CHAPTER 2

LITERATURE SURVEY

Prosthetic knee joint has been a topic of great interest in the past. Over time, various researchers have worked on the prosthetic knee joint trying to address the issues like geometric modeling, stress analysis between the articular surfaces, reliability and fatigue life, wear, dynamic analysis etc. A large amount of literature is available on this regard.

2.1 Joint

A joint is the location at which two or more bones make contact. There are 360 joints in the human body. They are constructed to allow movement (except for skull bones) and provide mechanical support. Fig 2.1 shows the Joints in human body which are mainly classified structurally and functionally. Structural classification is determined by how the bones connect to each other, while functional classification is determined by the degree of movement between the articulating bones. In practice, there is significant overlap between the two types of classifications.

2.1.1 Structural classification (Binding tissue)

According to the type of binding tissue that connects the bones to each other, there are three types of joints [Whiting et al., 2006].

- Fibrous joint
- Cartilaginous joint
- Synovial joint
2.1.2 Functional classification (movement)

According to the type and degree of movement they allow, there are three types of joints.

- Synarthrosis
- Amphiarthrosis
- Diarthrosis

Fig 2.1 Joints in the human body (www.arthroscopy.com)
2.2 Anatomy of knee joint

Knee joint is a synovial, diarthrosis complex joint. The knee is essentially made up of four bones. The **femur**, which is the large bone in your thigh, attaches by ligaments and a capsule to **tibia**. Just below and next to the tibia is the **fibula**, which runs parallel to the tibia. The **patella** or what we call the knee cap, rides on the knee joint as the knee bends.

When the knee moves, it does not just bend and straighten, or, as it is medically termed, flex and extend. There is also a slight rotational component in this motion. The knee muscles which go across the knee joint are the quadriceps and the hamstrings. The quadriceps muscles are on the front of the knee, and the hamstrings are on the back of the knee. The ligaments are equally important in the knee joint because they hold the joint together. In review, the bones support the knee and provide the rigid structure of the joint, the muscles move the joint, and the ligaments stabilize the joint. The knee joint also has a structure made of cartilage, which is called the meniscus or meniscal cartilage. The meniscus is a C-shaped piece of tissue which fits into the joint between the tibia and the femur. It helps to protect the joint and allows the bones to slide freely on each other. There is also a bursa around the knee joint. A bursa is a little fluid sac that helps the muscles and tendons slide freely as the knee moves. There are two cruciate ligaments located in the center of the knee joint. The anterior cruciate ligament (ACL) and the posterior cruciate ligament (PCL) are the major stabilizing ligaments of the knee.

Fig. 2.2 shows the anterior view of the right knee joint. Fig 2.3 shows the posterior view of the right joint. Fig 2.4 shows the interior ligaments of the right knee joint. Fig 2.5 shows the menisci and the attached ligaments and Fig 2.6 shows the sagittal section of right knee joint [http://education.yahoo.com].
Fig 2.2 Right knee Joint, Anterior view

Fig 2.3 Right knee Joint, Posterior view
Fig 2.4 Right knee Joint, showing interior ligaments

Fig 2.5 Head of right tibia, showing menisci and attachments of ligaments
2.3 Joint disorders

A joint disorder is termed an arthropathy and when involving inflammation of one or more joints the disorder is called arthritis. Most joint disorders involve arthritis.

2.3.1 Arthritis

Arthritis is the leading cause of disability in people over the age of 55. There are many different forms of arthritis, each of which has a different cause. The most common form of arthritis, osteoarthritis (also known as degenerative joint disease) occurs following trauma to the joint, following an infection of the joint or simply as a result of aging. The major complaint by individuals who have arthritis is joint pain. Pain is often a constant and may be localized to the joint affected. The pain from arthritis is due to inflammation that occurs around the joint, damage to the joint from disease, daily wear and tear of joint, muscle strains caused by forceful movements against stiff painful joints and fatigue [Wollenhaupt.j. et al., 1988].
2.3.2 Classification

There are several types of arthritis in which joint pain is considered as the main feature. Arthritis diseases include:

- Osteoarthritis
- Rheumatoid arthritis
- Gout and pseudo-gout
- Septic arthritis
- Ankylosing spondylitis
- Juvenile idiopathic arthritis
- Still’s disease

2.3.2.1 Osteoarthritis

Osteoarthritis is the most common form of arthritis. It can affect both the larger and the smaller joints of the body, including the hands, feet, back, hip, and knee. The disease is essentially one acquired from daily wear and tear of the joint; however, osteoarthritis can also occur as a result of injury. Osteoarthritis begins in the cartilage and eventually causes the two opposing bones to erode into each other. Initially, the condition starts with minor pain during activities, but soon the pain can be continuous and even occur while in a state of rest. The pain can be debilitating and prevent one from doing some activities. Osteoarthritis typically affects the weight-bearing joints, such as the back, spine, and pelvis. Unlike rheumatoid arthritis, osteoarthritis is most commonly a disease of the elderly. More than 30 percent of females have some degree of osteoarthritis by age 65. Risk factors for osteoarthritis include prior joint trauma, obesity, and a sedentary lifestyle.

Osteoarthritis, like rheumatoid arthritis, cannot be cured, but one can prevent the condition from worsening. Physical therapy to strengthen muscles and joints is very helpful. Pain medications are widely required by individuals with osteoarthritis. For some patients, weight loss can reduce the stress on the joints. When the disease is far advanced and the pain is continuous, surgery may be an option. Unlike rheumatoid arthritis, joint replacement does help many individuals with osteoarthritis [Witter J et al., 2004].
2.3.2.2 Diagnosis

Diagnosis is made by clinical examination from an appropriate health professional, and may be supported by other tests such as radiology and blood tests, depending on the type of suspected arthritis. Pain patterns may differ depending on the arthritides and the location. Rheumatoid arthritis is generally worse in the morning and associated with stiffness; in the early stages, patients often have no symptoms after a morning shower. Osteoarthritis, on the other hand, tends to be worse after exercise. In the aged and children.

Elements of the history of the disorder guide diagnosis. Important features are speed and time of onset, pattern of joint involvement, symmetry of symptoms, early morning stiffness, tenderness, gelling or locking with inactivity, aggravating and relieving factors, and other systemic symptoms. Physical examination may confirm the diagnosis, or may indicate systemic disease. Radiographs are often used to follow progression.

2.3.2.3 Treatment

There is no cure for either rheumatoid or osteoarthritis. Treatment options vary depending on the type of arthritis and include physical therapy, lifestyle changes (including exercise and weight control), and medications. Joint replacement surgery may be required in eroding forms of arthritis. Medications can help reduce inflammation in the joint which decreases pain. Moreover, by decreasing inflammation, the joint damage may be slowed [Ettinger Jr et al., 1997].

2.4 Prosthetic knee joint

Prosthesis or prosthetic is an artificial device extension that replaces a missing body part. There are four main types of prosthesis.

