



NATURAL BIO-COMPOSITES: AN INERT MATERIAL FOR TISSUE REPLACEMENT

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ABSTRACT

Hard tissues in the human body are natural composite materials and they serve as templates in the development of tissue replacement materials. Over the last two decades, various bioactive composites have been investigated for tissue replacement and tissue regeneration purposes. Each of these composites has its distinctive characteristics and may be used in specific clinical situations. The successful clinical use of bioactive composites has paved the way for further developing this type of biomaterials for various applications. With new knowledge being gained of natural tissues and the human body and the advancement of composite science and technology, newer and better composite materials will become available for substituting diseased, damaged or worn-out body parts. Natural tissues such as bone have the exceptional ability of self-repair. It remains a great challenge for man to produce what nature has made for us.

KEYWORDS: Hard Tissue replacement, Natural bio-composites, Hip joint prosthesis.

INTRODUCTION

The field of biomaterials is extensive, covering all divisions of materials science and many other scientific disciplines. Metals and metal alloys are used in orthopedics, dentistry and other load bearing applications; ceramics are used with emphasis on either their chemically inert nature or their high bioactivity; polymers are used for soft tissue replacement and used for many other non-structural applications.

All biomaterials are used to maintain a balance between the mechanical properties of the replaced tissues and the

biochemical effects of the material on the tissue. Both areas are of great importance and key to a materials clinical success. However, in most (if not all) biological systems a range of properties is required, biological activity, mechanical strength, chemical durability etc. Therefore, often a material that exhibits a complex combination of properties can only fulfill a clinical need. Use of composite technology has enabled biomedical material researchers to develop a wide range of new, tailored materials, 'biocomposites', which offer the promise to greatly improve the quality of life of many people.

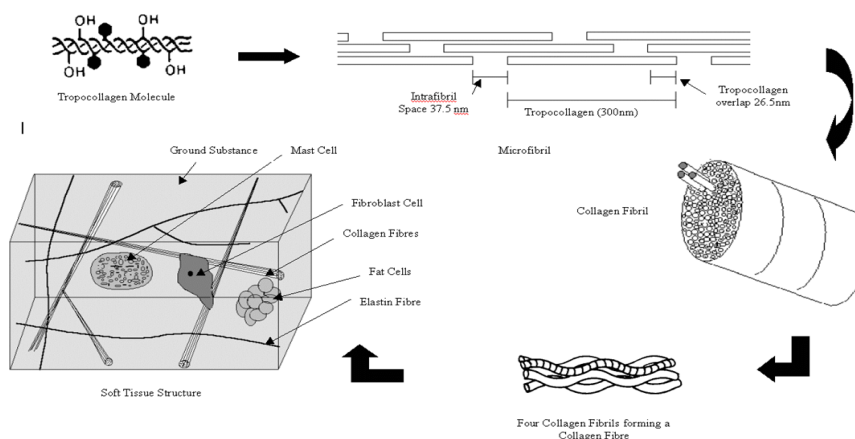


Figure-1: A schematic diagram of a generalized collagen fiber.

Natural Composites

Soft Tissues: Naturally occurring composites are within us all. On the macro scale, soft and hard tissues are formed from a complex structural array of organic fibers and matrix. Soft tissues are formed from elastic (elastin) and non-elastic fibers (collagen) with a cellular matrix between the fibers. Biological structures such as tendon, linking muscles to bone, are low in elastin thus allowing muscle movement to be translated to the bone. However, ligaments, linking bone to bone, are high in elastin allowing movement between bones but retaining sufficient support to stop joints dislocating. It is at the microstructural level that the natural tissues truly have the advantage over synthetic materials. Collagen is a highly abundant and varied protein with more than 14 types discovered. All variations are formed from tropocollagen molecules, which are inelastic. The tropocollagen molecule is formed from three peptide chains. Each chain is formed from 1/3 glycine, 1/3 proline and hydroxyproline and 1/3 other amino acids. The different collagen types are formed by variations in the sequence and number of amino acids found in the alpha-chains. The three chains are principally stabilized by Van de Waals bonds and some occasional covalent bonds forming a right-handed helix. The helix is 300nm in length and 1.5nm in diameter with a screw pitch of 0.27nm. The tropocollagen molecules are arranged in a quarter stagger array, with a 26.5nm overlap and a 37.5nm gap between each end of the molecule. A sequence of tropocollagen molecules is a microfibril.

