Chapter

Introductory Chapter: Past, Present, and Future of Prostheses and Rehabilitation

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1. Background

A prosthesis is defined as "...a device attached to the stump of an amputated body part due to traumatic or congenital conditions..." [1]. Prostheses have evolved over the past centuries, starting with a wooden toe to the highly mechanized robotic limbs of today. The evolution of prosthesis started in the Egyptian period during which wood was used as a replacement for a missing toe, coconut shell was used as a dental implant, and various other materials were used as an alternative to different body parts. There are various types of prostheses depending on the body part being replaced. These include upper and lower limb (LL) prostheses, neural prostheses (NP), retinal prostheses, maxillofacial prostheses, and various other types. Each prosthesis is designed and assembled based on the person's physical appearance, functional needs, and affordability [2–7]. The history of lower limb prosthesis is outlined in **Table 1**. This is a summary of our findings from [8, 9].

Amputations are estimated to occur between 300 and 500 times per day, leading to an increased usage of prostheses [10]. With increased need there are various factors which impact prosthesis usage, including whether the amputation is unilateral or bilateral, the time duration between amputation and prosthetic fitting, type of prosthesis used, physical health factors such as phantom-limb pain, and the psychological impact of amputation such as perception of symptoms, self-efficiency, balance confidence, treatment cost, and time taken to adapt to the prosthesis. The quality of life post-rehabilitation does not solely depend on the abovementioned factors but also includes functional utility and satisfaction over time. Improvements in quality of life are possible with recent innovations in design tools, materials, and different types of manufacturing, aiding in customizing prosthesis according to patient needs [11]. Novel rehabilitation methods, different types of prostheses, their limitations, and recent advancements will be discussed in this chapter.

2. Virtual reality rehabilitation

Upper limb (UL) paralysis and other motor deficits are common after a stroke. About 70% of acute phase patients and 50% of chronic phase patients experience such deficits. Upper limb paralysis affects tens of thousands worldwide, and all the forms of paralysis as a whole affect millions [12]. Currently, there is no way to safely cure paralysis. Instead, upper limb paralysis patients undergo rehabilitation treatment

Year	Type of prosthetic	Material/technology
600 B.C	Below knee	Wooden peg leg
1500	Below knee	Esthetic iron leg
1600	Below knee	Armor-based sheet metal leg
1650	Below knee	Metal casting with leather straps
1696	Below knee	Wooden foot with copper socket
1800	Above knee with ischial seat	First hardened leather with knee joint
1816	Anglesey leg	First wood and steel-based joint articulating leg
1851	Benjamin Palmer leg	Spring with metal tendons
1863	Dubois L. Parmelee	Pressure-based limb and socket attachment
1865	Dollinger foot	Foot with rocking sole
1900	Bumper foot	Solid rubber foot
1912	Leg	Aluminum-based lightweight leg
1915	Leg	Metal leg with lifelike appearance
1920	Leg	Metal replaced wood to reduce weight
1950	Leg	First adjustable steel bar-based prosthesis
1990	Knee	First microprocessor knee
2009	Leg	Carbon fiber-based sprinter

Table 1.
Evolution of lower limb prostheses.

which gradually improves their lost function with exercises and stretches. There are many different approaches to provide treatment, which include working with a physical therapist on hand motor and strength skills and using prosthetic devices, such as robotic exoskeletons. The exoskeleton is a wearable, electrical device that straps onto the impaired arm or hand. It improves the limb's strength and endurance and its motor abilities by allowing the brain and the upper limb to regain communication [13].

In recent years, the use of virtual reality (VR) simulations designed in environments such as Unity has emerged to provide post-trauma and post-stroke rehabilitation. Hardware such as VR goggles and the Leap Motion controller, as well as Cybergloves and joysticks, are used to manipulate objects in virtual reality to provide an alternative to conventional rehabilitation methods. Improvements in retention and ease of use are accomplished by creating more immersive and engaging exercises for patients than the standard approach. Games with goals and challenges, interesting environments, and different types of in-game rewards can provide extra motivation to the patient. There has been a wide variety of studies researching the use of a virtual reality environment for rehabilitation of different impairments. In one study, VR rehabilitation for a 6-DoF ankle prosthetic was used to supplement robotic therapy. Subjects were put into an environment where they needed to navigate a plane or a boat; results showed that the VR group showed a larger increase in walking speed as well as higher retention rates and 28% less audiovisual cues needed during the experiment than those who used the robot alone [14]. Upper limb rehabilitation was also performed for subjects learning to use complex prostheses with multiple dimensions [15]. Games like MindBalance require the subject to control an animated character and balance checkerboards on a tightrope, with a "3 strikes" approach to balance. During a test, subjects achieved 89% accuracy due to the EEG-based BCI performance [16]. Patients who experienced upper-extremity (UE) deficits improved forearm extension and movement as well as hand-eye coordination, control and endurance of the UE, strength of the UE, and flexibility through VR [17].

