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Towards a Smart Semi-Active Prosthetic Leg: Preliminary Assessment and Testing

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Abstract: This paper presents a development of a semi-active prosthetic knee, which can work in both active and passive modes based on the energy required during the gait cycle of various activities of daily livings (ADLs). The prosthetic limb is equipped with various sensors to measure the kinematic and kinetic parameters of both prosthetic limbs. This prosthetic knee is designed to be back-drivable in passive mode to provide a potential use in energy regeneration when there negative energy across the knee joint. Preliminary test has been performed on transfemoral amputee in passive mode to provide some insight to the amputee/prosthesis interaction and performance with the designed prosthetic knee.

Keywords: Bionics, Biomedical systems, Transfemoral amputee, Smart Bio-leg, Prosthetic knee, Prosthetic systems integration, Biomechatronics.

1. INTRODUCTION

Thousands of lower limb amputations are carried out around the world every year due to complications of diabetes, circulatory and vascular disease, trauma, or cancer (Cristian, 2005). The amputation process is one of the methods when reconstruction surgery cannot provide an adequate solution or the injury to the limb is too severe to recover. The lower limb amputation results loss in mobility of individuals which degrades the quality of amputees' life and lack in functional performance to maintain their activities of daily livings (ADLs). After the amputation was performed the most important goal of healthcare provider must be focused on amputee's return to his/her routine ADLs in the shortest period of time. After the recovery of a subject, a prosthetic leg is an essential assistive device to recover some of missing locomotion functions. During rehabilitation process, the physician assesses the amputee potential level of functional mobility and ability to use lower limb prosthesis and then classifies the lower limb amputees into a range of K-levels by providing a score (K0, K1, K2, K3, K4) (Hordacre et al., 2014). This classification classifies the transfemoral amputees (TFA) from do not have the ability to ambulate safely without assistance (K0) to who exceeds basic ambulation skills and exhibits performance of high impact stress activities (K4). This type of classification helps prosthetist/physician as a guiding rules for prosthetic prescription.

The lower limb prosthesis is defined as a device that substitutes the function of a missing limb either due to amputation or a congenital defect (Pitkin, 2010). The commercial lower limb prosthesis consists of off-the-shelf components and a custom-made socket that are attached to the user's residual limb (stump) as shown in Figure 1. The main prosthetic components of a TFA are socket, prosthetic knee and prosthetic ankle. The purpose of the prosthetic socket is to establish connect between the amputee's residual limb and the prosthesis in order to transmit forces from/to the stump (residual limb) to/from the prosthesis (amputee/prosthesis interaction) while the lower limb prosthesis is used to transfer the weight of the amputee to the ground and provide the main requirements for mobility (prosthesis/environment interaction).

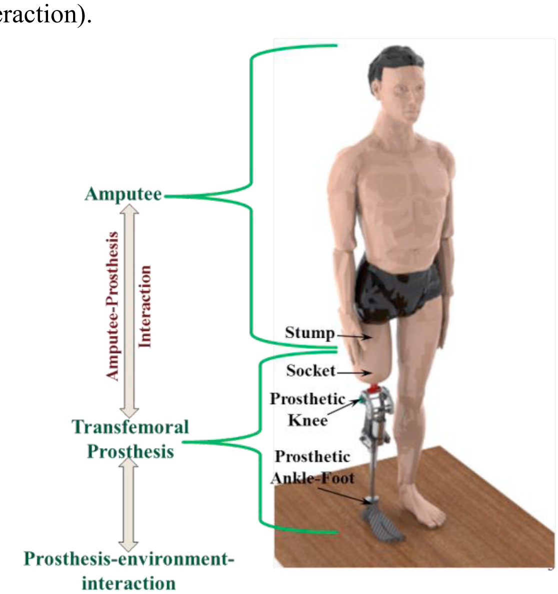

Fig. 1. Prosthetic leg components for transfemoral amputees (TFA).

Prostheses stability and comfort which partially maintained through proper fitting of the socket to the stump, is quite critical for amputees; hence, a well-constructed prosthesis system is important to provide stability and comfort ADLs.

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The TFA gait is associated with compensatory mechanisms that leads to the gait asymmetry due to lack of movements in the knee and the ankle joints to overcome the functional losses. One of the challenges an amputee experiences is to find an efficient prosthetic leg to decrease the gait asymmetry and metabolic energy consumption. Hence, developing a proper prosthetic leg system can help in reducing such compensatory efforts required from amputees to ambulate. In this paper, a development and preliminary testing of a semi-active instrumented prosthetic knee is presented.

Over the last few decades, a technological revolution in the prosthetic industry has taken place as a consequence of state-of-the-art advancements in materials, electronics, sensing, and actuators. Currently available lower limb prostheses can be divided into three main groups: *purely passive*, *active-damping controlled* and *powered* controlled prostheses.

