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Recent Developments in the use of Composites for Knee Cap Prosthetics

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Abstract: Common knee injuries are ligament tear, meniscus injuries, knee cap fracture and muscle strains. The prodrome stage includes pain, swelling, and difficulty in walking. Ligament swelling occurs due to the overuse of ligaments in particular exercises (such as running, jumping, or walking). Osteoarthritis is one of the most famous joint inflammations affecting the knee and usually requires treatment. Total knee arthroplasty (total knee arthroplasty) is a safe and inexpensive treatment for patients with end-stage arthralgia, with a survival rate of up to 80%. However, partial knee arthroplasty including kneecap replacement is found to be more effective because it is a less invasive medical procedure that requires reconstruction of the knee, the back and the front of the femur. Advances such as Freeman-Swanson's prosthetic pre-prosthesis (1970) and Kodak-Yamamoto prosthesis (1970) determined future plans, but the original form did not consider the pat bone. In recent years, new manufacturing strategies and new materials have improved the design of kneecap prostheses. Now, it can treat inflammation in both partial and total knee arthroplasty. The use of composite materials for prostheses is increasing at an unprecedented rate. The materials used for such prostheses should not be harmful, chemically and biologically stable, and they should have sufficient mechanical strength to withstand physiological stress. Each type of prosthesis produced is manufactured taking into account the individual needs of each customer. This article summarizes the development of composite materials, design strategies and in-depth research on the development and application of kneecap prostheses.

Keywords: Composites, Kneecap Prosthetics, Arthroplasty

1. Introduction

The knee is a complex joint, and the largest one in the human body. It typically consists of the tibia-femoral and patellar femoral synovial joint[4]. The anatomical diagram of the knee is shown in Figure 1. Its prime function is to control the body's centre of gravity and position in daily activities. This involves the capacity to move freely while still being able to lift hefty things. As a result, the existence of muscles, ligaments, and joint surfaces within these joints creates a conflict between stability and mobility of body parameters.[1–3]. The prostheses are used for degenerative diseases (osteoarthritis[5], severe deformities or severe injuries in the knee joint. All of these diseases cause the patient discomfort, as well as acute aches in the afflicted limb's movement.[6]. Implantation of the prosthesis allows the patient to resume normal daily activities and relieve pain[7].

With the help of special reflex therapy and rehabilitation exercises, mobility can be restored. Placing an implanted knee joint, called a prosthesis, is a crucial part of orthopedic surgery[8].

TKA (total knee arthroplasty) is a safe and affordable therapy for patients suffering from end-stage arthritis, with effectiveness rates as high as 80%. Component architecture, alignment procedures, surgical approaches, and, most specifically, the application of new technology to improve medical outcomes have all progressed significantly since the early 1970s developments.

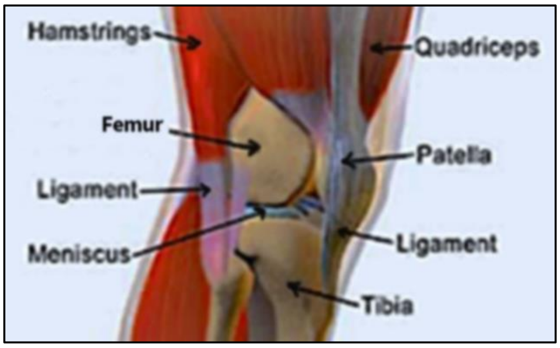

Fig. 1: Anatomical diagram of knee

Despite the fact that the patellofemoral articulation is a significant feature of TKA that has a substantial effect on result and can be a cumulative predictor for the procedure's ultimate performance, the patellofemoral articulation has a history of negligence[9-11].

Kneecap replacement surgery, also known as patellofemoral or patellofemoral arthroplasty, plastic or metal components are used to replace the damaged bone and cartilage. This type of surgery is a partial knee replacement because the surface of the knee repairs only partially. Knee-cap surgery is often necessary in patients with osteoarthritis, the cartilage that protects the knee bones gradually wears out and exposes the bone. Cartilage deficiency causes painful movements[12-13].