- Transtibial prosthesis
- Transfemoral prosthesis
- Transradial prosthesis
- Transhumeral prosthesis

Transtibial prosthesis is an artificial limb that replaces a leg missing below the knee. Transfemoral prosthesis is an artificial limb that replaces a leg missing above the knee. Transradial prosthesis is an artificial limb that replaces an arm missing below the
elbow. Transhumeral prosthesis is an artificial limb that replaces an arm missing above the elbow [http://www.uh.edu/engines/epi1705.htm].

Femur, tibia and patella are the three components (prostheses) of prosthetic knee joint used for knee arthroplasty during the knee joint replacement.

2.4.1 Knee joint replacement

Knee replacement or knee arthroplasty, is a surgical procedure to replace the weight-bearing surfaces of the knee joint to relieve pain and disability. It is most commonly performed for osteoarthritis [Simon H Palmer 2012]. Knee replacement surgery can be performed as a partial or a total knee replacement. In general, the surgery consists of replacing the diseased or damaged joint surfaces of the knee with metal and plastic components shaped to allow continued motion of the knee.

During knee joint replacement surgery, damaged cartilage and bone are removed from the knee joint. Man-made prostheses are then placed in the knee. These pieces may be placed in up to three surfaces in the knee joint:

- Lower end of the thigh bone. This bone is called the femur.
- Upper end of the shin bone—the large bone in your lower leg. This bone is called the tibia.
- Back side of patella (kneecap).

Usually femur and tibia are the two prosthetic components, which are used to replace the affected knee. Fig 2.7 shows the knee prostheses. The upper part is the femur and the lower part is the tibia. Fig 2.8 shows the femorotibial joint in which the femur component (metal surface) is fixed to femur bone and tibia insert (plastic surface) is fixed to tibia bone. The femur is made of metal or alloy and tibia is made of plastic. These materials are called biomaterials which have to be biocompatible.
2.5 Biomaterials

Biomaterial is defined as “a nonviable material used in medical device, intended to interact with biological systems” (Black 1992). Also, it is defined as “a synthetic material used to make devices to replace part of living system or to function in intimate contact with living tissue. According to these definitions a biomaterial is used to make devices to replace a part or a function of the body in a safe, reliable, economic, and physiologically acceptable manner (Hench and Erthridge, 1982). The classification of biomaterials may be
considered as metals, alloys, polymers, ceramics and composites. The performance of biomaterials in the body depends on the material properties, design and biocompatibility of the material used.

Biocompatibility involves the acceptance of an artificial implant by the surrounding tissues and by the body as a whole. The characteristics which are important in the function of an implant include adequate mechanical properties, appropriate optical properties, appropriate density, appropriate design and manufacturability. The failure modes depend on the type of implant, its location and function in the body.

2.5.1 Metals

Metals are used as biomaterials due to their excellent mechanical properties electrical and thermal conductivity. Since some electrons are independent in metals, they can quickly transfer an electric charge and thermal energy. The mobile free electrons act as the binding force to hold the positive metal ions together. This attraction is strong, as evidenced by the closely packed atomic arrangement resulting in high specific-gravity and high melting points of most metals. Since the metallic bond is essentially nondirectional, the position of the metal ions can be altered without destroying the crystal structure resulting in a plastically deformable solid. Some metals are used as passive substitutes for hard tissue replacement such as total hip and knee joints.

2.5.1.1 Stainless steel

The first stainless steel utilized for implant fabrication was the 18-8 (type 302 in modern classification), which is stronger and more resistant to corrosion than the vanadium steel. Vanadium steel is no longer used in implants since its corrosion resistance is inadequate. Later 18-8sMo stainless steel was introduced which contains a small percentage of molybdenum to improve the corrosion resistance in chloride solution (salt water). This alloy became known as type 316 stainless steel. In the 1950s the carbon content of 316 stainless steel was reduced from 0.08 to a maximum amount of 0.03% for better corrosion resistance to chloride solution and to minimize the sensitization, and hence became known as type 316L stainless steel.
The austenitic stainless steels, especially types 316 and 316L are most widely used for implant fabrication. These cannot be hardened by heat treatment but can be hardened by cold-working. This group of stainless steels is nonmagnetic and possesses better corrosion resistance than any others. The American Society for Testing and Materials (ASTM) recommends type 316L rather than 316 for implant fabrication. The specifications for 316L stainless steel are given in Table 2.1.

Table 2.1 Composition of 316L Stainless Steel (ASTM, 1992)

<table>
<thead>
<tr>
<th>Element</th>
<th>Composition (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon</td>
<td>0.03 max</td>
</tr>
<tr>
<td>Manganese</td>
<td>2.00 max</td>
</tr>
<tr>
<td>Phosphorus</td>
<td>0.03 max</td>
</tr>
<tr>
<td>Sulfur</td>
<td>0.03 max</td>
</tr>
<tr>
<td>Silicon</td>
<td>0.75 max</td>
</tr>
<tr>
<td>Chromium</td>
<td>17.00-20.00</td>
</tr>
<tr>
<td>Nickel</td>
<td>12.00-14.00</td>
</tr>
<tr>
<td>Molybdenum</td>
<td>2.00-4.00</td>
</tr>
</tbody>
</table>

2.5.2 Alloys

The first metal alloy developed specifically for human use was the "vanadium steel" which was used to manufacture bone fracture plates (Sherman plates) and screws. Most metals such as iron (Fe), chromium (Cr), cobalt (Co), nickel (Ni), titanium (Ti), tantalum (Ta), niobium (Nb), molybdenum (Mo), and tungsten (W) that were used to make alloys for manufacturing implants can only be tolerated by the body in minute amounts. Sometimes those metallic elements, in naturally occurring forms, are essential in red blood cell functions (Fe) or synthesis of a vitamin B_{12} (Co), but cannot be tolerated in large amounts in the body [Black, 1992]. The biocompatibility of the metallic implant is of considerable concern because these implants can corrode in an in vivo environment.
2.5.2.1 Cobalt-Chromium Alloys

The castable CoCrMo alloy has been used for many decades in dentistry and, relatively recently, in making artificial joints. The wrought CoNiCrMo alloy is relatively new, now used for making the stems of prostheses for heavily loaded joints such as the knee and hip.

The modulus of elasticity for the CoCr alloys does not change with the changes in their ultimate tensile strength. This may have some implications of different load transfer modes to the bone in artificial joint replacements, although the effect of the increased modulus on the fixation and longevity of implants is not clear. Low wear has been recognized as an advantage of metal-on-metal hip articulations because of its hardness and toughness [Schmalzried et al., 1996].

2.5.2.2 Titanium Alloys

Attempts to use titanium for implant fabrication dates to the late 1930s. Titanium's lightness (4.5 g/cm³) and good mechanochemical properties are salient features for implant application. There are four grades of unalloyed commercially pure titanium for surgical implant applications. According to ASTM, they are referred as grade 1, grade 2, grade 3 and grade 4. The impurity contents separate them; oxygen, iron, and nitrogen should be controlled carefully. Oxygen in particular has a great influence on the ductility and strength. Titanium alloy (Ti6Al4V) is widely used to manufacture implants and its chemical requirements are given in table 2.2.