As VR technology develops further, researchers must consider factors such as graphics design to maintain immersion without disorienting the patient. Elements from conventional rehabilitation known to promote good outcomes, such as task repetition [18], must also be incorporated into the design of the games. VR rehabilitation methods are becoming attractive alternatives to conventional physical/occupational therapy. They promise more efficient and less expensive therapies, increasing patient access and decreasing the amount of time necessary for rehabilitation.

3. Upper limb prosthesis

Upper limb prostheses are some of the most commonly used prosthetic devices since the human hand and arm is a vital tool for interaction, sensing, and working in an environment. Major limb amputations have been estimated to occur in 1 out of every 300 people in the United States, with 23% involving the upper extremity [19]. Unlike other types of amputation, most UL amputations are due to trauma. The evolution of UL prostheses has been exceptional over the past decades, resulting in highly mechanized devices which improve the quality of life of amputees by enabling them to perform activities of daily living (ADL).

UL prostheses can be classified based on the type of amputation and type of control mechanism. The type of amputation can be classified as trans-humeral, trans-radial, wrist, trans-metacarpal, and trans-phalangeal. Within these types, trans-radial is the most commonly used UL prostheses as it accounts for up to 10% of upper limb amputation [20]. Based on the type of control mechanism, these devices can be divided into body-powered, externally powered, and hybrid-controlled systems. Body-powered systems use body movements to control a terminal device or a joint like the elbow. Externally battery-powered systems use electric switches or myoelectric signals for control, activated by residual limb movements or electromyographic signals generated by the residual limb. Hybrid systems combine body and external power control to balance weight, cost, and cosmetics and accommodate different amputation levels.

Rejection rates for UL prostheses have been high, ranging from 3 to 60% in most studies with rates closer to 60%. This rate was shown to correlate to the proximity of amputation with 6% for trans-radial and 60% for shoulder disarticulation [20, 21]. Many studies show that amputees are not satisfied with their prosthetic, thus resulting in high abandonment rates. There are various factors which affect prosthetic usage, and there are a lot of discrepancies between the various studies. For example, a study conducted by Burger et al. in a group of 414 upper limb amputees showed that factors such as level of amputation, loss of dominant hand, and time between prosthesis fitting and amputation play an important role in prosthetic use [22]. Other studies consider factors related to demographic impacts such as education level, level of amputation acceptance, and economic factors such as prosthetic use and training expense. These can be collectively considered as psycho-economic factors [23]. Based on this, the factors being considered have to be better understood to know their actual impact on prosthetic use.

4. Lower limb prosthesis

Lower limb prostheses provide support and assist in locomotion for lower limb amputees. Lower limb prosthetics can assist many amputees to regain independence and mobility, thereby improving their quality of life. An estimate of 185,000 lower extremity amputations happens each year within the United States and may double by 2050. Unlike UL amputation, LL amputation is due to various reasons such as vascular diseases like diabetes, peripheral arterial disease, trauma, and cancer [24]. In the case of amputation related to vascular diseases, there is a likely chance that within the next few years, the other leg is also amputated. Diabetes is a major factor in the case of vascular-related amputation as it affects 8.3% of the US population with an incidence of 5.7 per 100,000 people [25]. Ninety percent of new amputations concern the lower extremity with 53% of patients requiring a transtibial amputation and 39% accounting for transfemoral amputation [26].

The main components of a lower limb prosthesis include the socket, suspension, knee unit (if required), foot/ankle complex, and any other components based on the patient's comfort level. LL prostheses can be classified into several different categories as transfemoral, transtibial, ankle, and foot-based devices. Each of these categories has its type of socket and suspension to improve contact and proper attachment. Types of transtibial socket designs include a patellar tendon bearing socket which uses the patellar ligament as a partial weight-bearing surface or a total surface bearing socket which distributes equal pressure on the stump. Transtibial suspension types include a supracondylar cuff, a lanyard system, a supracondylar suspension, or an older model which is a thigh corset with side joints. Transfemoral socket designs include quadrilateral and ischial containment. Suction is the most common form of a transfemoral suspension, with a pelvic band prescribed for some patients. Types of prosthetic knee include manual locking, which are single-axis knees with a single axis of rotation, hydraulics or pneumatic polycentric knees, and microprocessor-controlled knees. Microprocessor-controlled knees utilize a microprocessor to control the pneumatics or hydraulics throughout the gait cycle. Types of prosthetic foot include the solid ankle cushion heel (SACH), single-axis foot, multi-axis foot, and dynamic response feet. The latter have a flexible heel that stores potential energy during early stance phase that is then released through recoil of the material in the late stance and early swing phase. Partial foot prosthesis options include toe fillers with or without orthosis and shoe modifications [27].