1.1 Composites

Composites are traditionally composed of two or more phases. The two components of a composite are the continuous phase and the dispersed phase, differ at the interface. The 'continuous phase' is called a matrix and most often uses a polymer as a component. The 'dispersed phase' can be discontinuous (e.g., plate or filler) or continuous (e.g., fibre) and is usually stiffer than the matrix. Therefore, it improves the mechanical properties (strength and durability) of the matrix, making it a reinforcing component of composite materials [14]. However, some composites have a softer dispersed phase in the matrix, which improves the toughness of the composite (i.e., a rubber reinforced material in a plastic brittle polymer matrix or a metal reinforced material in a ceramic matrix). Interfaces play a crucial role in determining the mechanical properties and environmental resistance of composites [15]. The mechanical properties of composites depend on load transfer at the interface. The extent of bonding between the stiffener and the matrix material depends on the chemical or mechanical interaction between components. Mechanical bonding depends hugely on the shape of the surface and the shape of the stiffener, but chemical bonding is best achieved by surface treatment or coating processes[16]

Table 1. Advantages and disadvantages of composite materials for their use in prosthetics[17]

ADVANTAGES	DISADVANTAGES
Resistance to high temperatures and atmospheric influences.	Composite structure has more complex mechanical characteristics than metal structure.
High chemical stability	The repair process for composite materials is tedious as compared to metals.
High wear resistance due to the long life of the pre-preg matrix	Composite materials do not have the same high strength / tensile strength combination as metals.
Low smoke density, low flammability and low toxicity of decomposition products	High cost of production of composite materials,
Wide choice of sizes and shapes of components.	Composite materials do not necessarily give high performance in all properties used in material selection: corrosion resistance, availability, ductility, compatibility, strength and toughness.

Composites are one of the most important types of mechanical materials today, as they often offer combinations of rigidity, strength, toughness, lightness and corrosion resistance. Another reason is that there is a lot of room to adapt their design to operating conditions. The flexibility in altering their properties is especially beneficial for their use in the biomedical industry[18]. In many cases, sturdy and rigid material, often in elongated form, is embedded in a softer and more compliant constituent forming the Matrix. For example, bones and teeth majorly constitute hard minerals (hydroxyapatite or osteons) in a matrix of solid organic matter known as collagen[19]. There are several different types of composites as shown in figure 2. The matrix material may be polymeric, metallic or ceramic[20-21]. Polymeric composites may further be classified based on reinforcement configuration as laminate, particulates, fibre reinforced, monofilament and short fibres[18, 22,23] .

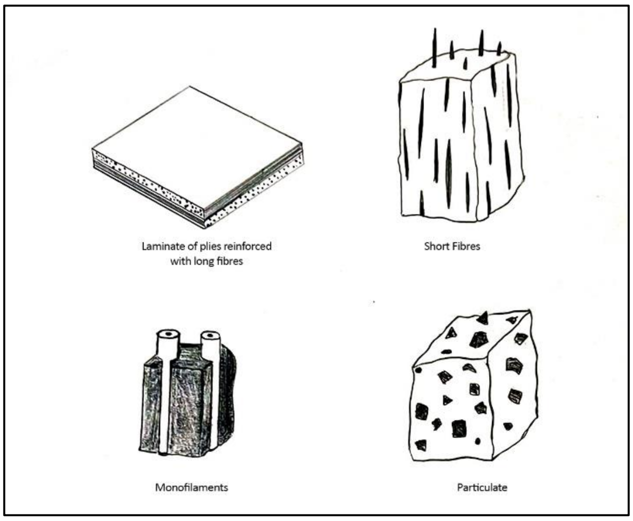

Fig. 2: Types of polymeric composites

1.2 Composites In Prosthetics

Biomaterials are natural or artificially created materials that are used in the human body's clinical device (prosthesis) to substitute disabled organs and bodily functions. Orthopedics and prosthetic surgeons treat people with disabilities use artificial means- prosthesis[24]. The materials used in prosthesis should be biologically and chemically inert and have sufficient strength to withstand the physiological load. The use of prosthetic devices is a strategy for repairing and stabilising knee ligament by avoiding the sacrifice of the tissues and decreases rehabilitation time[25, 26].

