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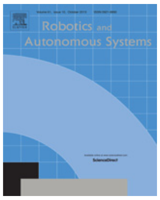

# Tele-impedance based assistive control for a compliant knee exoskeleton

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## HIGHLIGHTS

- We propose a tele-impedance based assistive control for a knee exoskeleton.
- An EMG-driven biomechanical model estimates the net torque and joint stiffness trend index.
- The outputs of the model are used to derive the trajectory and stiffness of the exoskeleton's impedance controller.
- The exoskeleton can generate assistive actions that are volitionally controlled by the user's muscle activity.

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## ABSTRACT

This paper presents a tele-impedance based assistive control scheme for a knee exoskeleton device. The proposed controller captures the user's intent to generate task-related assistive torques by means of the exoskeleton in different phases of the subject's normal activity. To do so, a detailed musculoskeletal model of the human knee is developed and experimentally calibrated to best match the user's kinematic and dynamic behavior. Three dominant antagonistic muscle pairs are used in our model, in which electromyography (EMG) signals are acquired, processed and used for the estimation of the knee joint torque, trajectory and the stiffness trend, in real time. The estimated stiffness trend is then scaled and mapped to a task-related stiffness interval to agree with the desired degree of assistance. The desired stiffness and equilibrium trajectories are then tracked by the exoskeleton's impedance controller. As a consequence, while minimum muscular activity corresponds to low stiffness, i.e. highly transparent motion, higher co-contractions result in a stiffer joint and a greater level of assistance. To evaluate the robustness of the proposed technique, a study of the dynamics of the human–exoskeleton system is conducted, while the stability in the steady state and transient condition is investigated. In addition, experimental results of standing-up and sitting-down tasks are demonstrated to further investigate the capabilities of the controller. The results indicate that the compliant knee exoskeleton, incorporating the proposed tele-impedance controller, can effectively generate assistive actions that are volitionally and intuitively controlled by the user's muscle activity.

## 1. Introduction

Powered exoskeletons have undergone continuous technological development over the past few years and have found various applications from military use to patient rehabilitation. Military exoskeletons' purpose is to augment the soldier's muscular force and endurance in carrying heavy loads [1]. On the other hand, rehabilitation exoskeletons aim at recovering the neuromusculoskeletal function of stroke or post-surgical patients [2–4], while assistive exoskeletons can assist elderly or individuals with mobility disorders during demanding, in terms of power, motion tasks [5–7].

Independently from the use, exoskeletons are robotic devices that are worn by the humans. Therefore, the application of forces in an appropriate manner as regards the timing, magnitude, direction and location on the human body, is a prerequisite [8]. In other words, the exoskeleton should effectively assist the natural human motion ensuring the safety and comfort of the user, and

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that his/her agility is not deteriorated. To address this immense challenge researchers have incorporate the detection of the user's intent into the control of exoskeletons. Common approach is to use joint angles to infer about the subject's posture [9], or ground reaction forces measurements to estimate the desired torques with an inverse dynamic model [1]. In [10] authors proposed an observer to correct the desired joint torques computed from the ground reaction forces. However, due to the increased need in exoskeletons for achieving desired response to disturbance, the integration of biological signals into the exoskeleton control has gained a lot of attention by many researchers over the last decade [6,11,12].

Furthermore, as exoskeletons not simply cooperate with the humans but assist or supplement the human motion (e.g replace muscle's work), it has been deemed imperative to develop exoskeletons that exhibit biological behavior and performance [13]. This is mainly related to the physical properties of the musculotendinous unit acting on the human joints and their resultant impedance. In particular, several biomechanical studies of human movement report that the impedance profiles of the human joints vary substantially during motion [14,15]. Therefore, exoskeletons should accordingly respond and adapt to these impedance profiles [16]. In this manner, their use becomes more effective and intuitive, while the agility and comfort of the user wearing the device are significantly increased.

To this end, researchers have put a lot of effort into employing variable impedance systems into exoskeletons, orthoses or prostheses that will be able to produce naturally human-like mechanics [17,18]. However, the planning of the impedance profiles of these devices has been deemed a highly challenging task and yet relies on indirect approaches such as modeling, gait phase detection, or off-line learning and optimization techniques. For instance, in [19] the active impedance of an ankle orthosis is modulated during the gait cycle using a finite-state machine that is triggered by ground reaction forces and joint angles. Additionally, the authors in [20] select to adjust the knee joint impedance of an assistive exoskeleton during motion with the target stiffness, damping and inertia parameters being identified based on the Recursive Least Square (RLS) method. Furthermore, variable-impedance assistance has been implemented in robot-aided gait rehabilitation to achieve patient-cooperative training and more interactive robotic therapies, that lead to an enhanced rehabilitation outcome [21,22]. In the latter an adaptive impedance controller utilizes an inverse-dynamics based estimation of the user's torque in order to adapt robotic assistance.