These microfibrils are organized in parallel to form a collagen fibril with a 50nm diameter. The collagen fibrils then twist together to form a single collagen strand.^[1] It is the cross-linking between the molecules at each structural level that gives collagen its high tensile strength. A schematic diagram of a generalized collagen fiber is shown in Figure-1. Elastin is formed cellularly in a similar fashion to that of collagen, however the amino sequence is primarily composed (55-70%) of glycine, alanine and serine, with the residual being comprised of other amino acids. Elastin lacks collagen's repetitive sequencing at the fibril stage; hence fibers are only 5 to 7mm in length. The amino sequence allows the material to be highly hydrophobic, which results in a 'crumpled' structure. Thus the elastic nature of the fiber is not due to bond stretching but an entropic force, causing a restoring resultant force.^[1]

Hard Tissues: The two most important naturally occurring forms of bone required for structural stability are termed, cancellous and cortical. Cancellous bone (also called trabecular or spongy bone) is a sponge like structure, which approximates to an isotropic material. In contrast, cortical bone is highly anisotropic with reinforcing structures along its loading axis and a highly organized blood supply called a haversian system.^[1] All hard tissues are formed from the four basic phases shown below. The relative fractions of each phase vary between bone types and conditions. The relative percentages of mass for a typical cortical bone are included:

Organic - Collagen Fibers (Type 1)	16%
Mineral - Hydroxyapatite (HA) $[\text{Ca}_{10}(\text{PO}_4)_6(\text{OH})_2]$	60%
Ground Substance	2%
Water	23%

The collagen fibers provide the framework and architecture of bone, with the HA particles located between the fibers. The ground substance is formed from proteins, polysaccharides and mucopolysaccharides which acts as a cement, filling the spaces between collagen fibers and HA mineral. These components are important and form the bulk of the bone, but do not provide the real 'dynamic' part of the bone. It is the voids that are fluid filled and contain the cells that create (Osteoblasts) and resorb (Osteoclasts) the surrounding bone, and it is this part of the bone that governs its structure and state of health. The collagen has the same ultra-structure as that described in the soft tissue section. However, in bone the hydroxyapatite $[\text{Ca}_{10}(\text{PO}_4)_6(\text{OH})_2]$ crystals fit in the 37.5nm gap between the 'heads and tails' of the microfibrils. The crystallites are 20-40nm in length and approximately 5nm thick, with the long axis orientated along the length of the fibril (Figure-2). The next microstructural level has two possible forms:

(1) Woven bone: The woven bone is an immature version of the more mature lamellar form. Woven bone is formed very rapidly and has no distinct structure. It is found in foetal bones and fracture repair sites prior to

maturation.

(2) Lamellar bone: Lamellar bone is formed into concentric rings called osteons with a central blood supply or haversian systems. Each osteon is formed from 4-20 rings, with each ring being 4-7mm thick and having a different fibre orientation. The arrangement of different fiber orientations in each layer gives the osteon the appearance of successive light and dark layers. In the centre of the rings there is a haversian canal, which contains the blood supply. Whilst the outermost layer is a cement layer (cement line) formed from ground substance, it is less mineralized than the rest of the bone and has no collagen fibres. Consequently, the cement line is a site of weakness. The structure of mature cortical bone is shown in Figure-2. Attached to the outer surface of the bone is the periosteum, a fibrous layer that contains osteoprogenitor cells. A second fibrous layer, endosteum, is on the inner surface of the bone, providing a transition from bone-to-bone marrow, again this contains osteoprogenitor cells. These structural features become of importance when discussing bioactive composites. The various microstructural options for cortical and cancellous bone result in a wide range of mechanical properties. It is not just the complex structure

of natural tissues that makes them difficult to replace, but also, their dynamic ability. All-natural tissues (with the exception of nerve tissues) have the ability to regenerate when damaged and also to remodel when the loading conditions change, i.e. the mass of bone mineral can be

increased with exercise, making bones less likely to fracture. Synthesis of a synthetic biocomposite has major obstacles to overcome as it cannot repair its self nor can it be as dynamic as natural tissues. The macro structure of bone is shown in Figure-3.

