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Research Article

Prosthetics, Artificial Limbs, Implants and Their Biomedical Applications

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Abstract

This article is a document which gives general information about the biomedical applications of prosthetics, artificial limbs, implants and their biomedical applications. Prosthetic and implant technologies constitute one of the most dynamic areas of modern medicine, based on both engineering and biology. The solutions developed in this field not only compensate for limb loss, but also offer functional and aesthetic improvements that directly affect the individual's quality of life. Prosthetic and implant technologies are likely to become much more functional, durable and biocompatible in the coming years, along with developments in rapidly advancing fields such as biomaterial science, microelectronics, artificial intelligence and tissue engineering. Prosthetics that can perform basic functions today are turning into smart systems that can perceive the user's intentions, adapt to environmental conditions and provide real-time feedback in the near future. Brain-computer interfaces, which specifically target neuromuscular interaction, are paving the way for revolutionary developments in prosthetic use. These technologies can provide more natural and intuitive control by communicating directly with the nervous system. Similarly, prosthetics equipped with sensors are reaching a level where they can perceive sensory data such as heat, pressure or touch and transmit it back to the user. In addition, hybrid structures that can integrate with living cells are being designed through tissue engineering, and it is aimed to integrate biological tissues developed in a laboratory environment with prosthetic systems. In terms of energy sources, studies on longer-lasting, lighter and wirelessly rechargeable battery systems are ongoing. Advanced battery technologies will increase the lifespan of implants and bionic prosthetics and reduce maintenance requirements. However, the development of prosthetic technologies is not limited to technical achievements alone. Issues such as ethics, social access and safety must also be considered in terms of sustainability and justice principles in this field. Retinal implants still face many technical challenges. Prosthesis and implant systems are one of the most strategic biomedical fields that contribute to human health with technological advances, and innovations in this field are likely to radically transform both clinical practices and individual lives in the coming period [1-73].

Keywords: Advanced Biomechanics; Anatomy; Artificial Ear; Artificial Eye; Artificial Limbs; Artificial Vision; Bioengineering; Biomechanical Analysis; Biomechanics; Bionic Ear; Bionic Eye; Cardiovascular System Prosthetics; Comparative Biomechanics; Energy Transfer; Fluid Mechanics; Health Science; Heat Transfer; Mathematics; Medical Engineering; Medical Technique; Medicine; Middle Ear Implant; Physiology; Prosthetics; Retina Implant; Thermodynamics

Introduction

Prosthetics and Biomedical Applications

In the human body, when an organ or limb loses its function, there are two basic solutions: regeneration or artificial replacement. Although biological regeneration is the ideal solution, this option is not always applicable. In such cases, replacement procedures with donor tissues or artificial materials are considered the second most appropriate approach. Artificial structures used in this context are generally called prosthesis. Prosthetics are biomedical devices that attempt to best replace lost limbs or organs. They are generally divided into two main groups: exoprostheses, which are located outside the body, and endoprosthetics (implants), which are placed directly inside the body. External support systems, such as wheelchairs or walkers, are not classified as prosthetics because they are not directly connected to the body. Exoprostheses combine the knowledge and experience of many advanced technology fields such as biomechanical engineering, material science, bionic systems, electronic circuits and computer-controlled technologies. Endoprostheses have a wide variety of structures, each requiring special designs in their own clinical context. However, the most fundamental requirement for the success of such implants is biocompatibility. Although it is not possible today to completely replace a fully functional organ with an artificial counterpart, temporary support devices such as ventricular support systems can provide a highly effective solution in critical situations. In orthopedic applications, implants that support existing structures are preferred rather than replacing them completely. The science of prosthetics dates back to ancient times. For example, the big toe prosthesis thought to belong to a woman named Tabaketenmut who lived in Ancient Egypt shows that early humans also sought a solution to this need. Today, advances in this field have been enriched with much more effective and user-oriented solutions thanks to advanced material technologies, micro-electronic systems and bioengineering applications [1-73].