**Table 2.2 Composition of Titanium Alloy (Ti6Al4V) (ASTM, 1992)**

(Aluminum 6.0%, Vanadium 4.0% and other elements 0.4% total)

<table>
<thead>
<tr>
<th>Element</th>
<th>Composition (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nitrogen</td>
<td>0.05</td>
</tr>
<tr>
<td>Carbon</td>
<td>0.08</td>
</tr>
<tr>
<td>Hydrogen</td>
<td>0.0125</td>
</tr>
<tr>
<td>Iron</td>
<td>0.25</td>
</tr>
<tr>
<td>Oxygen</td>
<td>0.13</td>
</tr>
<tr>
<td>Titanium</td>
<td>Balance</td>
</tr>
</tbody>
</table>
2.5.3 Polymers

Symmetric polymeric materials have been widely used in medical disposable supplies, prosthetic materials, dental materials, implants, dressings, like those of metal and ceramics substituent’s [Lee, 1989]. The main advantages of the polymeric biomaterials compared to metal or ceramic materials are ease of manufacturability to produce various shapes (latex, film, sheet, fibers, etc), ease of secondary processability, reasonable cost, and availability with desired mechanical and physical properties. The required properties of polymeric biomaterials are similar to other biomaterials, that is, biocompatibility, sterilizability, adequate mechanical and physical properties, and manufacturability.

2.5.3.1 Polymers Used as Biomaterials

Although hundreds of polymers are easily synthesized and could be used as biomaterials only 10 to 20 polymers are mainly used in medical device fabrications from disposable to long-term implants. The most commonly used polymers are polyvinylchloride (PVC), polyethylene (PE), polypropylene (PP), polymethylmetacrylate (PMMA), polystyrene (PS) and its Co-Polymers, polyesters, polyamides (Nylons), fluorocarbon polymers. Polyethylene is preferred for the fabrication of orthopedic implant.

Polyethylene is available commercially in five major grades high density (HDPE), low density (LDPE), linear low density (LLDPE), very low density (VLDPE) and ultra high molecular weight (UHMWPE). UHMWPE (MW > 2 x 10^6 g/ mol) has been used for orthopedic implant fabrications, especially for load bearing applications such as an acetabular cup of total hip and the tibial plateau and patellar surfaces of knee joints.

2.5.4 Ceramics

Ceramics are defined as the art and science of making and using solid articles that have as their essential component inorganic nonmetallic materials [Kingery et al., 1976]. Ceramics are refractory, polycrystalline compounds, usually inorganic, including silicates, metallic oxides, carbides and various refractory hybides, sulfides, and selenides. Oxides such as Al₂O₃, MgO, SiO₂, and ZrO₂ contain metallic and nonmetallic elements and ionic salts, such as NaCl, CsCl, and ZnS [Park and Lakes, 1992].
Ceramics in the form of pottery have been used by humans for thousands of years. Until recently, their use was somewhat limited because of their inherent brittleness, susceptibility to notches or micro cracks, low tensile strength, and low impact strength. However, within the last 100 years, innovative techniques for fabricating ceramics have led to their use as "high tech" materials. In recent years, humans have realized that ceramics and their composites can also be used to augment or replace various parts of the body, particularly bone. Thus, the ceramics used for the latter purposes are classified as bioceramics.

Their relative inertness to the body fluids, high compressive strength, and aesthetically pleasing appearance led to the use of ceramics in dentistry as dental crowns. Some carbons have found use as implants especially for blood interfacing applications such as heart valves. Due to their high specific strength as fibers and their biocompatibility, ceramics are also being used as reinforcing components of composite implant materials and for tensile loading applications such as artificial tendons and ligaments [Park and Lakes, 1992].

2.5.4.1 Alumina (Al₂O₃)

The main source of high purity alumina (aluminum oxide, Al₂O₃) is bauxite and native corundum. The commonly available alumina can be prepared by calcining alumina trihydrate. The chemical composition and density of commercially available pure calcined alumina are given in Table 2.3. The American society for testing and Materials (ASTM) specifies that alumina for implant use should contain 99.5 % pure alumina and less than 0.1 % combined SiO₂ and alkali oxides (mostly Na₂O).

<table>
<thead>
<tr>
<th>Table 2.3 Chemical Composition of Alumina</th>
</tr>
</thead>
<tbody>
<tr>
<td>[Park and Lakes, 1992]</td>
</tr>
<tr>
<td><strong>Element</strong></td>
</tr>
<tr>
<td>Al₂O₃</td>
</tr>
<tr>
<td>SiO₂</td>
</tr>
<tr>
<td>Fe₂O₃</td>
</tr>
<tr>
<td>Na₂O</td>
</tr>
</tbody>
</table>
2.5.5 Composites

Composite materials are defined as material systems consisting of mixture of or combination of two or more micro constituents insoluble in each other and differing in form and or material composition [Murthy et al., 2003]. Composites can also be defined as a material consisting of two or more suitably arranged phases with a separating interface between them [Agarwal & Sun 2004].

Composites are generally prepared by adding dissimilar materials together to work as a single mechanical unit and properties of such materials are different in scale and kind from those of any of its constituent. These materials may have a hard phase in soft matrix and vice-versa. In most cases, a hard phase is embedded in a soft matrix and it increases the modulus or strength of the matrix [Prasad 1991].

Composites can offer a combination of properties and a diversity of applications unobtainable with metals, ceramics, or polymers alone. Some of the properties that can be improved by forming a composite material are [Engg Mat hand book 1987]

- Strength
- Stiffness
- Corrosion and Wear resistance
- Weight reduction
- Fatigue life
- Temperature dependent behavior
- Thermal properties
- Electrical properties
- Acoustical insulation

2.5.5.1 Constituents of Composites

A matrix binder and reinforcing filler constitute the principal components of a composite material.

2.5.5.2 Matrix

Matrix is the material which binds the filler and holds it. Any solid can be processed so as to embed and adherently grip a reinforcing phase in a potential matrix material.
Essentially, a matrix material must be chemically compatible with reinforcement and with any interface between it and the reinforcement. Matrix generally is metals, ceramics and polymers. The matrix in the composite performs the following major roles:

- Acts as a medium by which externally applied stress is transmitted and distributed to the reinforcements and only a small portion of load is sustained by the matrix phase.
- Transfers the stress from individual reinforcement from surface damages as a result of abrasion or chemical reaction with the environment.
- It provides finish, color, texture, durability and other functional properties.

2.5.5.3 Metal Matrix

Metals are strong and tough. They can be plastically deformed and strengthened by a variety of metals mostly by obstructing the movement of linear defects called dislocations. Metal matrix may be aluminium and its alloys, copper and its alloys, titanium alloys, magnesium alloys and nickel based super alloys. They are suitable for high temperature applications (300 to 500°C) [Gayson & Martin 1983].