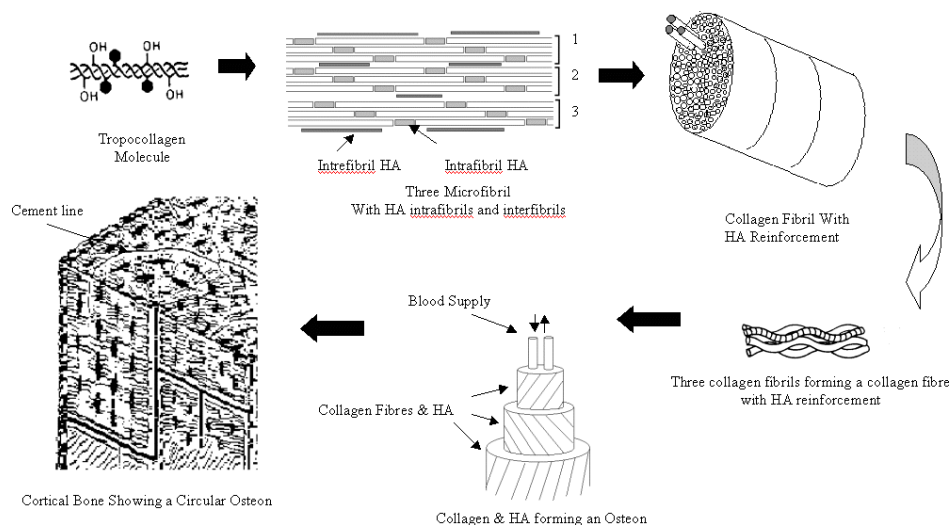


Figure-2: The structure of mature cortical bone.

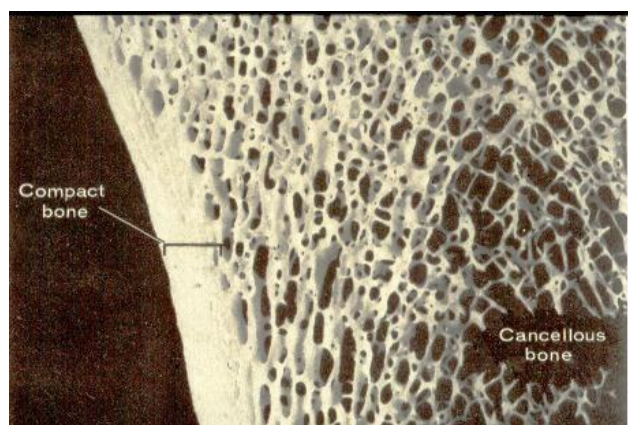


Figure-3: The macro structure of bone.

Biomechanics of the hip and hip prosthesis: The hip joint is a classic ball and socket joint, which allows movement in all three planes: coronal (flexion extension), sagittal (abduction-adduction), transverse (internal-external rotation). The femoral head is covered by articular cartilage that is thick centrally and thin peripherally, conversely the acetabular cartilage is thicker peripherally. The opposing surfaces are regularly and reciprocally curved, and at any given time only 2/5th of the femoral head occupies the acetabulum. The labrum serves to convert the bony acetabulum into a true hemisphere as well as deepening it thus increasing joint stability. The resultant force on the femoral head can be resolved into 3 components; a longitudinal force which produces compression and a bending moment, a transverse force which produces a valgus moment and an interoposterior component which produces a torsional moment. Furthermore, tensile and shear stresses are created along the surface of the implant and the interface. The magnitude of these stresses (+ the effect at the

interface) can be altered by:

(1) Size and location of concreting area (2) Geometry of implant (3) Nature of biomaterial (4) Implant fixation
These are dependent upon 2 variables:

(a) Femoral head position: This is dependent upon the medial offset, the vertical offset, as well as neck-shaft angle. As was demonstrated in the normal hip, normalization of the medial offset is important to minimize the pull of the abductor muscles via a lever arm effect. Vertical offset is important to restore leg length and torsion in the soft tissue and muscles.

(b) Femoral head diameter: This not only influences the contact stress at the head-cup interface, but also the frictional force, stability and range of motion. The original concept of Charnley's 22mm head was to reduce frictional force - however this has been shown to also increase contact stress with localized cup deformation as well as having a higher dislocate rate with reduced range of movement. Conversely, a 32mm head increases frictional force (with increased wear), but

reduces contact stresses with less cup deformation and a lower dislocation rate. The current optimum head size is 26mm or 28mm.

Several variables should be considered:

(1) Stem Configuration: This will effect how load is transferred to the bone as well as interface stress at the implant (cement) bone interface. Generally, a thin stem requires a cement mantle to transfer load whereas a large stem requires cement only to act as a grout. Maximal proximal femur filling of the implant as well as a cement mantel (greater than 2mm) is accepted to be biomechanically desirable in load transmission, interface stress reduction and reduced loosening rate.

