SimBionics: Neuromechanical Simulation and Sensory Feedback for the Control of Bionic Legs

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***Abstract*— Lower limb prosthetic technology has greatly advanced in the last decade, but there are still many challenges that need to be tackled to allow amputees to walk efficiently and safely on many different terrain conditions. Neuro-mechanical modelling and online simulations combined with somatosensory feedback, has the potential to address this challenge. By virtually reconstructing the missing limb together with the associated somatosensory feedback, this approach could enable amputees to potentially perceive the bionic legs as extensions of their bodies. A prosthesis equipped with such biologically inspired closed-loop control could duplicate the mechanics of walking far more accurately than conventional solutions. The project SimBionics aims to explore these opportunities and advance the state-of-the-art in lower limb prosthesis control.**

I. INTRODUCTION

THE human musculoskeletal system is complex but optimized to provide safe and efficient locomotion [1]. The central mechanisms in the motor control of locomotion include neuromechanical synergies (i.e. at joint, muscle and neural levels) that establish coupling between different joints, segments and muscles [2], [3]. The neuromechanical synergies result in cyclical and automated movement patterns with rhythmic and coordinated motions of the trunk and lower extremities. However, after an amputation, the synergies are compromised, and the motions of the joints of a prosthetic device are not in synchrony with the movement of the rest of the body, which often results in non-natural compensatory movements. The compensatory movements have been considered as the leading cause for the lack of comfort, higher energy requirements during walking and standing, and cumulative trauma disorders [4].

In recent time, the mechatronic knee and ankle prostheses have improved substantially in terms of technology, and now a range of solutions from semi- to fully-actuated are available. However, robust and intuitive control of these devices is still a major challenge. Most commercial and research systems are controlled by using a hard-coded set of rules that trigger predefined changes in the damping and activation of the knee and ankle joints [5], [6]. This is in a sharp contrast to the activation of biological joints, which is based on continuous modulation of impedance (e.g. stiffness) and active forces (e.g. torque) in response, or in advance, to biomechanical demands of the task and the environment (e.g., terrain roughness and inclination). Furthermore, none of the current commercial prostheses provides explicit somatosensory feedback to the user. Therefore, the user needs to rely on incidental cues (e.g., forces through the socket) or visual observation to assess the state of his/her lower limb [7] This leads to increased cognitive load as well as inefficient walking with asymmetric gait, slower cadence, and poor balance [8], [9]. The research on this topic is scarce, and the proposed non-invasive feedback systems are rather simple. Typically, the systems are based on a single stimulation point (a vibration motor) delivering simple information (e.g., heel strike). Also, due to delays in the embedded and biological system, the prosthesis user perceives and interprets the stimulation signal with a considerable delay, which makes it less effective in activities of daily living. This is far from the timely, continuous and spatially distributed feedback that able-bodied humans receive from their lower limbs.

II. NEUROMECHANICAL SIMULATION FOR CONTROL OF PROSTHESIS

Using neuromechanical modelling and online simulations of the musculoskeletal system to control assistive device is not a new concept and have been proposed by several research groups in the past. Eilenberg et al. [10] proposed a muscle reflex controller based on simulation studies that mimic the neuromechanics of the ankle plantar flexor. This type of controller allows adaptability of an ankle prosthesis to different conditions by emulating the spinal reflexes that are activated while walking. Although simple, the approach has proven to be effective in some activities of daily living. For examples, the Empower ankle prosthesis from Ottobock uses this control concept to generate the desire output power of the device while walking. However, due to the reactive nature of this approach, it can only provide support in certain activities. Also, this approach cannot be easily scaled for controlling a more complex system (e.g. knee-ankle prosthesis) or a semi-active prosthesis that does not provide positive torque but changes the joint characteristics (e.g. stiffness, dampening).

Neuromechanical simulations have also been proposed for the control of other assistive and rehabilitation devices. Pizzolato et al. [11] provide a general outlook on how neuromusculoskeletal modelling could be integrated with a variety of rehabilitation devices to improve the performance of the human-machine interface. Durandau et al. [12] successfully applied neuromechanical modelling to allow a

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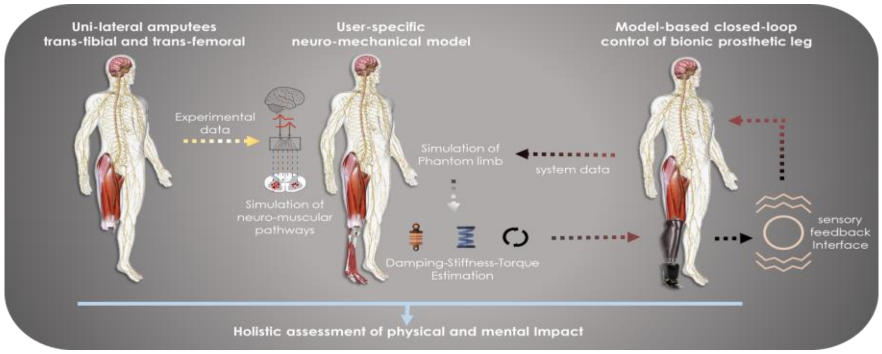

Fig. 1. The overview of the SimBionics concept. Neuromechanical modeling and online simulation will be combined with somatosensory feedback to provide a biologically plausible closed-loop control of an active lower limb prosthesis.

neurologically impaired patient to achieve voluntary control of a lower limb exoskeleton. A similar approach was employed by Sartori et al. [15] for the continuous control of a prosthetic hand. The results of these and other studies [13] [14] illustrate the potential of neuromechanical modelling and simulation for developing a biologically plausible control of wearable robotic systems. Specifically for lower limb amputees, this approach can be used to reproduce and approximate the missing limb by using its virtual substitute. The virtual limb will be simulated online to calculate the musculoskeletal dynamics and kinematics during balance and locomotion. This could be a game changer in the field of lower limb prostheses. A patient-specific simulation can be used to enhance the control of an assistive device by calculating the torque and impedance profiles that are optimal for that specific user during the whole gait cycle. Importantly, as demonstrated in [15], the neuromechanical simulation can enable continuous and voluntary control of multiple degrees of freedom in a myoelectric prosthetic hand by amputees.

III. SimBionics Project

SimBionics Project is funded by the EU - Marie Curie Skłodowska Action as a European Industrial Doctorate research network. The goal is to combine neuro-mechanical modelling and sensory feedback into a real-time, closed-loop and biomimetic control framework for bionic legs.

To achieve this goal, we will implement a control framework in which the feedforward control and somatosensory feedback signals are internally consistent (Fig 1). To this aim, both components of the control loop will be developed in parallel throughout the project, with specific emphasis on their successful integration and interaction. Thus, the characteristics of the somatosensory feedback (e.g., resolution, range, and bandwidth) will complement the dynamics of the control commands and the system and vice versa. By doing so, we expect that the control performance and embodiment of the device will significantly increase. Importantly, the neuromechanical model will be able to estimate biomechanical parameters simultaneously within (e.g. joint stiffness and damping, together with torque) and across joints (e.g. knee and ankle). In addition, the feedback will be delivered using multichannel stimulation to increase the quantity of information that can be transmitted to the user. The tactile stimulation will be modulated in time and distributed spatially, mimicking the pressure patterns that are characteristic for the biological feedback. This approach will thereby yield a robust, safe and intuitive interface between transfemoral amputees and the bionic leg while walking and balancing during the activities of daily living.

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