2.5.5.4 Ceramic Matrix

Ceramics are defined as products made from inorganic nonmetallic matrix processed at high temperature at some time during their manufacture. The ceramic is used as matrix material owing to their high refractoriness, good chemical resistance, high hardness and non-conducting properties. Some of the ceramics used are aluminium oxide, aluminium nitride, silicon carbide, silicon nitride, titanium carbide and titanium nitride etc. [Agarwal and Sun 2004]

2.5.5.5 Polymer Matrix

Polymers are much more complex than metals or ceramics. They are cheap and easily processable. The equipment required for production of polymer composites is simple. They have lower strength and modulus, hence polymers have been widely accepted as a matrix and the reinforced polymers have qualified for structural applications. Because of predominantly covalent bonding, polymers are generally poor conductors of heat and electricity. They are more resistant to chemicals than metals. Structurally, they are giant
chain like molecules with covalently bonded carbon atom forming the backbone of the chain [Wheeltun John et al., 1987].

2.5.5.6 Reinforcements

Reinforcement material is the one, which gives strength to the two phase material. It improves and imparts stiffness. It prolongs the life of a composite by improvement of mechanical and physical properties such as thermal and electrical conductivity. Based on aspect ratio (length to thickness) reinforcements are classified as,

- Fibers
- Whiskers
- Platelets and flakes
- Particulate

2.5.5.7 Fibers

Fibers are materials that have very long axis having more strength in their longitudinal direction. These are available in many diameters and lengths including continuous, which can be used as it is, or chopped to the desired length. These can be polycrystalline or amorphous and forms the principal constituents in a fiber-reinforced composite with polymer or ceramic or metal matrices. They occupy the largest volume fraction in a composite and share the major portion of the load acting. Because of their extremely large aspect ratio they are effective and influence the following properties of a composite.

- Specific gravity.
- Tensile strength and modulus.
- Compressive strength and modulus.
- Fatigue strength and fatigue failure mechanism.
- Electrical & thermal conductivity.
- Cost.

Some of the important fibers are glass, carbon, Kevlar, boron, SiC and Al₂O₃.

2.5.5.8 Whiskers

Whiskers are very thin acicular (needle) single crystals with a diameter in the range of 0.01 – 1.0µm and an aspect ratio of usually over 10. They have a very large surface to
volume ratio and a noncircular cross-section (like triangular, hexagonal, and rhombohedral). Their diameter is defined as the square root of the cross-sectional surface area. Because of their large aspect ratio they are efficient. The shape of the whiskers affects the total whisker matrix interfacial area. The interface in turn has a strong influence on physical and mechanical properties of the composites. The low density of defects in whiskers is due to the single crystalline form and low dimensions which imparts them the strength.

Whiskers are incorporated in metals primarily for stiffness, creep and wear resistance. Whiskers enhance fracture toughness, wear & creep resistance when it is reinforced with ceramic matrix. Whiskers are used in polymer composites to improve thermal and electrical properties. Some important whiskers are asbestos, carbon, silicon carbide, silicon nitride, alumina, mullite, titanium, titanium carbide, titanium nitride, aluminium borate, calcium carbonate, SiO₂, niobium carbide, aluminium nitride, tin oxide, cadmium oxide.

2.5.5.9 Flakes and platelets

Platelets and flakes have an aspect ratio in the range of 30-120. Width usually ranges from 20 to 500µm. These reinforcements are attractive with ceramic matrix materials. Because of its smooth surfaces, flake and platelets filled composites exhibits less anisotropic microstructure and lower tendency of wrapping. Mica, SiC, boron carbide, aluminium, copper are some of the important platelets.

2.5.5.10 Particulates

Particulates can be considered as small microscopic material in the form of a powder. They have low aspect ratio. The dimensions of a particulate reinforcement are approximately equal in all directions. The shape of the particle may be spherical, cubic, plate like or irregular or regular geometry. The efficiency of the particulate reinforcement depends on the factors like size, geometry, distribution and volume fraction. The particulates are selected according to the type of adhesion with the matrix phase and they are of two forms. i) Non-metallic ii) Metallic.
2.5.5.11 Classification of Composites

Composites are classified as two phase system. Based on the types of reinforcement; they are classified as continuous and discontinuous composites. Based on the matrix materials used, they are classified as:

- Organic matrix composites
- Polymer matrix composites
- Carbon matrix composites
- Metal matrix composites
- Ceramic matrix composites

The matrix is continuous and surrounds the other phase which is often called dispersed phase or dispersoid. The properties of the composites depend mainly on the amount, geometry and properties of the dispersed phase. The geometry of the dispersed phase includes its particle size, aspect ratio, size and distribution orientation. They can be classified according to size and shape of the dispersed phase as, Microscopic and Macroscopic.

2.5.5.12 Microscopic

a) Dispersion strengthened
b) Particle reinforced
c) Fiber reinforced

2.5.5.13 Macroscopic

a) Fibers  
i) Continuous
   ii) Discontinuous
b) Whisker
c) Concrete
d) Laminates

2.5.5.14 Dispersion–Strengthened Composites

It consists of a matrix phase in which very fine inter-metallic precipitates are distributed whose diameter ranges between 0.01 to 0.1mm. These precipitates are uniformly dispersed usually in volume concentration up to 15%. Metals or metal alloys may be strengthened by uniform dispersion of several volume percent of fine particles of inter-metallic precipitates which are very hard. The dispersed phase may be metallic or non
metallic. The mechanism of strengthening is similar to that of precipitation hardening. The matrix bears a major portion of load, while the small dispersed particles obstruct the motion of dislocation. Hence, plastic deformation is restricted resulting in improvement of higher tensile strength as well as hardness.

2.5.5.15 Particle Reinforced Composites

It consists of particles of one or more materials suspended or dispersed in a matrix of another material. Particles of size 1µm or more in diameter up to 71µm is used up to a volume percentage of 25 to 50 or more. The reinforced particle affects the properties of matrix material generally by increasing its tensile modulus and the tensile strength. However there is reduction in creep strength and impact resistance. The improvement in mechanical behaviour of composites depends to a larger extent on the interfacial bond between the reinforcing particle and the matrix. Stronger the bond, superior will be the mechanical properties [Rohatgi 1996].