(1) Stem Length: The benefit of a long stem (increased stress distribution with reduced interface stress) has to be balanced by difficulty of revisions. In general, a stem should engage the femoral isthmus to increase fixation of the implant.

(2) Cross-Sectional Area: Crowninshield measured the maximum tensile and compressive stress developed in the proximal bone cement with different proximal prosthesis cross-section shapes. Lower instances of cement failure due to overloading can be expected from stems of cross-sections with high bending stiffness, smoothed contours, and shapes that rely less on cement tensile loading and more in cement compressive load.^[2]

(3) Collars: The function of the proximal medial femoral collars has been the subject of considerable debate with the emergence of 3 different designs - collared, semicollared, and collarless. The aim using collared implant was to increase collar loading and subsequently reduce proximal cement load (and interface stress). With collarless prosthesis, the maximum collar compressive stresses are reduced by 80-90% from physiological levels. Collared prosthesis has the potential to alternate this loss of stress and to load the proximal femur at 50-70% physiological levels.

The phenomenon of collar resorption is thought to be related to a "stress-shielding" effect and is observed in less flexible implants. As to whether the presence of a collar aides cement pressurization or prevent sinkage of the prosthesis (thus causing it to act as a collar pivot) is still controversial.

(4) Surface Finish: (pre-coating, porous finish, smooth finish) This is important for load transmission, amount of debris production and degree of mechanical interlock at the interface.^[3] The materials modules of elasticity (i.e. material stiffness) and the material strength influences the stress distribution along the implant as well as interface stress, load transmission to bone plus fatigue strength.

(i) Modules of elasticity: The structural stiffness is a function of the stem cross-sectional size, shape and modulus of elasticity of its constituent material. The more flexible implants (titanium) with a low modulus will transfer load to proximal femur and to proximal bone cement greater than stiffer implants (Chrome-cobalt alloys).

(ii) Material Strength: Fatigue failure is the

progressive fracture of a part subjected to repeat cyclic or fluctuating loads - heating can alter this permanently. The manufacture of porous implants involves a process of sintering whereby metallurgic bonding of the surface layer to the implant is achieved by exposure to high temperatures.

Varying the head size would effect the magnitude of contact stress plus the frictional force which ultimately effects the location and degree of polyethylene cup deformation.

(iii) Stresses in the Acetabular Cement Bone Interface: The magnitude of these interface stresses can be influenced by several factors.

(a) Cup Coverage: Uncoverage of the cup generates high local shear and tensile stresses, which cannot be transmitted to bone leading to cup deformation/migration and failure.

(b) Cup Fixation: The use of cement plugs to reduce shear and torsional stress have been widely accepted. In cementless cup replacement a press fit cup with or without screw fixation has been demonstrated to be superior to screw-in cups.^[4]

(c) Flanged Cup: This was introduced by Charnley in the late 1970's with the twin aims of improving cement pressurization and improving accuracy of cup placement. This also allowed direct seating of the cup on the bony margin with increased stress transfer to cortical bone. The disadvantage of these extended cups was that impingement of the neck of the femoral component against the cup was common in full flexion and abduction - the increased torque generated when impingement occurs increases stress at the cement-bone interface contributing to loosening.

Anatomy of the hip: The hip consists of the two coxal bones. Here is the right in an anterior view. Each coxal bone was developed in a fusion of three bones. The superior ilium fuses with the inferior and anterior pubis and also with the inferior and posterior ischium. The superior border of the ilium is the iliac crest, which ends in the anterior superior iliac spine. The pubis carries the symphysis pubis, which is a joint connecting the right and left coxal bones. The acetabulum is a deep fossa on the lateral side of each coxal bone where the ilium, pubis and ischium combined. The largest bone in the body is the femur. On its proximal end, the rounded head of the femur articulates with the coxal bone, within the acetabulum. The head narrows distally into the neck. Lateral to the neck is a massive projection called the greater trochanter. Medial and inferior is the lesser trochanter. This trochanter serves as sites for muscle attachments.

The hip is a synovial, ball-and-socket type joint formed by the head of the femur and acetabulum of the coxal bone (Figure-4). The acetabulum fits tightly around the head of the femur so that unlike the shoulder, the hip sacrifices degree of movement for additional stability.



Figure-4: Anatomy of hip.