LL prostheses can be categorized into three types of control mechanisms: passive, semi-active, and active. Passive devices perform like a fixed spring and damper and hence offer only basic functionality. Semi-active prostheses are capable of instantaneously altering movement, utilizing microprocessors to react to situations. They offer greater flexibility than passive devices but are limited to generating resistive forces. Active prostheses are externally powered by batteries and driven by motors regulating their movement. This gives active prostheses the ability to act instead of react without a lag compared to the former types. Thus they offer greater performance and functionality, but the overall system is highly complex and heavy [28]. While the different types of LL devices have their advantages, disadvantages, and constraints, these qualities are being overcome by technological innovations. New design tools and manufacturing techniques like 3D printing mitigate the constraints of the current state of the art and support in customizing prosthetics according to patient needs.

5. Neural prosthesis

The foremost intent of neural prostheses is to form an interface between a device and neural tissue to directly interact with the nervous system of individuals with neurological disorders like amyotrophic lateral sclerosis. This interface is known as the brain machine interface which is the core of NP and makes it feasible to study brain mechanisms. An estimation of 11,000 and 700,000 spinal cord injury and stroke cases has been reported per year, respectively, with an increasing need for NPs that can be utilized for sensory restoration to improve the quality of life of individuals [29]. An NP can either be an input device which converts surrounding information into perceptions, such as cochlear implants, or an output interface which converts the brain's intentions into activity. There are many types of neuroprosthetics that can be broadly classified as invasive or noninvasive. The former is more complicated since any fault with the device or the connection will require a revision surgery, which will impact the patient both physically and economically [30]. NPs include devices ranging from basic electrical stimulators to multichannel percutaneously implanted electrode systems.

NPs can be further classified into two types based on the type of stimulation, such as functional neuromuscular stimulation (FNS) or cerebellar stimulation. In FNS, electrical stimulation is used to activate or inhibit skeletal muscles based on the type of injury. FNS is used for various applications like lower and upper extremity rehabilitation, auditory prostheses, and respiratory disorders. In lower extremity rehabilitation, NPs were used to correct foot drop in stroke patients by stimulation of the peroneal nerve with resultant activation of the tibialis muscle during the swing phase of gait [29]. Upper extremity rehabilitation involves restoring the ability to elevate the shoulder, raise the upper arm, and flex the elbow in the presence of a paralyzed lower arm and hand. FNS-based NPs are used to treat sensory deafness if the hair cells are still intact with the brain to produce sensations of sound by electrically stimulating the fibers. Ondine's curse, a respiratory disorder caused by the lesion of upper motor neurons, results in the ineffective movement of the diaphragm which can be treated by stimulation of phrenic nerves. This is called FNS-based electrophrenic prosthesis and has replaced mechanical respirators. In the case of cerebellar stimulation, electrical current is passed through electrodes placed on the surface of the cerebellum. This technique is used as a treatment option for various conditions such as intractable epilepsy, multiple sclerosis, cerebral palsy, intention tremor, and many different types of motor disorders [29].

There are various limitations of NPs. First, the contact area between the sensory implant and the neural tissue is relatively small compared to anatomical neurons in the sensory pathway. Second, implants are placed in the sensory pathways that have been severed. With a lesion in this pathway, there is usually less chance of regeneration due to reduced interface with the electrode. Third, electrodes contacting the neural tissue are prone to rejection and degradation with a chance of potential damage to the stimulating neural tissue. Fourth, refractory properties limit the number of electrical impulses a neuron will respond to in a given time interval. Fifth, size, biocompatibility, durability, and energy supply are some of the basic problems with NPs [29]. Other factors include treatment cost, recovery, and handling. These problems become serious issues as a majority of stroke patients are elderly people who cannot withstand such intense operations and require more recovery time than young adults. Thus, with further advancements, the complexity of NP can also be reduced, thereby increasing its applications.

6. Retinal prostheses

The first visual prostheses were invented in the 1960s, demonstrating that visual perception of the subject can be restored by electrical stimulation of the visual cortex using 180 cortical surface electrodes [31]. In normal visual perception, light travels through various chambers of the eye including the cornea, aqueous humor, pupil, lens, and vitreous chamber to activate photoreceptors and set up the trans-synaptic connections of the retina [32]. Four important parts of the eye in visual perception are the lens, cornea, retina, and retinal pigmented epithelium. Any defect in one of these parts can cause blindness. Several intractable blinding conditions are due to retinal damage, the most common type being retinal degeneration. This can be broadly classified into two categories: photoreceptor rod degeneration like retinitis pigmentosa, and macular photoreceptor cone degeneration like age-related macular degeneration (AMD). The prevalence of rod degeneration is estimated to be about 1 in 3500 around the world. It is also estimated that 2 million Americans above the age of 55 have AMD, with another 7 million being pre-symptomatic [33]. Retinal prostheses try to reactivate the residual circuitry in a blind patient's retina to produce a synthetic form of usable vision. Using an array of stimulus electrodes or light-sensitive proteins, the neurons in the degenerate retinal network are activated to elicit a series of light percepts termed "phosphenes." This acts as independent spatial percepts in their visual field, restoring a crude form of vision [34].