Durable temporary or permanent implants must have biocompatibility and mechanical strength. When multiple implants, such as plates and screws, are joined for an inner sheath that self-repairs the bone, corrosion resistance is also important. Implants must be stiff and resistant to deformation in order for bones to endure pressure loads. The tensile properties of the composites are judged by scanning electron microscopy (SEM) micrographs of tensile fracture surfaces[27]. It must also be elastic to absorb the energy of any possible deformation, shortening and expansion in compression. Regardless of its mechanical characteristics, the material must be physiologically inert since it interacts with the human body's fine and solid tissues, blood, and intracellular and extracellular fluids. To last longer, it must have biomechanical similarity, biocompatibility, high resistance to abrasion and osteoclastic fusion[28-29].

These qualities and needs have steadily developed to allow for the development of improved devices that better address the clinical problem of implant failure owing to infection, corrosion, dislocation, and other factors, while limiting toxicity to the host. The second age of biomaterials was driven by the ability to interact with the organic climate, improve tissue stress, and gradually break down as new tissues are rebuilt and repaired. Today we have the third age of biomaterials capable of activating cellular responses at the subatomic level. Despite major advances, a long-lasting craniofacial transplant and prosthesis are needed in this area[30].

1.3 Knee Cap

The patella, or kneecap, is a flat, rounded triangular bone, as shown in Figure 3, that articulates with the femur and covers and protects the anterior articular surface of the knee joint. The prime functional role of the kneecap is knee extension. The kneecap increases the load that the quadriceps tendon can put on the femur and increases the angle at which it acts. The kneecap attaches to the tendons of the quadriceps muscle to straighten or straighten the knee. The kneecap is an important part of TKA and has a big influence on the result since it can anticipate the surgery's overall success. The desirable properties of the materials used to replace the kneecap joint are summarized. Fatigue resistance to Deformation while maintaining high strength, modulus of elasticity, fracture toughness and mechanical reliability; While walking properly, the body burden varies from 3 kN to 8 kN when sprinting or stumbling. For biological stability and in vivo biocompatibility, high corrosion resistance is required. Long-term wear resistance and minimal friction are ensured by high hardness and superior surface condition. For bodily lubrication, good wettability at the contact between the bearing surface and the synovial fluid.[25, 31, 32].

Fig. 3: Human knee cap from front (left) and behind (right)

1.4 Evolution of Kneecap Prosthetic Designs

The anatomical design used for the first reported replacement of kneecap is very consistent and showed the most impressive external contact stress characteristics, but misalignment of femoral or kneecap components lead to instability and increased wear. Shear stress at the prosthetic-bone junction and anterior knee discomfort are other consequences. The anatomical components of the removable abutment designed to adapt to this situation have shown promising results but are already facing complications related to the metal brace and misalignment between the prostheses. The dome-shaped patella Fig. 4A) components can be forgiving in an appropriately shaped femoral component. However, with increasing degrees of flexion in the deepening femoral sulcus, they tend to increase contact stress and consequent wear, and they are harmful to wear because bearings operate best when softer materials are concave rather than convex. In deep bending, a modified dome or Gaussian form (Fig. 4D the offset dome form allows the kneecap components to medialize for better tracking. The dome or a version of the dome is still the most prevalent kneecap shape. The cylindrical design (Fig. 4E) also showed reduced contact stress but raised concerns due to breakage of the large centre bar, over-restraint, and application of inlay techniques[34-37].

1.5 Materials and manufacturing

Each device manufactured is tailor-made and takes into account the individual needs of each customer. There are several steps involved in creating a prosthesis and learning to use it. Some prostheses are powered and require muscle signals from the wearer's body to function, while others do not require energy. Various manufacturing techniques like additive manufacturing[38–40], 3D printing[41], electron beam deposition[42-43] and so on may be used for the production of prostheses.