Method, Findings and Discussion

Exoprostheses

Exoprostheses aim to restore mobility, especially in cases of lower and upper extremity loss. Designs aimed at providing mechanical and functional integrity with the body are based on biomechanical principles. Modern exoprostheses, especially developed in the fields of sports and rehabilitation, aim to provide the user with more independence in daily life activities.

Lower Limb Prosthetics

Prosthetics for the lower limbs are designed to adapt to the natural rhythm of movements such as walking, running, and climbing stairs. Whether the prosthesis starts above or below the knee joint is a determining factor in terms of both design and ease of use. Transtibial (below the knee) prostheses are generally less complex and consist of components such as the socket part of the prosthesis, the tibial structure that stabilizes the leg, and the foot unit located at the bottom. Functions such as shock absorption, balance, and energy conversion are at the forefront of these prostheses. Advanced models may include components such as inner liners, vacuum-supported connections, and carbon springs that provide energy recovery. Prosthetics designed for sports activities are often manufactured using flexible carbon wings. These designs are optimized to flex and recover energy during walking and running.

Transfemoral Prosthetics

Above-knee amputations require more complex systems. Sensor-supported and microprocessor-controlled knee mechanisms stand out in these types of prostheses. The sensors inside the prosthesis transfer data such as knee movements and the force applied to the ground to the microprocessors; knee movement is regulated with the help of hydraulic systems in line with this data. In this way, the prosthesis adapts to the user's walking rhythm, providing a more natural gait. In such systems, rechargeable batteries are usually used as the energy source. The performance of the device is far superior to traditional mechanical systems in terms of improving the user's quality of life, supporting the ability to go up and down stairs and general freedom of movement. However, it also has limitations such as weight, charging requirements and maintenance requirements.

Upper Extremity Prosthetics

Upper limb prostheses are of vital importance for the continuation of daily life, especially in cases of loss of functional areas such as hands, wrists and elbows. Such prostheses not only provide an aesthetic appearance, but also attempt to enable complex motor skills such as grasping, lifting and writing. Some of these prostheses operate mechanically, while more advanced ones are bionic structures controlled by electrical signals. In systems that use Electromyographic (EMG) signals in particular, it is possible to direct the prosthesis motors by sensing the electrical activity in the user's remaining muscle tissue. In this way, functions such as opening and closing of fingers, wrist rotation or grip strength can be controlled. Simpler models have cable systems that work depending on body movement. The prosthesis is opened or closed by the movement of the shoulder or back muscles. Such systems do not require an energy source, but may be insufficient for performing delicate and multi-directional movements. In advanced bionic prosthetics, it is possible to produce more natural movements compatible with user movements thanks to multiple motor systems and artificial intelligence-supported control units. However, such devices are generally more costly and require advanced technical support.

Endoprosthesis

Endoprostheses are artificial implants that are placed inside the body and usually function permanently. These prostheses aim to regain function by replacing tissues damaged by trauma, degenerative diseases, congenital disorders or tumors. Endoprostheses are mostly used in different areas of expertise such as orthopedics, dentistry, cardiology and neurosurgery. One of the most common examples is orthopedic endoprostheses, which involve replacing large joints such as the hip and knee. These types of prostheses are used to compensate for wear on the joint surfaces and provide painless mobility. The shape, size and material of the prosthesis are determined specifically according to the patient's anatomy, age, activity level and the condition of the existing bone tissue. The materials used include stainless steel, titanium alloys, ceramics and polymer-based materials. These materials must be biocompatible, mechanically durable and provide long-term usability. Polyethylene-based interfaces, especially used in joint areas, reduce friction and extend the life of the prosthesis. The placement of endoprostheses is usually performed surgically. The implant is attached to the bone with cement or special porous coatings that allow the bone tissue to adhere to the implant surface over time. Modern surface coating techniques and biological substances such as hydroxyapatite added to the coating accelerate the integration of the bone with the prosthesis and reduce the risk of loosening. Dental implants used in dentistry are also a type of endoprosthesis. These artificial tooth roots, fixed on titanium screws placed in the jawbone, allow the missing teeth to be completed in terms of function and aesthetics. Thanks to the process called osseointegration, the implant is firmly attached to the bone. In the cardiovascular system, stents and artificial heart valves are examples of endoprostheses. These structures, which are placed to maintain vascular patency or replace damaged heart valves, are usually applied with minimally invasive methods. Both the biocompatibility of the material used and the fact that it does not cause clotting are of great importance. Brain pacemaker systems (neurostimulators) used in brain surgery are also included in the endoprosthesis class. They aim to reduce symptoms by delivering low-voltage electrical impulses to brain regions, especially in the control of neurological disorders such as Parkinson's disease. Endoprostheses have important applications in many different areas of modern medicine. For a successful endoprosthesis application, appropriate material selection, correct surgical technique and biomechanical compatibility as well as careful evaluation of the patient's clinical needs are required.

