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Review Article

Neuroprosthetics in amputee and brain injury rehabilitation

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A B S T R A C T

The goals of rehabilitation medicine programs are to promote health, restore functional impairments and improve quality of life. The field of neuroprosthetics has evolved over the last decade given an improved understanding of neuroscience and the incorporation of advanced biotechnology and neuroengineering in the rehabilitation setting to develop adaptable applications to help facilitate recovery for individuals with amputations and brain injury. These applications may include a simple cognitive prosthetics aid for impaired memory in brain-injured individuals to myoelectric prosthetics arms with artificial proprioceptive feedback for those with upper extremity amputations. The integration of neuroprosthetics into the existing framework of current rehabilitation approaches not only improves quality-of-care and outcomes but help broadens current rehabilitation treatment paradigms. Although, we are in the infancy of the understanding the true benefit of neuroprosthetics and its clinical applications in the rehabilitation setting there is tremendous amount of promise for future research and development of tools to help facilitate recovery and improve quality of life in individuals with disabilities.

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1. Introduction

Neuroprosthetics are devices, which can augment or facilitate motor, sensory or cognitive-communication function after injury by tapping into spared brain and spinal circuits with the goal of restoring function (Borton et al., 2013). The field of neuroprosthetics dates back to the 18th century when the Italian physician and physicist Luigi Galvani discovered "animal electricity" when he activated skeletal

Abbreviations: IDT, Interdisciplinary team; EMG, Electromyography; EEG, Electroencephalogram; ECoG, Eclectrocorticography; ICMS, Intracortical microstimulation; MPL, Modular Prosthetic Limb; IMES, Implanted, myoelectric sensors; TBI, Traumatic Brain Injury; DARPA, Defense Advanced Research Projects Agency; DBS, Deep Brain Stimulator; TMS, Transmagnetic stimulation; rTMS, Repetitive transmagnetic stimulation; tDCS, Transcranial direct current stimulation; FES, Functional Electrical Stimulation.

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muscle contraction with an electric current (Piccolino, 1998). Since that time there have been significant advances in the understanding of basic biology and physiology which led to the first successful prosthesis which was developed in 1898 by Miller Hutchinson called Akouphone or more commonly known as the hearing aid (Politis et al., 2015). Then in the mid-20th century the field evolved further with the advent of the transistor and integrated circuits thereby decreasing size, improved signal amplification and provide better control of currents. Then in 1961, House and Doyle implanted the first cochlear implant where electrodes were placed on the auditory nerve causing electrical stimulation of the ear to produce the sense of sound (Mudry and Mills, 2013). Later that year, a prosthetic device was developed to address foot drop in hemiplegics due to motor loss but it was not until the mid-1990's the clinical trials proved functional electrical stimulation (FES) of motor nerves and muscles showed efficacy(Lyons et al., 2002). In the mid-1980's, the Food and Drug Administration (FDA) approved the cochlear implant. Currently there are a number of neuroprosthetic devices that have been FDA approved and are widely accepted for clinical use, such as, the deep brain stimulator (DBS) for Parkinson Disease symptoms, spinal cord stimulators for chronic pain, sacral neuromodulation for neurogenic bladder and the DEKA arm for enhanced proprioceptive feedback, grip and movement (Benabid et al., 1999; Cameron, 2004; Joussain and Denys, 2015; Resnik et al., 2012).

The field of rehabilitation medicine was established after the First World War with the goal of restoring physical, cognitive and psychological health to premorbid levels, all-while promoting functional independence and improving quality-of-life. Since that that time, advances in the acute management of injury from the civilian emergency rooms to battlefield medicine have led to an unprecedented number of individuals surviving injures leading to increased disability and morbidity. Current treatment paradigms in rehabilitation medicine involve providing a holistic interdisciplinary team (IDT) approach to management of injury and preventing secondary complications while teaching individuals to optimize impairments into functional gains (Eapen et al., 2015). The field of rehabilitation medicine has expanded considerably both in the technique of rehabilitating patients and incorporating the use of technology to supplement current rehabilitation care and to improve function. The marriage of rehabilitation and neuroprosthetics has also rapidly expanded due to an improved understanding of neuroscience, neuropharmacology, biotechnology and neuroengineering thus further enhancing care and rehabilitation. In this article we will highlight the current rehabilitation treatments for amputee and traumatic brain injury (TBI) care and describe how implementation of neuroprosthetics has advanced rehabilitation care for these populations.