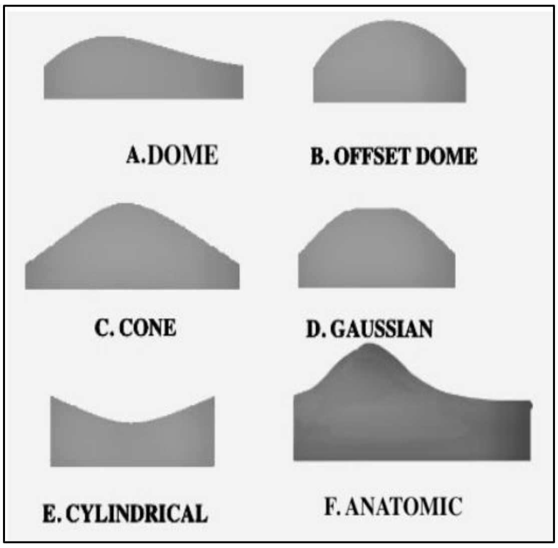

Fig. 4. Evolution of kneecap prosthetic design

Table 2. Technology employed in prosthetics different parts of lower limb

Body part	Product name	Description	Reference
Foot-ankle	Jaipur foot	Rubber/ foam-rubber foot with rubber/ cotton heel	44-45)
	Bicycle seat foot	Bicycle seat adapted to function a foot	
Knee	ICRC knee	Single axis with manual lock	46)
	DAV/ Seattle knee	Compliant polycentric	
	LEGS M1 knee	Four bar- allowing control of knee stability over a limited range of knee flexion and not just at heel contact and push off.	
	LC knee	Single axis with automatic lock	
	Friction knee	Weigh-activated friction	
	C leg	MPK (microprocessor knee technology). Offers several function modes. The new standing mode allows you to lock the leg at any angle between 7 and 70 degrees. With the cordless handheld remote, you may switch between moons	47)
	Rheo	MPK. When charged, MR fluid travels between blades that bind the MR fluid for resistance. The benefit is that, unlike fluids moving through components and cylinders, slow motions in restricted spaces have no minimum resistance.	48)
	Adaptive	MPK. Two stepper motor valves are controlled by the microcontroller. Stance, flexion, and ultimate impact are all controlled by the hydraulic system. The pneumatic element of the system controls the swing phase and extension assistance.	49-50)
	Agility	MPK. Advanced microprocessor programming allows the knee to make near-instantaneous modifications to knee position and velocity, resulting in improved water resistance.	51)

Table 3. Comparison of different types of composite materials used in Kneecap prosthetics

Properties	**Stainless Steel**	**Co-Cr**	**Ti6Al4V**	**UHMWPE**
Young's modulus	205 MPa	220-230 GPa	100-110GPa	130 GPa
Compressive strength	2100 MPa	550-800 MPa	222.6 MPa	26 MPa
Tensile strength	620 MPa	145-270 MPa	862- 1200 MPa	50.4 MPa
shear strength	81 GPa	48.387 MPa	15.841 MPa	20.68 MPa
Specific density	8.06 g/ cm3	10 g/ cm3	4.4-4.5 g/ cm3	0.95 g/ cm3
Fatigue Resistance	260	200 MPa	410 MPa	31 MPa
Fracture toughness	228 MPa √m	100 MPa √m	84-107 MPa √m	2.8 MPa √m
Yield strength	215 MPa	470-1600 MPa	950 MPa	12 MPa
Biocompatibility	Overtime ions diffuse and accumulate over tissue, used for temporary implants only.	Requires plasma spraying or electron beam deposition	Yes	Yes

1.6 Stainless steel

Stainless steel's (SS) capacity to resist corrosion in the human body for an extended period of time is restricted[52]. Hence SS screws and plates are used for temporary implants.

Applications:- Guidewires and sensor wires use type 304 and 316 austenitic stainless steels in cardiovascular applications, for instrument applications traditional stainless steels are most commonly used etc.[54-55].

1.7 Co-Cr alloys

This material is strong, rigid, wear-resistant and biocompatible. Besides titanium, cobalt chromium alloys are one of the most commonly used materials in knee prostheses. There are very few patients who have allergies associated with the use of cobalt-chromium alloy. One of the drawback of metal ions is that they diffuse in the body due to joint movements[56-58].