Hip Prosthetics

The hip is a ball-and-socket type joint located between the femur and pelvis, providing movement in three axes. The femoral head fits into the acetabular socket, making this mobility possible. The bony surfaces in this joint are covered with articular cartilage and lubricated by synovial fluid. The joint is fixed by both central and peripheral ligaments. The iliofemoral ligament in particular is one of the strongest ligaments in the body and must be cut during prosthetic surgery. Hip fractures most often occur in the femoral neck, and this often requires surgical intervention. Hip replacements involve replacing the femoral head and/or acetabular socket structures with artificial materials. In cases where only the femoral head is replaced, it is called a "Half Endoprosthetic Prosthesis" (HEP), while in cases where both the head and socket are replaced, it is called a "Full Endoprosthetic Prosthesis" (TEP). TEP is also known as a Total Hip Replacement (THR) or Total Hip Arthroplasty (THA). The three most common reasons for hip replacement are:

Deterioration of joint cartilage due to osteoarthritis (60%),

Femoral neck fractures due to osteoporosis (30%),

Fractures resulting from trauma (8%).

In addition to these, rarer causes such as rheumatoid arthritis, osteonecrosis and tumors may also require a prosthesis. The first examples of hip prostheses began to be used in the 1960s and have increased significantly since then. According to research conducted in the USA, TEP procedures have doubled between 2000 and 2010 alone. Today, more than 4.5 million people in the USA live with artificial hips. This increase can be explained by both the increase in the elderly population and the use of surgery by younger individuals. The rate of TEP applications, especially in the 45-64 age group, has increased by over 100% in recent years. During surgery, the existing hip joint is removed, the natural socket is cleaned, and an artificial socket is placed in its place. The femoral head is removed and a suitable shaft is placed in the femur. An artificial ball is added to the end of the shaft, creating a new joint between the ball and the socket. These parts are usually made of titanium alloy, ceramic, plastic, or a combination of these. The appropriate dimensions of the prosthesis are determined by imaging and simulations before the surgery. Surgery requires careful planning and implementation, as it requires preservation of muscle, nerve, and vascular tissues. Minimally invasive techniques offer shorter recovery times by causing minimal damage to muscles and tendons. However, as with any surgery, there are points to consider in hip replacement surgery. The success of the implant depends on material biocompatibility, wear resistance and mechanical force distribution compatible with the body. Incorrect application or incompatibility can lead to permanent deformations in the bone.

Types of Hip Replacement

(a) Cemented and Cementless Dentures: There are two basic fixation methods for hip replacement: cemented and uncemented. In cemented implants, the implants are fixed to the bone with acrylic cement, while uncemented implants have rough surfaces that allow the bone to grow naturally into the implant surface. The method to be preferred is usually determined by the patient's bone quality, and the decision can be changed during surgery. Today, some prosthetic systems allow for both cemented and uncemented applications with the same instruments. Uncemented surfaces promote bone-like mineralization, providing long-term stability.

(b) Hip Body: The hip body provides load transfer between the socket and the femur and helps distribute this load evenly throughout the bone structure. The body design is optimized with finite element analysis to obtain the closest result to physiological stress distribution. It is important for the long-term success of the prosthesis to mimic natural stress patterns.