In addition the size, shape and extent of uniformity in distribution of the dispersoid particles also play a prominent role in improving the mechanical properties. Mechanical properties are enhanced with increased volume fraction, even distribution and with reduced size of dispersed phase. For particle reinforced composites (discontinuous reinforcement), the dispersoid may be either metallic or non-metallic as can be the matrix. Common combinations of these are:

- Non-metallic in Non-metallic composite. Ex:-Graphite in epoxy polymers [Rohatgi 1996].
- Metallic in non metallic composites. Ex:-Fine aluminium metal in polyethylene.
- Metallic in metallic composites. Ex:-Lead particles in copper alloys to improve tribological properties.
- Non metallic particles especially ceramics are dispersed in a metallic matrix and the resulting composite is known as cermet. The ceramic used have high strength, high values of tensile modulus and high hardness but they are brittle in nature. Various ceramic particles such as quartz, alumina, zircon, mullite, SiC, flyash have been tried out in different metal matrices.
2.5.5.16 Fiber Reinforced Composites

Fiber will be in the dispersed phase with its length many times larger than their diameter in a continuous matrix phase. The fiber may be continuous or discontinuous. The main characteristics of these composites are that their strength to weight ratio is very high. Investigators have reported the friction and wear behaviour of discontinuous carbon short fiber reinforced in al-alloys [Liu et al., 2008]. Further, hybrid composites reinforced with 12vol% Al$_2$O$_3$ and 8vol% Carbon fibers in Al-Si alloy possesses high wear resistance.

2.5.5.17 Polymer matrix composites

Polymers are much more complex than metals or ceramics. They are cheap and easily processable. The equipment required for production of polymer composites is simple. They have lower strength and modulus, hence polymers have been widely accepted as a matrix and the reinforced polymers have qualified for structural applications. Because of predominantly covalent bonding, polymers are generally poor conductors of heat and electricity. They are more resistant to chemicals than metals. Structurally, they are giant chain like molecules with covalently bonded carbon atom forming the backbone of the chain [Wheelton John et al., 1987].

Fibers incorporated in a polymer metrics increase the stiffness, strength fatigue and other properties. Fibers are mechanically more effective in achieving a stiff and strong composite than particles [Schwartz, 1992]. If stiffness and strength are needed in all directions, the fibers may be oriented randomly. To reduce the wear of ultra-high-molecular-weight-polyethylene used in total knee replacements and to increase the life of the implant, carbon fibers may be incorporated in the ultra-high-molecular-weight-polyethylene [Scilppa et al., 1973].

2.6 Geometric modeling of prosthetic knee joint

Geometric modeling in CAD applications has evolved through a series of phases in order to improve the geometric representation of physical artifacts. Wireframe and surface models are not able to fully define real objects, and have been replaced by more sophisticated solid-based systems for engineering design, however, they are still widely used for documentation. Solid models provide a complete mathematical description of the mass and boundary of an object, and are useful in providing a complete, unambiguous
representation of the geometry of any physical object. Thus, solid models are useful for visualization and analysis in engineering design for a multitude of applications.

Basically there are three types of geometric modeling, which are in practice since 1960’s.

- Wireframe modeling
- Surface modeling
- Solid modeling

2.6.1 Wireframe modeling

Early CAD systems developed in the late 1960's were little more than electronic drafting devices, using the computer monitor or pen plotter as the output device. Draftsmen and designers used these systems to produce orthographic, axonometric and pictorial drawings using conventional techniques of projection theory and descriptive geometry. Objects were represented as 2-D wireframe models consisting of a collection of lines, arcs, circles and splines, with additional design information such as dimensions and text notes included in the database. These systems provided a marked improvement in productivity due to the ease of editing the drawings, however, they did not alter the basic methods used to represent the geometry of the object. Three-dimensional wireframe modeling was introduced in the 1970s (Chasen, 1996). The object is still represented using wireframe entities such as lines and arcs. The limitation is that they cannot provide an unambiguous representation of the solid object.

2.6.2 Surface Modeling

Due to the limitations of wireframe modeling, CAD systems were developed further to include not only the edges but the bounding surfaces of the object. Surface entities such as planar, cylindrical, conical and spherical faces can be represented using analytical equations (Zied, 1991). In addition, more complex surfaces are defined using blends such as ruled surfaces, B-spline surfaces, Bezier surfaces, linear and rotational sweeps. These shapes can be used to define more complex geometries such as those found in forged and molded parts, sculptured surfaces and transitions. Unlike wireframe models, surface models provide a more complete description of the object. A surface model can be used to generate images with hidden line removal, to generate tool paths, and to perform mass properties analysis.
2.6.3 Solid Modeling

Solid modeling was introduced in the 1980's, and was touted as the ultimate tool for design engineers. Solid models include not only the edges and surfaces of the object, but also the volume enclosed by those surfaces.

The major advantage of solid modeling is that the spatial integrity of the solid model can be verified computationally (Orr, 1996). Solid modeling systems allow the designer to construct virtual or "software" prototypes for visualization and analysis. Two basic techniques are used to represent solids in the computer database, Constructive Solid Geometry (CSG) and Boundary Representation (B-Rep). Constructive Solid Geometry (CSG) methods are based on the use of solid primitives as building blocks from which the model is constructed. Typical solids included in commercial modelers may include rectangular prism, cylinder, cone, sphere, torus, wedge and frustum. A solid model is constructed by combining these primitives using the Boolean operators of union, intersection and difference. The model can be represented in the CAD database using a binary tree structure wherein each primitive occupies a leaf or terminal node of the tree, and the internal nodes or branches represent the Boolean operators used to combine the primitives (Mortenson, 1985). CSG modelers provide a compact database and are simple and intuitive to use, however, due to the limited number of primitives in the modeling system, CSG models are unable to represent objects with complex sculptured surfaces. Therefore, alternative methods are used in conjunction with CSG systems. Boundary Representation (B-Rep) methods are used to define the bounding surfaces of a solid object. Common techniques include extrusion, revolving, sweeping and blending of 2-D profile curves. Closed composite curves are created to represent the edges of a surface or profile of the object. These curves are then swept through space along a linear path, revolved around an axis, or mathematically blended with other profiles to define the volume of the solid. Boundary representation methods can be used to define more complex solids, which can then be used in hybrid B-Rep/CSG modelers. Feature-based modeling systems were developed to enhance the productivity of designers using solid modeling systems. A feature-based modeling system has the ability to group solid entities into form features such as pockets, ribs, bosses, flanges, slots, and various types of holes. Thus, the designer is not required to specify each of the individual primitives or profiles needed to create the
complex solid geometry, and some economy can be achieved due to common or shared parameters for entities within the same feature.

Design is an iterative process, and thus, geometries of parts are subject to many changes during the lifecycle of the product. The designer needs a tool that will not only allow him or her to create geometric models, but also to alter the designs easily. To address this need, dimension-driven modeling systems were developed. In these systems, the geometry is defined using variables or parameters to specify the dimensions of the entities. Mathematical and topological relationships between the entities are used to control the dimensions and geometric integrity of the model. These modelers are commonly referred to as constraint based systems (Hanratty, 1995).

