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Motorized Biomechatronic Upper and Lower Limb Prostheses—Clinically Relevant Outcomes

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Abstract

People with major limb amputations are severely impaired when it comes to activity, body structure and function, as well as participation. Demographic statistics predict a dramatic increase of this population and additional challenges with their increasing age and higher levels of amputation. Prosthetic use has been shown to have a positive impact on mobility and depression, thereby affecting the quality of life. Biomechatronic prostheses are at the forefront of prosthetic development. Actively powered designs are now regularly used for upper limb prosthetic fittings, whereas for lower limbs the clinical use of actively powered prostheses has been limited to a very low number of applications. Actively powered prostheses enhance restoration of the lost physical functions of an amputee but are yet to allow intuitive user control. This paper provides a review of the status of biomechatronic developments in upper and lower limb prostheses in the context of the various challenges of amputation and the clinically relevant outcomes. Whereas most of the evidence regarding lower limb prostheses addresses biomechanical issues, the evidence for upper limb prostheses relates to activities of daily living (ADL) and instrumental ADL through diverse outcome measures and tools.

Introduction

Despite an expected decrease in incidence of lower extremity amputations [1], the total number of amputations are estimated to increase from 1.6 million in 2005 to 3.6 million individuals by 2050 in the United States [2]. It is estimated that 65% of amputations involve the lower limb and 38% of all amputations are major lower limb amputations [2]. Lower limb amputations are classified as major if occurring at the foot or more proximal and upper limb amputations are classified as major if occurring at the wrist or more proximal. Upper limb amputations constitute 35% of all amputations, but only 8% are major [2]. Major upper or lower limb loss is a severe form of impairment affecting activity, body functions, body structure, and participation classified by the level of functioning and disability [3]. With the upper limb population, there is a discrepancy between the classification of major amputation (proximal to the wrist) and impact on function. The American Medical Association [4] rated the loss of all fingers and thumbs with the palm intact as a 54% whole person impairment whereas loss of a lower limb at the hip level (anatomically considered a major amputation) is rated as a 40% impairment. Generally, functional impairment increases the more proximal the upper or lower limb of amputation is for all ages and activity groups [5,6].

Biomechatronic prostheses are defined as prosthetic solutions that integrate biology, mechanics, and electronics. They are described as functional components within the ISO structure of prosthetic definitions (13405-2:2015(E)), and below we will explain their functions and how they may affect the rehabilitation of either the person with lower limb or upper limb amputation.

Biomechatronic prostheses reduce limitations of standard prosthetic devices which are limited to 1 activity or a set of gait tasks and require constant manual adjustment of their inherent characteristics to follow the user's needs through activities of daily living (ADL). Biomechatronic devices have the capacity to extend their operational

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range through dynamically reconfiguring their operating point based on the input from the environment or user.

The purpose of this article is to review how the biomechatronic technology may impact users' rehabilitation outcomes after limb amputation. The selection of references is intended to provide an idea of the state-of-the-art components in prosthetics and a look into future solutions.

Literature Review Methodology

A literature search was conducted in December 2017 and January 2018. With a limited pool of publications in this young field of research, we searched for publications after 1990 using PubMed, Cochrane, Web of Science, Scopus, and ProQuest, entering an all-text search of ampu*, biomech*, power, passive, rehab*, proth* metabolic and combinations with AND and OR. The results were screened by 2 subject matter experts, subdivided into lower limb prostheses (LLPs) and upper limb prostheses (ULPs). Only articles in the English language reporting on clinical outcomes that specified a motorized actively powered prosthetic component fitted with a conventional socket were considered. Publications reporting on technology optimization or not measuring primarily clinical outcomes, were excluded. Publications were added by the authors and obtained from personal communication with researchers and engineers in the field of biomechatronic prostheses.

Summary of Published Literature

Publications found on biomechatronic prostheses are listed in Tables 1 and 2.

Discussion

Lower Limb Prostheses

The provision of an LLP is reported to vary between 30% and 100% [52,53]. The prosthetic prescription is meant to be a multidisciplinary team decision based on a thorough evaluation of the patient's wishes, medical and cognitive status, and factors such as wound healing, residual limb health, contralateral limb health, and rehabilitation goals [54]. Studies estimating the use of LLPs ranges from 11% to 22% abandonment [53,55] after 1 year. One to 7 years after receiving their first lower limb prosthesis, only 11% to 37% use their prostheses indoors.

The LLPs support the body weight and allow balance and mobility during transfers and terrain and gait speed adaptations during walking or even nonambulatory functions with the aim of imitating the lost physiological functions. This review focuses on literature including motorized and actively powered microprocessor-controlled knees and ankles (A-MPK, A-MPA) and actively powered knee and ankle combinations (A-MPK-A) that report on clinically relevant outcomes (Figure 1).

Not considered in this review are passive microprocessor-controlled knees and ankles (P-MPK, P-MPA) and non—microprocessor-controlled knees and ankles (N-MPK, N-MPA) but mentioned as comparisons to the actively powered technology. The P-components are defined as biomechatronic as they mimic eccentric or isometric muscle function or springlike elastic function. In addition, the motorized actively powered prosthetic components, reviewed in this article, provide positive power to a joint and thereby add functionality.

With the focus on clinically relevant outcomes, we subdivided the LLP section by typical challenges encountered in an amputee's rehabilitation related to prosthetic use and comparing them to the nonamputee population as follows:

1. increased frequency of stumbles and falls [56], impaired balance [57];
2. increased metabolic cost [5], slower walking speeds [58];
3. issues with gait abnormalities/deviations [59]; and
4. ADL, that is, sit to stand, stand to sit [60], negotiating uneven terrain [61], ramps [62], and stairs [63].

The development of biomechatronic prostheses is an attempt to improve the restoration of physiological function and thereby mitigate the challenges listed above. The A-MPKs and A-MPAs deliver mechanical power, autonomously adapt to the user's changing movements or aim to restore sensory feedback [64] and volitional control [65]. Together with a motor that provides mechanical power, a control framework [66] is needed to close the control loop. As described by Tucker et al, a control framework generally consists of 3 levels, in which the high level perceives the users' intent, translated by the midlevel into defined activity modes that the low-level controller tracks and applies to the given law, that is, impedance, velocity, position, torque, or clearance, to execute the command. High-level activity mode recognition has a latency when switching activity, that is, from stair to level ground, and the "critical time" needed by the system to switch modes must be reduced [67] to make the individual feel secure with the device performance. Another relevant aspect for development of control strategies are the variety of amputees and their individual gait adaptations and motion patterns. The system robustness is critical to accommodate for deviations from expected conditions. There are examples of long-term users of A-MPK-A using surface electromyography (EMG) to interact with the onboard sensors of the prosthesis [68] to accurately respond to the user's intent.

Fall Risk / Balance

Amputees fall more often than their able-bodied counterparts [56]. Compared with N-MPK and N-MPA,