(c) Shafts: Hip replacement shafts are produced in different lengths, angles, shapes, surface coatings and material types. Today, short shafts are preferred more often due to the advantage of being easily replaceable in the long term. Shaft materials include Co-Cr-Mo alloys, titanium and titanium-based biocompatible alloys such as Ti6Al4V or Ti6Al7Nb. These materials provide high tensile strength and biocompatibility with bone. Shaft surfaces can be supported with biocoatings such as hydroxyapatite, which promote bone growth.

(d) Material Combinations: Various combinations of materials are used between the ball and socket:

Metal–Plastic (UHMWPE): The most common and economical option. Although there is a risk of wear, it provides the advantage of low cost.

Metal–Ceramic: More resistant to wear and tear, increasing durability.

Metal–Metal (MoM): Although it was previously preferred for active patients, its use has been discontinued due to health problems caused by metal particles.

Ceramic–Plastic: Due to its surface smoothness, wear is lower and it is compatible with plastic.

Ceramic – Ceramic: The least wear-resistant, but most expensive option. Current versions have overcome the breakage and squeaking issues of the past.

(e) Length Adjustment: Leg length adjustments are limited in hip prostheses. Generally, a rough adjustment can be made thanks to the conical connection structure. If a difference is determined by the measurements made before and after surgery, precise adjustments can be made with screw-connected mechanisms in advanced systems.

(f) Load Sensors: In experimental studies, the forces generated during various activities were measured by the load sensors placed inside the prostheses. These sensors contribute to the development of implant designs by analyzing the loads on the hip joint during actions such as walking, running, and climbing stairs. According to the findings, forces equivalent to approximately 2.5 times the body weight occur during walking and 5 times the body weight during running.

(g) Alternative Approaches: The materials, surgical techniques and planning tools used in hip replacements are constantly evolving. However, if the bone structure is intact but there is only cartilage damage, more conservative approaches may be preferred over a full replacement. In recent years, successful applications have been reported in the laboratory environment for cartilage production from the patient's own stem cells. This development opens the door to bioengineering solutions that could replace artificial replacements in the future.

Knee Prosthetics

Knee replacement surgery is similar to hip replacement surgery in its basic aspects, but it has some important differences. The most common reason for application is osteoarthritis, but the revision (replacement) rate in knee replacements is twice as high as in hip replacements. Knee replacements are generally divided into two types: total knee replacement and partial knee replacement. Compared to the hip, the knee joint has a more complex structure and shows anatomical differences in each individual. Therefore, standard parts are not always sufficient in knee replacement; patient-specific planning is required. Data obtained using imaging methods such as MRI and CT are processed in simulation programs and the appropriate implant design is made. The knee is the largest joint in the body and consists of the thigh (femur), tibia (tibia) and patella bones. The contact surfaces of these bones are covered with articular cartilage. The knee is a modified hinge joint and provides limited rotation with flexion and extension movement on a single axis. The normal flexion angle is approximately 135°. While the menisci located inside the joint act as shock absorbers, the Anterior And Posterior Cruciate Ligaments (ACL, PCL) and Lateral Ligaments (LCL) provide joint stability. The fluid secreted by the synovial membrane reduces friction by lubricating the joint surfaces. The ACL and PCL are usually removed during knee replacement surgery because modern implants provide the stability provided by these ligaments mechanically. Lateral ligaments such as the LCL are preserved to provide additional stability to the prosthesis. The choice of prosthesis varies depending on whether it is complete or partial. In partial knee replacements, only the damaged section is replaced and the ligaments are preserved; in complete replacements, all joint surfaces are reconstructed. The most common material combination for all knee implants is metal and plastic. The metal parts are usually made of Co-Cr-Mo or Ti6Al4V alloy, while the plastic component is made of UHMWPE (Ultra-High Molecular Weight Polyethylene). This combination is preferred for both mechanical strength and biocompatibility.