2. Fabrication process of Co-Cr prosthesis: electron beam deposition

An electron gun creates and focusses an electron beam and electromagnetically scanned in layers of powder that are gravity fed from a cassette and mechanically cut into layers approximately 75 to 100 micrometres thick. The thickness in the case of the Co-based alloy powder is 40 µm in diameter. It melts certain parts of the layer, adds it to the next layer and finally creates a three-dimensional (layered) structure as the building components lower with each additional layer. Before melting, the light beam is scanned several times (about 11 times) through a computer-aided design (CAD) program on the newly cut layer to preheat it. For an electron beam current of ~30 mA, the preheat scan rate is ~104 mm/s, while at a reduced beam current of 6-10 mA, the preheat scan rate is ~400 mm/s[59].

Applications:- Removable partial denture manufacturing using Selective Laser Melting (SLM), Cobalt-chromium alloys are often used as bearing surfaces in orthopedic implants.

2.1 Ti6Al4V

It has a decent strength-weight proportion, good strength-density proportion, excellent resistance to corrosion and is lightweight. Hence, the skeletal load on the patient is generally equally appropriated between the bone and the implant, which empowers a more characteristic walk. A layer of titanium fibres is attached to the implant surface that permits the bone tissue and implant to bond better for more grounded securing. Ti6Al4V is most commonly used in knee implants. Titanium composites are profoundly consumption safe, making them a dormant biomaterial, have a lower density than different metals utilized in knee prostheses, which implies more noteworthy corrosion resistance[60]. Thus, the titanium implant acts more like a characteristic joint, lessening the danger of specific difficulties like bone resorption and decay. Cement is utilized as a transitional layer to improve the pressure appropriation in steel and Co-based implants however it isn't required when Ti composites are utilized[61-63].

2.2 Kneecap fabrication using Ti6Al4V

After marking 8.5 mm extrusion[66], it is inclined 30 ° to the base. 5 mm connecting spokes are used. The above doesn’t lead to the fixate holes of the kneecap component of the prosthesis. Their diameter of the spokes is 5 mm with 4 mm depth.

The first step in metal casting process is the "reverse" shape of the part we need. The metal is heated in a furnace and then poured into the mould cavity. The liquid fills the cavity and takes the shape of the part. In stir casting, a mechanical stirrer is connected to a variable speed motor to control the speed of the stirrer. There are different levels of the paddle mixer: single-stage, two-stage and multi-stage. Mixing plays a critical role in the final microstructure and mechanical properties of cast composites as it controls the distribution of reinforcement in the matrix. Optimal mechanical properties can be achieved by evenly distributing the reinforcement in stir-casting. The agitation speed should be maintained at 500-700 rpm for 10-15 minutes. Casting can construct complex geometry with cavities and hollow profiles[64, 65].

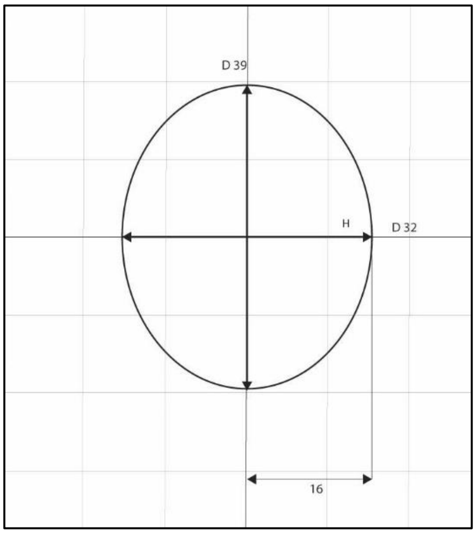

Fig. 5. Sketch for modelling the Patella

Application:- aerospace industry (airframe and engine parts) and biomechanics (implants and prostheses).

2.3 Ultra High Molecular Weight Polyethylene (UHMWPE)

The components of the tibia and knee caps are made of polyethylene. The standard polyethylene surface has low wear on the knee implant, as the bearing surface is flatter and does not cause wear. The use of ultra-high molecular weight polyethylene (UHMWPE) minimizes wear and significantly prolongs knee replacement. UHMWPE offers high durability, strength and biocompatibility. It is often used in stents as a support material with a ceramic or metal-coated surface. However, UHMWPE implants have a limited lifespan due to wear and tear complications.