Purely passive prostheses depend on mechanical systems such as a polycentric knee joint, four bar linkages, locking mechanisms and passive hydraulic/pneumatic cylinders. This type of prostheses requires a significant voluntary control effort from amputees. *Active-damping controlled* prostheses were introduced during the 1990s with the release of the Intelligent Knee (Nabtesco, Japan), the Intelligent Prosthesis (IP) (Zahedi, 1998) (Chas. A. Blatchford & Sons, UK), and the C-Leg (Otto Bock, German). For example, the C-leg (Otto Bock) controls the damping effect using a hydraulic cylinder, and monitors the knee flexion and extension by means of an angle sensor. Other commercial prostheses use either a pneumatic swing control unit; such as the smart IP (Chas. A. Blatchford & Sons, UK), magnetoroheological fluid stance and swing control unit as in the REHO knee (Össur, Iceland) , or combination of hydraulic stance and pneumatic swing control. More advanced intelligent active-damping controlled prostheses were recently presented, which are adjusting the damping torque during the gait using microprocessor, such as Orion microprocessor knee (Zahedi et al., 2005) and the Genium microprocessor knee (OttoBock). The microprocessor prostheses use a wide variety of sensors to measure the load transfer and the knee angle in order to determine when knee flexion and extension is needed and to avoid buckling the knee during stance phase and provide safe progression during walking.

In the case of *active-damping controlled prostheses*, above-knee amputees often compensate for the loss of function in both the knee and the ankle by regulating the transferred energy via the residual limb. This is acceptable during most level ground walking phases and while descending stairs, as the net energy required from the knee is negative and needs to be absorbed. However, these prostheses cannot provide the positive power required during some tasks or walking phases as for early push off during level ground walking and ascending stairs. *Powered prostheses*, such as the Victhom knee (Bedard, 2004, Bedard, 2006, Bédard and Roy, 2008), commercially known as the Power Knee and distributed by Ossur are fully actuated. These prostheses are powered using either DC motors (Fite et al., 2007, Sup et al., 2008, Goldfarb, 2013, Goldfarb et al., 2013, Shultz et al., 2014), or pneumatic actuators (Sup and Goldfarb, 2006). Although these prostheses are able to supply positive power, they consume more power than the human joint (Unal et al., 2014). The reason for this is that they use an external power source to generate motion which deteriorates the overall dynamic performance of the system (Unal et al., 2014) in addition to the energy conversation efficiency of the actuation system while the walking process of humans is considered to be mechanically energy-efficient cyclic activity as consequences of comfortable dynamics interaction between human segments. Also, the human muscles show high levels of activity during stance phase, and less activity during the swing phase for level ground walking (Collins et al., 2005). With regard to robotic systems, for example, Honda's ASIMO, which is a completely powered robot, represents ‘specific cost of transport’ of 3.23 (Hobbelen and Wisse, 2007, Collins and Ruina, 2005) to travel unit distance while the Cornell efficient semi-powered biped expends 0.20 (Collins and Ruina, 2005, Collins et al., 2005) the same ‘specific cost of transport’ as humans. The passive dynamic walking concept was introduced in 1990 by McGeer (McGeer, 1990b, McGeer, 1990a) such systems are more efficient than powered bipedal walkers as their movements are sustained by the dynamic swing of the limbs rather than powered actuators. The consequence is that completely passive dynamic walking machines powered only by gravity can walk like humans on modest inclines and with a small initial impulse providing an excellent natural gait on slopes without using actuators and relying solely on gravity, inertia and energy transfer between the segments of the walking machine. This produces very energetic and efficient walking cycle based on just the machine dynamics without the need for a complex control or actuation system.

This explains how above-knee amputees with purely passive or actively damping controlled prostheses can walk by controlling the movements of the residual limbs. Energy is transferred from the residual limbs to the prosthetic knee and produces movement of the prosthetic knee due to the dynamic coupling effect. The amputee’s hip is thus considered the main engine and power source for voluntary control of the prosthesis. However, this requires more metabolic energy and mental effort in comparison to healthy subjects. McNealy et al. (McNealy and Gard, 2008) have shown that energy of the hip joint in TFA has been increased compared with able-bodied subjects . Despite the technological advancement in the prostheses sector, the lower extremity prosthetic legs still have long way to fully emulate human biological limb functionality and provide efficient functional artificial limb.

This paper introduces the mechatronics system design and development of an instrumented semi-active prosthetic leg. This prosthetic knee has back-driveable capability to operate passively in unactuated phase depending on the amputee-prosthesis-environment system dynamics in addition to providing assistive power in actuated phase when positive energy is required. Initial testing of the prosthetic leg on transfemoral amputee in unactuated phase was presented in this paper.

2. BIOMECHANICAL CONSIDERATIONS FOR EFFICIENT DESIGN

Bipedal walking is the human body’s natural method for moving from one location to another and is usually the most convenient way to travel distances. Bipedal walking uses a