1.1. Amputee rehabilitation

Since at least the time of Egypt humankind has attempted to replace amputated limbs with prosthetic devices. Ambroise Pare, a French barber surgeon, was among early battlefield surgeons who not only performed lifesaving amputations but also designed and created prostheses to replace missing body parts (Hernigou, 2013). Thus for some time society has attempted to provide prosthetic devices that would satisfy functional, cosmetic and psychological needs. In this steady evolution of rehabilitation, the overarching goal has been to provide the amputee with a prosthesis that would allow the individual to approximate the functions of the missing limb as closely as possible. Of course aside from the actual amputated limb the connection to both the peripheral and central nervous system has been severed. With the loss of this connection, voluntary control of the prosthesis becomes more problematic. The efforts to connect the brain with the prosthesis to duplicate the level of pre-amputation control and function of a limb have engendered the field of neuroprosthetics. Further discussion of this field will occur at a later point.

The type of prosthesis prescribed for any given amputee depends on the level of amputation (Murphy, 2014). For the lower extremity the primary levels are partial foot, Symes, transtibial, knee disarticulation, transfemoral, hip disarticulation and hemipelvectomy. Those for the upper extremity include finger(s), partial hand, transradial, transhumeral and shoulder disarticulation. Furthermore transradial amputations are subdivided into wrist disarticulation, long transradial, short transradial and very short transradial. Similarly transhumeral amputations have the following subdivisions: elbow disarticulation, standard transhumeral, short transhumeral, humeral neck. Dillingham studied the incidence and etiology of limb amputation from 1988 to 1996 (Dillingham et al., 2002). Amputation due to vascular conditions accounted for 82% of limb-loss discharges. Trauma was the second most common etiology whereas malignancy and congential causes were relatively rare causes. Lower extremity amputations due to vascular causes comprised 97% of limb-loss discharges. 25.8% of dysvascular amputations were at the transfemoral level and 27.6% were at the transtibial level. Amputation of a toe or toes accounted for 31% of amputations. Trauma-related amputations were more prevalent in the upper extremities (68.6% of trauma-related amputations during this period).

The goal of any prosthesis is to restore the capabilities of the missing limb to the amputee. Upper limbs and lower limbs clearly provide a wide variety of functions from practical ones such as walking to and from destinations to cosmetic ones involving issues of self-image and self-esteem to ones of intimacy and personal relationships. The greatest strides have occurred in the areas of restoring function although cosmetic concerns and even issues of interpersonal relationship have also seen progress.

For the lower extremity functional goals in relation to the prosthesis have centered around the K levels established by the Centers for Medicare and Medicaid Services. These are also known as the Medicare Functional Classification Levels. The following are some key characteristics of each level: K0-no potential for prosthetic use, K1-household ambulation, K2-community ambulation, K3-active ambulation including negotiation of barriers in the environment and ambulation that involves a variable cadence, and the K4 level which indicates the most advanced user such as someone engaged in demanding sports such as mountain biking or snowboarding. The appropriateness of prosthetic components is tailored to the K level assigned to a given individual with an amputation.

Multiple factors in addition to the K level are considered in the prescription of a prosthesis. Some of these would include the shape and nature of the residual limb, cognition, recreational and vocational pursuits, body habitus and many others. The vast majority of prostheses today are prescribed in modular form with the primary components being the socket, knee joint for above knee and knee disarticulation prostheses, pylon and foot/ankle complex (Murphy, 2014). Consideration is given also to the type of suspension (system which keeps the prosthesis on the residual limb). A basic overview of these areas will be given.

The choice of a suspension system includes vacuum systems, suction, semi-suction, the “pin and lock” system, lanyard suspension. Sleeves, liners and suspension belts can assist with suspension.

For sockets the fundamental type is the ischial containment socket where the ischial tuberosity is contained within the socket. This may or may not include a flexible, removable inner socket with or without a fenestrated, hard outer socket. In the past quadrilateral sockets were used and with this socket the ischial tuberosity rested on a ledge. Currently the quadrilateral socket is used infrequently.

Three basic types of knee joints have been used prior to the advent of microprocessor ones. These are the single axis knee, the polycentric knee and the ones utilizing a hydraulic system with a cylinder and piston that pushes either fluid or air through valves. Combinations are also in use. For example a polycentric knee might also have a hydraulic cylinder for better control during swing phase. Microprocessor knees have added a significant level of refinement to the options for knee joints. Most are more suited for amputees at the higher K-levels although some also accommodate the less active user. These knees have gyroscopes and accelerometers that sample knee and ankle joint angles