The hip allows movement in all three planes of motion including flexion-extension, abduction-adduction and medial to lateral rotation. Abduction is movement of the leg away from midline and is limited by the greater trochanter contacting the outer ridge of the acetabulum. Adduction is movement of the leg towards the midline. Medial rotation is seen by rotating the leg inward about a vertical axis. Lateral rotation is a more extensive movement for the hip, and is outward about a vertical axis. There are many conditions that can result in degeneration of hip joint (Figure-5). Osteoarthritis is perhaps the most common cause that patients need to undergo hip replacement surgery. This condition is commonly referred to as "wear and tear arthritis". Osteoarthritis can occur with no previous history of injury to the hip joint - the hip simply "wears out". There may be a genetic tendency in some people that increases their chances of developing osteoarthritis.



Figure-5: Degeneration of hip joint.

A vascular necrosis is another curious cause of degeneration of the hip joint. In this condition, the femoral head (the ball portion) loses a portion of its blood supply and actually dies. This leads to collapse of the femoral head and degeneration of the joint. A vascular necrosis (AVN) has been linked to alcoholism, fractures and dislocations of the hip, and long-term cortisone treatment for other diseases. Abnormalities of hip joint function resulting from fractures of the hip and some types of hip conditions that appear in childhood can lead to degeneration many years after the injury. The mechanical abnormality leads to excessive wear and tear - just like the out of balance tire that wears out too soon on.

Symptoms: The symptoms of a degenerative hip joint usually begin as pain while bearing weight on the affected hip. The degeneration will lead to a reduction in the range of motion of the affected hip. Bony spurs will usually develop which can limit how far the hip can move. Finally, as the condition becomes worse, the pain may be present all the time.

Diagnosis: The diagnosis of a degenerative hip starts with a complete history and physical examination by doctor. X-rays will be required to determine the extent of the degenerative process and suggest a cause for the degeneration. Other tests may be required if there is reason to believe that other conditions are contributing to the degenerative process. MRI Scanning may be necessary to determine whether a vascular necrosis is causing your hip condition. Blood tests may be required to rule out systemic arthritis or infection in the hip.

Medical Treatment: Not all hip conditions require a hip replacement as the initial treatment. Doctor may suggest several alternative treatments to put off the decision for replacing the hip as long as possible. Using a cane may help alleviate pain and allow walking more comfortably. Anti-inflammatory medications may reduce the inflammation from the arthritis and reduce pain.

Surgery: A painful hip can severely affect your ability to lead a full active life. Over the last twenty-five years, major advancements in hip replacement have improved the outcome of the surgery greatly. Hip replacement surgery is becoming more and more common as the population of the world begins to age. Most degenerative problems will finally require replacement of the painful hip (Figure-6) with an artificial hip replacement. Once the decision to proceed with surgery is made, there are several things that may need to be done. Orthopedic surgeon may suggest a complete physical examination.



Figure-6: Replacement of femoral head.

The Artificial Hip: There are two major types of artificial hip replacements: Both are still widely used. The surgeon based on age, lifestyle, and the surgeon's experience usually makes the choice. Each prosthesis is made up of two parts: The acetabular component (socket portion) replaces the acetabulum. The femoral component (stem portion) replaces the femoral head. The femoral component is made of metal (some actually have a ceramic ball attached to the metal stem). The is made of a metal shell with a plastic inner socket liner that acts like a bearing. The plastic used is very tough and very

slick. A cemented prosthesis is held in place by a type of bone cement that attaches the metal to the bone (Figure-7). An uncemented prosthesis has a fine mesh of holes on the surface that allows bone to grow into the mesh and attach the prosthesis to the bone.

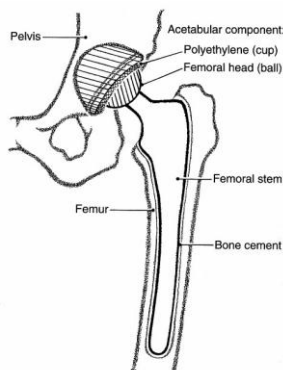


Figure-7: Schematic diagram of an artificial hip joint.

The Operation: The steps involved in replacing the hip begin with making an incision on the side of the thigh to allow access to the hip joint. There are several different approaches used to make the incision, usually based on the surgeon's training and preferences. Once the hip joint is entered, the femoral head is actually dislocated from the acetabulum and the femoral head is removed by cutting through the femoral neck with a power saw.

Reaming the Acetabulum: Attention is then turned towards the socket, where using a power drill and a special reamer, the cartilage is removed from the acetabulum and the bone is formed in a hemispherical shape to exactly fit the metal shell of the acetabular component.