2.4 Kneecap made of UHMWPE

A "Shaft" operation applied to the model, achieving a revolution up to 180 °. In the next phase, the posterior part of the prosthetic component undergoes 'grinding' and a thickness of 7 mm with a radius of 7 mm is achieved. In the final step, the prosthetic kneecap's feet made for the fixation of the kneecap have a diameter of 5 mm and a height of 4 mm. Finally, the rotating joint – kneecap's prosthetic components obtained assembles[8)]

Application:- UHMWPE used in the production of hydraulic seals and bearings. It is best suited for medium mechanical stresses in water, hydraulics, pneumatics and dry systems, UHMWPE film as coated stents in cardiovascular applications. Low profile combined with mechanical strength and controlled pore size etc.

2.5 Carbon Fibre

The properties of carbon fibres, like high rigidity, low weight, high chemical resistance, high-temperature resistance and low thermal expansion, high specific strength and specific modulus. Materials with high responsive elastic deformation are typically not pliable: the particular modulus of wood is equivalent to that of steel, magnesium, titanium, or aluminium, though that of carbon fibre built up composites is around multiple times as high[67)]. It was resolved that the material was fragile and brittle, which was a reason for serious concern. Carbon fibre can likewise be expensive contrasted with different materials with comparable properties[68-71)].

3 Fabrication technique- 3D Printing

Material requirements for 3D printing a carbon fiber composite part are that the material must match the area of bone it is replacing. The carbon fiber composite material must mimic the properties of the replaced bone, in every direction as bone is anisotropic, as closely as possible in order for that part to retain its original function. FEA analysis reveals the weakest areas of bone and bone implants. This analysis is crucial to set parameters for printed bone implants, as it shows the exact areas that need strengthening[67)].

Application:- In specialized high-performance products such as aeroplanes, racing cars, and sports equipment. It is often used in imaging equipment to support limbs that have had an x-ray or radiation treatment[72)].

3.1 MWCNT/UHMWPE composite

As the first sliding part of artificial joints to have both high wear resistance and high impact resistance, the MWCNT/UHMWPE composite is a novel biomaterial that is believed to be safe for clinical use in both total hip and total knee arthroplasty.

3.2 Fabrication technique- Thermal compression using multiwall carbon nanotubes (MWCNTs)

The UHMWPE is first mixed with MWCNTs, and the mixture is heated in a biaxial extruder while fermenting. The mixture is thermally compressed and then divided into tiny bits. These procedures generate a wide range of MWCNT/UHMWPE composites with various loading formulations and biaxial extruder heating levels. Scanning electron microscopy of MWCNT/UHMWPE composites revealed a honeycomb structure made of MWCNT layers encircling a block of UHMWPE. In interaction with MWCNTs, UHMWPE heated up and disintegrated[73–77).]

Applications:- novel stress sensor that can be embedded into the tibial knee bearing, electrically conducting nanocomposite and orthopedic applications.

4. Conclusion

It was found that when one of the three compartments in the knee is affected by joint discomfort and the other two are healthy, partial knee arthroplasty is explored.

The downside of partial knee replacement surgery is that it does not last as long as whole knee replacement surgery. Prosthetics show promising outcomes in relieving the patient from the torment caused by degenerative diseases (osteoarthritis), extreme deformation or severe injury to the knee joint; Metals and their composites like Ti6Al4V have great strength, high fatigue strength and high malleability. Ultra-High Molecular Weight Polyethylene (UHMWPE) is a generally utilized polymer composite in biomechanics because of its high chemical resistance, biocompatibility, mechanical and tribological properties. Hip and shoulder arthroplasty, knee substitution and intervertebral disc replacement use UHMWPE for the prosthesis.

5. Future scope

So far, due to extensive research, we can provide theoretical answers to the required properties of the biomaterials as the end product greatly depend on the process factors which greatly influence various properties like-macro-porosity, grain size, surface roughness, et cetera determine the mechanical and biological properties of that material. These factors are often overlooked in literature, so standardization and careful review of the interactions between bone and prosthetic surface, the biotic environment at the atomic level and various subtle movements of the implant in the main body. Extensive research is required to understand several aspects, such as the surface wear of equipment, the biological response to wear and corrosion residues and biocompatibility to develop prostheses that can last longer in the human body.

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