The size of the knee joint varies from person to person depending on the head of the femur bone. To customize the prosthetic knee joint for a person, three dimensional morphometry of femoral condyles is done using an optical device. It is reported that the results of this study is useful in the formulation of the finite element models of the knee joint for static analysis [Nuno N et al., 2003]. Also, the solid model can be generated using the medical images of a particular knee joint. Investigators have reported 3D digitization of knee joint is possible by using MRI and CT data. Further, it is concluded that at any position of the knee 3D digitization from MRI data is accurate than other methods [McPherson A et al., 2005]. In computer aided design process, the physical aspects of the geometric model can be verified with a prototype model produced by a latest technique called rapid prototyping. Fig 2.9 shows the impact of geometric model in CAD process [www.imperial.ac.uk/geometricmodelling].
2.7 Rapid prototyping

Rapid Prototyping (RP) refers to the layer-by-layer fabrication of three-dimensional physical models directly from a computer-aided design (CAD). This additive manufacturing process provides designers and engineers the capability to literally print out their ideas in three dimensions. The Rapid Prototyping processes provide a fast and inexpensive alternative for producing prototypes and functional models as compared to the conventional routes for part production [Kochan, D., 1995].

The advantage of building a part in layers is that it allows you to build complex shapes that would be virtually impossible to machine, in addition to the more simple designs. Rapid Prototyping can build intricate internal structures, parts inside of parts, and very thin-wall features just as easily as building a simple cube. All of the Rapid Prototyping processes construct objects by producing very thin cross sections of the part, one on top of the other, until the solid physical part is completed. The roles that prototypes play in the product development process are several. They include the following:

- Experimentation and learning
- Testing and proofing
- Communication and interaction
- Synthesis and integration
- Scheduling and markers
2.7.1 Classification of Rapid Prototyping

One of the better ways is to classify Rapid Prototyping systems broadly by the initial form of its material, i.e. the material that the prototype or part is built with. In this manner, all Rapid Prototyping systems can be easily categorized into

- Liquid-based
- Solid-based
- Powder-based

Liquid-based Rapid Prototyping systems have the initial form of its material in liquid state. Through a process commonly known as curing, the liquid is converted into the solid state. Solid-based Rapid Prototyping systems are meant to encompass all forms of material in the solid state. In this context, the solid form can include the shape in the form of a wire, a roll, laminates and pellets. Powder is by-and-large in the solid state. However, it is intentionally created as a category outside the solid-based Rapid Prototyping systems to mean powder in grain-like form.

2.8 Finite Element Analysis of prosthetic knee joint

Finite Element Analysis (FEA) was first developed in 1943 by R. Courant, who utilized the Ritz method of numerical analysis and minimization of variational calculus to obtain approximate solutions to vibration systems. Shortly thereafter, a paper published in 1956 by M. J. Turner, R. W. Clough, H. C. Martin, and L. J. Topp established a broader definition of numerical analysis. The paper centered on the "stiffness and deflection of complex structures". By the early 70's, FEA was limited to expensive mainframe computers generally owned by the aeronautics, automotive, defense, and nuclear industries. Since the rapid decline in the cost of computers and the phenomenal increase in computing power, FEA has been developed to an incredible precision. Present day supercomputers are now able to produce accurate results for all kinds of parameters.

Finite element analysis consists of a computer model of a material or design that is stressed and analyzed for specific results. It is used in new product design, and existing product refinement. A company is able to verify a proposed design will be able to perform to the client's specifications prior to manufacturing or construction. Modifying an existing product or structure is utilized to qualify the product or structure for a new service
condition. In case of structural failure, FEA may be used to help determine the design modifications to meet the new condition. The user can insert numerous algorithms (functions) which may make the system behave linearly or non-linearly. Linear systems are far less complex and generally do not take into account plastic deformation. Non-linear systems do account for plastic deformation, and many also are capable of testing a material all the way to fracture.

Finite element analysis uses a complex system of points called nodes which makes a grid called a mesh. This mesh is programmed to contain the material and structural properties which define how the structure will react to certain loading conditions. Nodes are assigned at a certain density throughout the material depending on the anticipated stress levels of a particular area. Regions which will receive large amounts of stress usually have a higher node density than those which experience little or no stress.

To confirm the functional aspects of the prosthetic knee joint after the implantation, thorough analysis is required regarding the issues like stresses involved, dynamic behavior and prediction of wear. Inevitably, Finite element analysis has been used as a numerical solution technique to solve biomedical and other various engineering problems.

2.8.1 Stress analysis

To understand the behavior of the prosthetic knee joint both, non contact and contact analysis have been investigated by researchers. Convergence of finite element solution was studied to determine the affect of bone deformations on contact behavior. It is concluded that between the range 5mm to 1mm element size, the solution is converged for an average element size of 2mm. Also, by treating the bones as rigid, accurate solutions of femerotibial contact behavior are obtained [Tammy L. et al., 2002]. Different sagittal profiles of articular surfaces of femoral condyles were measured using laser range finder and average sagittal profile is used for femerotibial contact analysis [Nuno N. et al., 2001]. The predicted stresses are dependent on the mesh density [Godest A.C. et al., 2002].

The rigid body analysis reproduce the kinematics, contact pressure distribution and contact area of a deformable system [Jason P. Halloran et al., 2005]. A photoelastic study of contact stress on the tibial insert of non restricted geometry, bi-surface and complete
flexion knee prostheses is done and it is reported by implanting complete flexion knee, the patient can make a complete knee flexion as much as 180 degrees [Ansaurullah LAWI et al., 2008].

2.8.2 Dynamic Analysis

Three-dimensional dynamic response of the human knee joint is studied and is reported most isolated posterior cruciate ligament injuries and combined injuries to the posterior cruciate and the medial collateral result from a posterior impact on a flexed knee [Eihab Muhammed Abdel-Rahman et al., 1998]. Multibody dynamic musculoskeletal models are capable of predicting muscle forces and joint contact pressures simultaneously [Yanhong Bei et al., 2004]. A two-dimensional dynamic model of the human knee joint by employing cartilage model is used to prove the effect of cartilage on ligaments’ responses is insignificant except for the behavior of the anterior portion of the anterior cruciate ligament at large flexion angles [Haluk Kucuk, 2006]. Anterior cruciate ligament force is small in late stance because the anterior shear forces supplied by the patellar tendon, gastrocnemius, and tibiofemoral contact were nearly balanced by the posterior component of the ground reaction [Kevin B. Shelburne et al., 2004]. Dynamic knee simulators attempt to reproduce the estimated forces, moments, and motions of both the patello-femoral and tibio-femoral joints during a squat [Trent M. Guess et al., 2005].

2.9 Thermal Analysis

Polymers used as biomaterial for tibia component undergo a substantial change in their properties as a function of temperature. Friction generates surface heat during articulation of total knee systems which results in damage to and failure of ultrahigh molecular weight polyethylene (UHMWPE) tibial inserts. Investigation on clinically retrieved components was done to prove that severity of the subsurface damage increased with the length of time that the component had been implanted. The performance of artificial joint prostheses should minimize the thermal effects at the subsurface of the articular components [Young TH et al., 1999].
2.10 Finite Element Analysis Software

A general purpose FEA program consists of three modules a pre-processor, a solver, and a post-processor. Commercial FEA programs can handle very large number of nodes and nodal degrees of freedom provided a powerful hardware is made available. User’s manual, theoretical manual, and verification problems manual, document a commercial FEA program.