Inserting the Acetabular component (Figure-8): Once the right size and shape is determined for the acetabulum, the acetabular component is inserted into place. In the uncemented variety of artificial hip replacement, the metal shell is simply held in place by the tightness of the fit or by using screws to hold the metal shell in place. In the cemented variety, type cement is used to anchor the acetabular component with bone that is called bone cement.

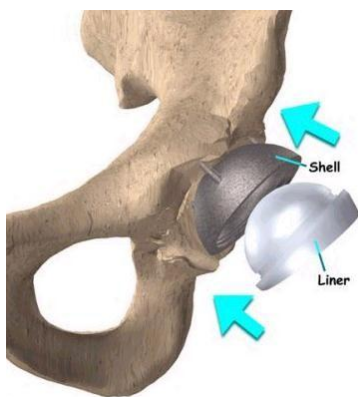


Figure-8: Inserting the acetabular component.

Preparing the Femoral Canal (Figure-9): To begin replacing the femur, special rasps are used to shape the hollow femur to the exact shape of the metal stem of the femoral component.



Figure-9: Preparing the Femoral Canal.

Inserting the Femoral Stem: Once the size and shape are satisfactory, the stem is inserted into the femoral canal. Again, in the uncemented variety of femoral component the stem is held in place by the tightness of the fit into the bone (similar to the friction that holds a nail driven into a hole drilled into wooden board - with a slightly smaller diameter than the nail).

Attaching the Femoral Head: The metal ball that makes up the femoral head is attached.

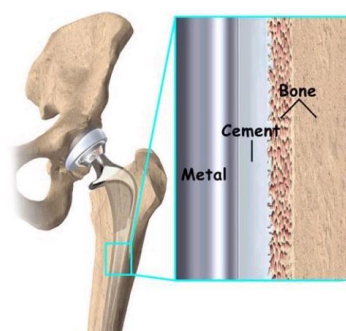


Figure-10: Total artificial hip joint replacement.

Complications: As with all major surgical procedures, complications can occur. Some of the most common complications following hip replacement are:

(a) Thrombophlebitis (b) Infection (c) Dislocation (d) Loosening

These are not intended to be a complete list of the possible complications, but are the most common.

a) Thrombophlebitis: Thrombophlebitis, sometimes called Deep Venous Thrombosis (DVT), can occur after any operation, but is more likely to occur following surgery on the hip, pelvis, or knee. DVT occurs when the blood in the large veins of the leg forms blood clots within the veins. This may cause the leg to swell and become warm to the touch and painful. If the blood clots in the veins break apart, they can travel to the lung, where they get lodged in the capillaries of the lung and cut off the blood supply to a portion of the lung. This is called a pulmonary embolism. (Pulmonary = lung, embolism = fragment of something traveling through the vascular system). Most surgeons' take

preventing DVT very seriously.

- b) **Infection:** Infection can be a very serious complication following an artificial joint. The chance of getting an infection following total hip replacement is probably somewhere around 1%. Some infections may show up very early - before you leave the hospital. Others may not become apparent for months, or even years, after the operation. Infection can spread into the artificial joint from other infected areas.
- c) **Dislocation:** Just like real hip, and artificial hip can dislocate (where the ball comes out of the socket). There is a greater risk just after surgery, before the tissues have healed around the new joint, but there is always a risk. The therapist will instruct very carefully how to avoid activities and positions which may have a tendency to cause a hip dislocation. A hip that dislocates more than once may have to be revised (which means another operation) to make it more stable.
- d) **Loosening:** The major reason that artificial joints eventually fail continues to be a process of loosening where the metal or cement meets the bone. There have been great advances in extending how long an artificial joint will last, but most will eventually loosen and require a revision. Hopefully, you can expect 12-15 years of service from an artificial hip, but in some cases the hip will loosen earlier than that. A loose hip is a problem because it causes pain.^[5,6,7] Once the pain becomes unbearable, another operation will probably be required to revise the hip.

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CONCLUSION

Naturally occurring composites are within us all. On the macro scale, soft and hard tissues are formed from a complex structural array of organic fibers and matrix. Soft tissues are formed from elastic (elastin) and non-elastic fibers (collagen) with a cellular matrix between the fibers. The hip is a synovial, ball-and-socket type joint formed by the head of the femur and acetabulum of the coxal bone. The use of artificial materials in surgical implants is one of the fastest growing market sectors in the healthcare industry. These materials have to perform satisfactorily in a very rigorous environment and cause no associated side effects. Several inter-dependent engineering factors also affect the success of these materials on bone replacement. Suitable biocompatible polymer, metal, ceramic materials are used for total hip joint prosthesis.

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