Cardiovascular System Prosthetics: Prosthetics for the cardiovascular system cover a wide range of applications, including vascular grafts, artificial heart valves, and stents. Vascular grafts are generally used to repair pathological dilatations such as aneurysms, while stents are used to restore patency to narrowed vessels. These structures are usually made of stainless steel, nitinol, or polymer materials. Artificial heart valves are replaced with biological or mechanical prosthetics in cases such as valve insufficiency. Mechanical valves are long-lasting but require lifelong use of anticoagulant medication. Biological valves have the advantage of tissue compatibility, but can wear out more quickly. For these prosthetics to be successful, the surfaces that come into direct contact with blood must have antithrombogenic (anti-clotting) properties. Coatings are being developed with smart material technologies to prevent such complications.

Cardiovascular System Endoprosthetics: Endoprosthetics used in the cardiovascular system are designed to repair or replace structural or functional disorders in the circulatory system. The most common structures encountered in this context are vascular grafts, heart valves and stents. Since these prosthetics are in direct contact with blood, they should be meticulously evaluated in terms of biocompatibility and antithrombogenic properties. Vascular grafts are used to bypass occluded or damaged vascular sections. They are usually made of synthetic polymers such as Dacron and Polytetrafluoroethylene (PTFE). The compatibility and flexibility of the graft with the body are important for successful circulatory continuity. Heart valve prostheses are used in cases where the mitral, aortic, tricuspid or pulmonary valves have lost their function. These prostheses are divided into two groups: mechanical valves and biological valves. While mechanical structures are made of titanium or carbon alloys, biological valves are obtained from pig, cattle or cadaver tissue. Mechanical valves have a longer lifespan but require lifelong use of anticoagulant medication. Biological valves, on the other hand, tend to clot less due to their closer proximity to the natural structure, but they function for a limited time. Stents are mesh-like structures used to open narrowings in coronary arteries and keep the vessel open. They are made of expandable metals and placed inside the vessel using the balloon angioplasty method. Coated (drug-eluting stent) models that release drugs aim to reduce the risk of re-stenosis. Artificial vessels are also used in dialysis patients who need to have arteriovenous fistulas. In order for these systems to maintain their long-term patency, both the risk of thrombosis is reduced and their mechanical durability is high. The success of cardiovascular system prostheses is closely related to the quality of biomaterials, appropriate surgical technique, adaptation to the patient's individual physiology and long-term follow-up protocols.

Sensory System Implants: Sensory system implants are currently limited to restoring visual and auditory perception only. Functional prosthetic solutions have not yet been developed for other senses such as taste, touch, smell and pressure.

Middle Ear Implants: In the rehabilitation of hearing loss, outer, middle and inner ear structures are targeted. In particular, in middle ear implants, a distinction is made between bone conduction hearing aids and active Middle Ear Implants (MEI).

Repair of Eardrum and Conduction Structures: The eardrum is the conduction medium between the outer ear and the middle ear. With the myringoplasty procedure, the eardrum can be repaired with fascia or perichondrium to increase sound conduction capacity. In cases of deterioration in the middle ear ossicles, sound transmission can be achieved using various metal prosthetic structures. Although these implants are manufactured from traditional metal materials, 3D printing technologies have the potential to develop more natural ossicles replacements in the future.

Active Middle Ear Implants (MEI): Active MEI systems provide direct stimulation to the middle ear structures by converting environmental sound waves into mechanical vibrations. There are two main types: piezoelectric and electromagnetic. The most common of these is the electromagnetic MEI system, called the "vibration sound bridge." In this system, signals from an external receiver placed behind the ear activate a magnetic transducer inside the implant. The magnet vibrates back and forth in parallel with the sound signals, sending mechanical stimulation directly to the ossicular chain or oval window. The advantages of MEI systems include wide frequency response, natural sound perception, and low acoustic feedback. However, there are limitations that should be noted when used with MRI. In piezoelectric systems, sound waves are converted into electrical signals and mechanical vibration is created again by a second transducer. These systems offer an effective solution, especially for conductive hearing loss.

Total Deafness and Cochlear Approaches: MEIs are only effective in conductive hearing loss. In cases of total deafness or nerve deafness, cochlear implants also provide limited results because the cochlea or auditory nerves are no longer functioning. Current research is focusing on genetically regenerating cochlear hair cells.