The type of prosthesis is chosen based on the condition of the subject's vision. Different types of retinal prostheses include epiretinal prosthetics, in which the device is implanted into the vitreous cavity, and subretinal prosthetics, where the device is implanted in the potential space between the retinal pigment epithelium and neurosensory retina to stimulate the outer retina. Epiretinal prostheses like the Argus II include an imaging device like a camera which transforms visual information into patterns of electrical stimulation administered to viable retinal neurons. In the case of subretinal prosthesis, a micro-photodiode array (MPDA) is implanted between the retinal pigment epithelium and bipolar cell layer, which enhances vision in patients with RP and AMD. It can be considered as a replacement for lost photoreceptors [35].

Epiretinal and subretinal devices have their advantages and disadvantages. Advantages of subretinal devices include a lower current requirement and the lack of a need for mechanical fixation due to its proximity to the visual neurons. Disadvantages include the limited subretinal space and the increased risk of thermal damage to the neurons due to heat dissipation in the vitreous humor [36]. Advantages of epiretinal devices include reduced thermal damage to the neurons, a reduced number of electrodes, and a flexible procedure for subsequent surgeries. Disadvantages include increased electrical current requirements and adhesion of the device to the inner retina, which is more technically challenging [37].

7. Maxillofacial prostheses

A maxillofacial prosthesis is an artificial replacement for facial features to restore oral functions such as swallowing, mastication, and speech. There are numerous causes which can be congenital, traumatic, or disease-borne in nature. Maxillofacial prosthetics are a better option than conventional surgery when multiple procedures would be required. Also, surgical reconstruction may be limited by insufficient residual tissue, vascular compromise after radiation, age, the inadequacy of the donor site, or patient preference. Rehabilitation with maxillofacial prosthesis aims to restore an effective division between oral, nasal, and orbital cavities and gives faster reconstructive possibilities simplifying the post-surgery period and recovering an adequate patient lifestyle. Maxillofacial prosthetics are a subspecialty of prosthodontics which is a collaboration of ear, nose, and throat specialists, plastic surgeons, oral surgeons, and radiation oncologists in the case of cancer patients. Thus, it is a multidisciplinary branch which focuses on improving quality of life by preserving residual structures, restoring oral functions, and improving esthetic appearances [38].

The need for maxillofacial prostheses is increasing in recent years with the 6% increased prevalence of oral cancer, with the incidence being more in males in the ratio of 2:1 [39]. Maxillofacial defects can be classified as either intraoral or extra-oral. Intraoral include defects of the maxilla, mandible, tongue, soft palate, or hard palate and comprise mostly of birth defects like cleft lips. Extraoral defects include any other part of the head and neck. This defect inclines more towards trauma and tumor resurrection [39]. The obturators are prosthesis used to close palatal defects after maxillectomy, to restore masticatory function and to improve speech. Types of obturator can be broadly divided into surgical palatal obturator or fixed prosthetics, interim palatal obturator, and definitive palatal obturator. Surgical palatal obturator enables the palate and the pharyngeal muscles to contract, thereby restoring oral activities. The interim obturator is a removable prosthesis but is less preferable due to difficult retention techniques. Definitive palatal obturator extends into the nasal cavity instead of the hypopharynx and is prescribed for irreparable damage to the hard tissue or soft palate. Choosing the correct type of prostheses depends on the type of defect, age, location, and volume of residual tissue [40].

8. Conclusion

Throughout history, prosthetics have consistently improved on the degree of functional restoration possible for amputees and those with lost function. This improvement in their ability to perform ADL has led to improvements in quality of life. Recent trends in technology such as microprocessors, robotics, manufacturing, and biomechanics promise to improve both the functional and esthetic aspects of prosthetics, giving them a lifelike quality in both form and function. In this book, we explore some of these cutting-edge developments and how they will lead to better devices, ranging from limb replacements to retinal and maxillofacial prostheses. Future progress will be determined largely by patient needs, with economic restrictions leading to a desire for lower-cost yet reliable devices. Technological developments in neighboring fields such as aerospace and computer technology can lead to further innovative designs, making the future of prosthetics a promising one.

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