Zirconium	Biocompatible, low wear rate	Femoral and Tibial Components

With less distortion, the four materials are more advantageous for hip and knee joints. In terms of deformation values, the Co-Cr-Mo alloy has greater positive impacts on the hip and knee joints, with the maximum deformation being Ti 6Al–4V. For a patient with a hip or knee prosthesis, standing and walking are deemed to be healthy activities; however, jumping and running are not advised because of the high stress and deformation. With the use of CAD software, this method generates 3D physical models from a series of cross sections that are assembled automatically to form the final design. Selective laser sintering (SLS), selective laser melting (SLM), electron beam melting (EBM), and poly-jet photopolymer are AM technologies utilised in the fabrication of knee implants. Biomedical implants made of different metallic alloys (such as Co-Cr, Ti-alloy, and stainless steel) that are biocompatible have been widely employed. Since biocompatible, it is impossible to prevent issues like cytotoxicity, local infection, organ pain, body inflammation, and implant corrosion. For biomedical applications, hydroxyapatite, a common biomaterial, is employed as powders, coatings, and composites. However, there are a few obstacles to using hydroxyapatite covering over implants, including poor adherence, low load-bearing capacity, high dissolution, low wear resistance, and inherent fragility. Therefore, research and development of substitute biomaterials and their coatings for metallic implants—such as dental, orthopaedic, metallic stents, pacemakers, etc.—must be the primary focus. These days, forsterite and its composites are coated on metal implants to increase their biocompatibility and prevent numerous complications.

CONCLUSION

The overview of the literature makes it easier to comprehend how FEM is used in knee implant research and analysis. FEM has been employed by several writers as a tool to comprehend the many types of stress placed on knee implants. Furthermore, several research have shown how additive manufacturing is applied to knee implants. It has also been demonstrated that knee implants can be manufactured using both the metal AM process and the polymer AM approach. Research on clinical tests demonstrated the effectiveness of additive manufacturing as a manufacturing technique.

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