Surveys of general-purpose programs for finite element analysis have been published. At present FEA programs are used rather than written, Understanding of the organization, capabilities, and limitations of commercial FEA programs is generally more important than an ability to develop or even modify a FEA code. The four components shown in Fig. 2.10 are common to virtually all general purpose FEA programs. The INPUT phase enables the user to provide information relating to geometric representation, finite element discretization, support conditions, applied loads and material properties. The more sophisticated commercial FEM systems facilitate automated generation of nodes and elements and provide access to a material property database, Plotting of the finite element model is also possible so that the errors if any, in the input phase may be detected and corrected prior to performing computations.

Fig.2.10 Components of a general purpose finite element analysis program
The finite element library comprises the element matrix generation modules. Herein resides the coded formulative process for the individual finite elements. Ideally, the element library is open-ended and capable of accommodating new elements to any degree of complexity. This phase generates the required element matrices and vectors. The assembly module includes all matrix operations necessary to position the element matrices for connection to neighbouring elements and the connection process itself. The latter operation thereby produces the global matrix equation of the finite element model.

The solution phase operates on the governing matrix equation of the problem derived in the previous phase. In the case of a linear static analysis, this may mean no more than the solution of a set of linear algebraic equations for a known right-hand side. In the case of linear vibration and buckling analysis, this may mean the extraction of eigen values and eigen vectors, Transient response analysis will require computations over a time history of applied load.

Finally, the results phase provides the analyst with a record of the solution. The record is commonly a printed list of nodal degrees of freedom, element strains and stresses, reaction forces corresponding to constrained degrees of freedom and a host of other requested information. As in input phase, there is a trend toward graphical output of results such as plots of displacement and stress contours, modes of vibration and buckling, etc. A commercial FEM system therefore consists of three basic modules: preprocessor; solver; and post-processor. The preprocessor allows the user to create geometry or input CAD geometry, and provides the tools for meshing the geometry. The solver takes the finite element model provided by the pre-processor and computes the required response. The postprocessor takes the data from the solver and presents it in a form that the user can understand. The functions of these modules are,

a) Pre-processor
   - Read control parameters
   - Read/Generate nodal coordinates and boundary conditions
   - Read /Generate element connectivity and elements loads
   - Read material properties or constitutive matrices
   - Read nodal nodes and loading conditions
b) Solver
- Computer parameters for memory/file management
- Computer element matrices and vectors
- Form global matrices
- Solution of governing matrix and equations

c) Post-processor
- Print/plot deformed mesh over undeformed mesh
- Print/Plot contours of displacements
- Compute element strains, stresses, etc.
- Print/Plot contours of stresses
- Display locations of max/min. stress
- Print/Plot contours of failure index

### 2.10.1 Finite Element Analysis Software Capabilities

The desirable features of a general-purpose FEA program are a large number of material models; a good library of finite elements; a good number of analysis procedures; and ability to manage the associated data.

a) Material models

To cover a large number of metallic and nonmetallic materials and a wide range of their behaviour, a general purpose FEA program should provide a library of material models. Like,

- Homogeneous, isotropic, linear, elastic
- Orthotropic
- Anisotropic
- Laminated composite
- Nonlinear elastic
- Elastic plastic
- Viscoelastic
- Viscoplastic
- Hyperelastic
- Temperature-dependent material properties
b) Element library

The available elements are for solid, structural, thermal and fluid flow analysis. They can be classified as follows:

- One-dimensional elements
- Two-dimensional elements
- Axisymmetric ring elements
- Three-dimensional elements
- Beam elements
- Plate elements
- Shell elements
- Special elements

Some of these elements are formulated to handle large displacements, large rotations and finite strains. Some formulations use reduced integration with hourglass control.

c) Procedures library

The different types of analysis are done to get the solution for a problem.

- Linear static analysis
- Linear dynamic analysis
- Linear buckling analysis
- Non linear analysis
- Aero-elastic analysis
- Design optimization (sensitivity analysis)
- Thermal analysis: computational
- Fluid dynamics: computational
- Fracture mechanics: computational
- Electromagnetics
- Electrostatics
- Magnetostatics

This allows the user to perform a wide variety of analyses. These procedures provide solutions for linear or nonlinear behaviour under static or dynamic loads. Large
deformation and finite strain problems, contact problems, can also be addressed using these procedures.

d) Data processing ability

- Super elements
- Automated multilevel sub structuring
- Fourier analysis: axisymmetric bodies/shells under non-axisymmetric loads
- Cyclic symmetry
- Efficient numerical methods
- Efficient computer systems
- Automatic adaptive mesh refinement

2.10.2 Types of finite element analysis software’s

The knowledge and current capabilities of widely distributed commercial FEA programs is required by the user. Some of the popular FEA software’s preferred are,

2.10.2.1 MSC.Nastran

NASA Structural Analysis (Nastran) is a general-purpose program based on the finite element method developed by MacNeal Seewdler Corporation (MSC). The associated pre and post-processor is called MSC.Patran, This premier FEA software is now available on the PC and runs both on DOS and Windows operating systems. MSC.Patran provides the industry’s most comprehensive and powerful tools for the creation of accurate finite element models. Backed by the world’s largest CAE support organization and enhanced by continual use at some of the largest manufacturers MSC.Patran sets the standard for finite element pre- and post-processing.

MSC.Nastran is the world standard in element analysis solutions. Its analysis capabilities give the user the competitive edge. With open choice of platforms front desktop PCs to super computers; MSC.Nastran is available where it is needed. MSC.Nastran’s unique element technologies provide highly accurate results with lower modelling effort, less solution time, and reduced computer requirements, Using MSC.Nastran one can optimize designs without increasing design cycle time. MSC provides the best documentation, customer supports, and user training.
2.10.2.2 NISA

Numerically Integrated Finite Elements for systems Analysis (NISA) is a family of general-purpose finite element programs for PCs, workstations and supercomputers developed by Engineering Mechanics Research Corporation (EMRC). The associated pre- and post-processor is called DISPLAY. The distinguishing features of the NISA programs are: user-friendly documentation; excellent technical support; flexible purchase options; and best price/performance in the industry. NISA offers independent modules for a variety of analysis: linear statics; nonlinear statics; dynamics; heat transfer; composites; optimization: fatigue and fracture; fluid dynamics; printed circuit boards; electromagnetic fields; kinematic and dynamic analysis of mechanical systems.

NISA provides an excellent library of isoparametric finite elements, a special module NISA.P ADAPT utilizes P elements. This program continually increases the order of the polynomial on a fixed finite element mesh until a reasonable convergence is reached. P refinement and properly designed mesh is efficient and reliable.