Retinal Implants

The aim of retinal implants is to restore basic visual perception in blind individuals. However, the structural integrity of the retina (especially the ganglion cells and nerve fibers) must be preserved at least partially. Retinal implants are divided into two main groups according to their location:

(a) Epiretinal Microelectrode Array (MEA): In this approach, visual information from the outside world is perceived by a digital camera mounted on the glasses. The image is processed and transmitted wirelessly to a MEA placed on the surface of the retina. The MEA electrically excites ganglion cells, generating action potentials in the visual cortex via the optic nerve. The most common example, the Argus II system, has a 10×6 electrode array. It has been shown that patients can perform visual tasks more effectively and perceive Braille characters with this system.

(b) Subretinal Micro-Photodiode Array (MPDA): In subretinal implants, light coming directly from the lens of the eye is detected by photodiodes placed under the retina. Each photodiode electrically stimulates the relevant cells according to the light intensity. This approach uses natural eye movements and does not require an image processing unit. However, there are technical limitations such as heat generated during signal transmission and low light sensitivity. In order to overcome these problems, hybrid systems working with infrared light have been proposed. In these systems, the camera image is converted to infrared light and detected by the subretinal implant. [1-73].

Conclusion

Prosthetic and implant technologies constitute one of the most dynamic areas of modern medicine, based on both engineering and biology. The solutions developed in this field not only compensate for limb loss, but also offer functional and aesthetic improvements that directly affect the individual's quality of life. Prosthetic and implant technologies are likely to become much more functional, durable and biocompatible in the coming years, along with developments in rapidly advancing fields such as biomaterial science, microelectronics, artificial intelligence and tissue engineering. Prosthetics that can perform basic functions today are turning into smart systems that can perceive the user's intentions, adapt to environmental conditions and provide real-time feedback in the near future. Brain-computer interfaces, which specifically target nerve-muscle interaction, are paving the way for revolutionary developments in prosthetic use. These technologies can provide more natural and intuitive control by communicating directly with the nervous system. Similarly, prosthetics equipped with sensors are reaching a level where they can perceive sensory data such as heat, pressure or touch and transmit them back to the user. Biocompatible 3D printing technologies enable patient-specific prosthetic production; they strengthen the concept of personalized treatment. In addition, hybrid structures that can integrate with living cells are being designed thanks to tissue engineering, and it is aimed to integrate biological tissues developed in a laboratory environment with prosthetic systems. As for energy sources, studies on longer-lasting, lighter and wirelessly rechargeable battery systems are ongoing. Advanced battery technologies will increase the lifespan of implants and bionic prostheses and reduce maintenance requirements. In this expanding range from exoprostheses to endoprostheses, from sensory implants to cardiovascular system supports, biocompatibility, functionality and user comfort are the main determinants. Today, prosthetics are becoming more intuitive, more effective and more integrated thanks to bionic systems, microprocessors, artificial intelligence-controlled mechanisms and personalized designs. However, the development of prosthetic technologies is not limited to technical achievements alone. Issues such as ethics, social access and security should also be considered in terms of sustainability and justice principles in this field. Retinal implants still face many technical challenges. Factors such as limited spatial resolution, low contrast, narrow angle of view, limited dynamic range and power consumption cause performance to be insufficient for widespread clinical use. Therefore, it is aimed to increase performance with supporting strategies such as advanced image processing algorithms, foreground highlighting and contrast enhancement. Prosthetic and implant systems are one of the most strategic biomedical fields that contribute to human health with technological advances, and innovations in this field are candidates to radically transform both clinical practices and individual lives in the coming period. The study was carried out within the scope of a doctoral course given by Dr. Emin Taner ELMAS. The name of this doctoral course is "Medical Engineering and Advanced Biomechanics" and is given in the Department of Bioengineering and Sciences, Iğdır University. İsmail KUNDURACIOĞLU is a doctoral student and one of the students taking this course. This article was prepared as a part of one of the assignments prepared using the summary translation of Reference [22]: Book-Chapter 15 (İsmail KUNDURACIOĞLU) [1-73].

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