Alternatively to these approaches, which are constrained either by highly nonlinear models [20,22] or by optimization criteria problems [23], in this series of preliminary case studies we propose to select and control the impedance of the exoskeleton joint based on real-time stiffness measurements of the corresponding human joint. The current manuscript is an extended and enriched version of the initial work in [24] to provide an exhaustive analysis and discussion especially on the proposed control scheme and its experimental evaluation. Particular attention is paid to the dynamics of the physical human–exoskeleton system, the performance of the controller in the frequency domain, and the stability of the closed-loop system both in steady state and time-varying condition.

The presented control method requires modeling of musculoskeletal bio-feedbacks such as muscular forces-moments. This can be addressed with two general approaches. Inverse dynamic methods, investigate this problem by means of measurements of the joint positions and applied external forces. However, several drawbacks are attributed to such techniques [25]. For instance, the muscles acting on each joint are grouped and divided to agonist and antagonist blocks and consequently, the external flexion and extension moments are balanced. Therefore, these methods are not reliable enough for individual estimation of muscular forces since a priori assumptions are made on the role of individual muscles during the optimization of a predefined cost function [26]. The problem grows when modeling complex tasks which combine highly nonlinear muscle activation and contraction dynamics and geometry variations. As a result, a second group of general solutions which are associated with forward dynamic approaches have been proposed. In these methods, neural commands are extracted and fed to the detailed neuro-musculoskeletal model of the limbs [27].

Therefore, an EMG-driven musculoskeletal model of the knee joint has been developed that blends results of different biomechanical studies. The outputs of the model are then exploited in real-time by the impedance controller implemented in the exoskeleton joint. Regarding the hardware, a knee exoskeleton was used for this study that is a passively compliant device demonstrating inherently soft interaction based on the series elastic actuation (SEA) principle [2,8]. We envisage this assistive device combined with the proposed control to assist either individuals with limited physical capabilities (e.g. elderly) during their activities of daily living, or healthy people during repetitive tasks at work for reducing their average muscle forces. However, the presented control algorithm could be eventually used under conditions (i.e. sound muscle excitations) in a rehabilitation setting for improved patient-driven therapies.

The rest of the paper is structured as follows. Section 2 presents the musculoskeletal model of the knee joint while Section 3 discusses the knee model identification and calibration. Section 4 describes the exoskeleton hardware and Section 5 introduces the tele-impedance based assistive control scheme. Section 6 discusses the dynamics of the physical system and the stability of the proposed control, while Section 7 demonstrates the experimental trials. Moreover, Section 8 provides a general discussion on this work and Section 9 addresses the conclusions.

## 2. EMG-driven musculoskeletal model

This section describes mathematically the electromyography-driven musculoskeletal model of the human knee joint, which is used to account for the net torque and joint stiffness trend index. Three antagonistic muscle groups (six muscles) which are denoted as being the dominant surface muscles acting on the knee joint were chosen in order to form the presented musculoskeletal model. Fig. 1 illustrates the anatomy of the thigh muscles and the placement of the electrodes. In particular, six electrodes (Bagnoli-16, Delsys Inc.) were attached to the extensor [rectus femoris (RF), vastus medialis (VM) and vastus lateralis (VL)] and flexor [biceps femoris (BF), semimembranosus (SM) and semitendinosus (ST)] muscles. Furthermore, for the reader's convenience in Fig. 2 is depicted an overview of the adopted model structure which consists of the muscle activation dynamics, muscle contraction dynamics and musculoskeletal geometry sections. As shown, from the processed electromyography of each muscle $u_i$ are derived the muscle activations $a_i$ and then the muscle–tendon forces $F_i^{mt}$ which result in the net torque $\tau_{net}$ and the knee joint stiffness trend $STI$.

### 2.1. Activation dynamics

Electromyography (EMG) signals inherit patterns of activations of involved muscles. In order to extract muscular activations, the raw EMG signals must be processed. First, these signals are high-pass filtered to remove offsets and movement artifacts. This stage is followed by full rectification techniques [28]. Consequently, the resulting signals are low-pass filtered and normalized in order to provide traces of the neural activation of the muscles. In