2.10.2.3 LS-DYNA

LS-DYNA is a general-purpose code based on the FEM for analyzing large/elastic/inelastic deformation dynamic response of solids and structures including structures coupled to fluids. The main solution procedure is based on explicit time integration. An implicit solver is also available with somewhat limited capabilities for structural and heat transfer analysis. A contact impact algorithm allows difficult contact problems to be easily treated with heat transfer included across the contact interfaces. Spatial discretization is achieved by the use of four-node tetrahedral, eight-node hexahedral solid elements; two-node beam elements; three-node triangular and four-node quadrilateral shell elements; eight-noded solid shell elements; truss elements; membrane elements; discrete elements; and rigid bodies A variety of formulations are available for each element type (solid, fluid, structural, discrete). Specialized capabilities for modelling airbags, sensors, and seat belts have tailored LS-DYNA for applications in the automotive industry.

Adaptive meshing is available for shell elements and is widely used in sheet metal stamping simulations. LS-DYNA currently has over two hundred material models and over
ten equations of state to cover a wide range of material behavior. The associated pre- and post-processor is called LS-TAURUS. LS-DYNA and LS-TAURUS are developed by Livermore Software Technology Corporation.

2.10.2.4 ANSYS

ANSYS is an integrated design analysis tool based on the FEM developed by ANSYS, Inc. It has its own tightly integrated pre- and post-processor. The ANSYS product documentation is excellent and it includes commands reference; operations guide; modeling and meshing guide: basic analysis procedures guide: advanced analysis guide; element reference; theory reference: structural analysis guide; thermal analysis guide; electromagnetic fields analysis guide; fluid dynamics guide; and coupled field analysis guide. Taken together, these manuals provide descriptions of the procedures, commands, elements, and theoretical details needed to use the ANSYS program. All of the above manuals except the ANSYS theory reference are available online through the ANSYS help system, which can be accessed either as a standalone system or from within the ANSYS program.

Engineering capabilities of ANSYS products are: structural analysis (linear stress, nonlinear stress, dynamic, buckling); thermal analysis (steady state, transient, conduction, convention, radiation, and phase change); CFD analysis (steady state, transient, incompressible, compressible, laminar, turbulent); electromagnetic fields analysis (magnetostatics, electrostatics); field and coupled field analysis (acoustics, fluid—structural, fluid—thermal, magnetic—fluid, magnetic—structural, magnetic—thermal, Piezoelectric, thermal—electric, thermal—structural, electric—magnetic); sub-modelling; optimization; and parametric design language.

Element library in ANSYS lists 185 finite elements, they are broadly grouped into: LINK, PLANE, BEAM, SOLID, CONTACT, COMBIN, PIPE, MASS, SHELL, FLUID, SOURCE, MATRIX, HYPER, VISCO, INFIN, INTER, SURF, etc. Under each type, different shapes and orders complete the list. Obviously, ANSYS has the best elements in its library. Analysis procedures in ANSYS can be grouped into: static analysis; transient analysis; mode frequency analysis; harmonic response analysis; buckling analysis; sub-structuring analysis, and spectrum analysis.
In ANSYS, there are two fundamentally different types of optimization. The first is referred to as design optimization; it works entirely with the ANSYS parametric design language and is contained within its own module (ANSYS /OPT). The second is topology optimization, a form of shape optimization.

ANSYS finite element analysis software enables engineers to perform the following tasks:

- Build computer models or transfer CAD models of structures, products, components, or systems.
- Apply operating loads or other design performance conditions.
- Study physical response, such as stress levels, temperature distributions or electromagnetic fields.
- Optimize a design early in the product development process to reduce production costs.
- Do prototype testing in environments where it otherwise would be undesirable or impossible.

2.10.2.5 RADIOSS

RADIOSS belongs to the family of hydro-codes, in which the material is considered as a non viscous fluid. These hydro-codes find their origin in the work supported by the American Department of Energy at the end of the 70's and which lead to software like DYNA2D/3D, HEMP, PRONTO, STEALTH, HONDO and WHAM. This software is a leading structural analysis solver for highly non-linear problems under dynamic loadings. It is highly differentiated for Scalability, Quality and Robustness, and consists of features for multiphysics simulation and advanced materials such as composites. RADIOSS is used across all industry worldwide to improve the crashworthiness, safety, and manufacturability of structural designs.

For over 20 years, RADIOSS has established itself as a leader and an industry standard for automotive crash thermal analysis and impact analysis. Automotive and aerospace companies value the contribution it makes in understanding and predicting design behavior in complex environments such as automotive crash simulation. In recent years thru the addition of implicit finite element solver capabilities RADIOSS has become a viable option for various engineering problems. The main features of RADIOSS are 3D
Lagrangian formulation for mesh description, small time steps, simplicity, non-iterative approaches and highly vectorized implementation.

### 2.10.2.6 HyperMesh

HyperMesh provides a robust, common FEA modeling framework by minimizing modeling tool investments and training costs. With automatic and semi-automatic shell, tetra, and hexahedron meshing capabilities, HyperMesh simplifies the modeling process of complex geometries. A flexible set of morphing tools allows users to modify legacy meshes without re-meshing.

The benefits of this software are high-speed, high-quality meshing, increase end-user efficiency with batch meshing and automated model assembly, Interactive feature and volume-based morphing tools.

### 2.11 Material properties

The structural and thermal analysis of femorotibial joint for different material combinations is done with reference to the mechanical and thermal properties of bio materials shown in the table 2.4. These values are adapted from American Society for Testing and Materials.

Table 2.4 Mechanical and thermal properties of bio materials


<table>
<thead>
<tr>
<th>Material</th>
<th>Modulus of elasticity</th>
<th>Poisson’s ratio</th>
<th>Density g/cc</th>
<th>Thermal conductivity W/m deg K</th>
<th>Coefficient of thermal expansion µm/m deg K</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stainless steel (316L)</td>
<td>193 GPa</td>
<td>0.3</td>
<td>7.9</td>
<td>9.4</td>
<td>8.9*10e-6</td>
</tr>
<tr>
<td>Titanium alloy (Ti6,Al4)</td>
<td>120 GPa</td>
<td>0.39</td>
<td>4.5</td>
<td>6.7</td>
<td>8.6*10e-6</td>
</tr>
<tr>
<td>Alumina Ceramic</td>
<td>350000 MPa</td>
<td>0.2</td>
<td>3.9</td>
<td>25</td>
<td>6.8*10e-6</td>
</tr>
<tr>
<td>Polyethylene (UHMWPE- Ultra high molecular weight Polyethylene)</td>
<td>900 MPa</td>
<td>0.4</td>
<td>0.946</td>
<td>0.43</td>
<td>179</td>
</tr>
<tr>
<td>Polyethylene with Chopped Carbon Fiber</td>
<td>87000 MPa</td>
<td>0.3</td>
<td>0.950</td>
<td>0.43</td>
<td>179</td>
</tr>
</tbody>
</table>