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Robotic assessment of neuromuscular characteristics using musculoskeletal models: A pilot study

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ABSTRACT

Objective: Non-invasive neuromuscular characterization aims to provide greater insight into the effectiveness of existing and emerging rehabilitation therapies by quantifying neuromuscular characteristics relating to force production, muscle viscoelasticity and voluntary neural activation. In this paper, we propose a novel approach to evaluate neuromuscular characteristics, such as muscle fiber stiffness and viscosity, by combining robotic and HD-sEMG measurements with computational musculoskeletal modeling. This pilot study investigates the efficacy of this approach on a healthy population and provides new insight on potential limitations of conventional musculoskeletal models for this application.

Methods: Subject-specific neuromuscular characteristics of the biceps and triceps brachii were evaluated using robot-measured kinetics, kinematics and EMG activity as inputs to a musculoskeletal model.

Results: Repeatability experiments in five participants revealed large variability within each subjects evaluated characteristics, with almost all experiencing variation greater than 50% of full scale when repeating the same task.

Conclusion: The use of robotics and HD-sEMG, in conjunction with musculoskeletal modeling, to quantify neuromuscular characteristics has been explored. Despite the ability to predict joint kinematics with relatively high accuracy, parameter characterization was inconsistent i.e. many parameter combinations gave rise to minimal kinematic error. Significance: The proposed technique is a novel approach for in vivo neuromuscular characterization and is a step towards the realization of objective in-home robot-assisted rehabilitation. Importantly, the results have confirmed the technical (robot and HD-sEMG) feasibility while highlighting the need to develop new musculoskeletal models and optimization techniques capable of achieving consistent results across a range of dynamic tasks.

1. Introduction

Neurological injuries such as cerebral palsy and stroke are among the leading causes of physical disability in the developed world [1]. The effects of these injuries commonly include impairments such as muscle weakness, increased joint spasticity and reduced joint coordination which lead to functional deficits.

Physical and cognitive rehabilitation is typically undertaken to improve impaired motor function resulting from neurological injury. Current rehabilitative care is goal-orientated, focusing on the assessment of quantifiable time-dependent goals against a set of desired patient-specific outcomes [2]. These treatments are often performed at the functional or impairment level, with little or no ability to accurately assess underlying neuromuscular characteristics.

Neuromuscular characteristics relating to muscle force production, muscle viscoelasticity and voluntary neural activation [3] can be estimated using phenomenological models and may provide insights into the underlying physiological properties of muscle [4]. Characteristics such as muscle fiber stiffness and viscosity, could be used as objective measures to test interventions and track patient progress during therapy [5].

The ability to non-invasively diagnose and track underlying physiological characteristics, in-vivo, may help unveil neural recovery mechanisms and could be used to evaluate existing therapies and develop new individualized rehabilitation treatments [6]. For example, it is assumed that hypertonia in spastic cerebral palsy leads to increased muscle fiber stiffness [7], and the ability to directly quantify changes in fiber stiffness may provide further insight into treatment effectiveness. Treatments that may give rise to structural changes in muscle include physiotherapy, splinting and

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Botulinum Neurotoxin-A. Previous studies regarding non-invasive diagnosis techniques have been for the knee [8], ankle [5] and wrist joint [9]. These model-based approaches use electromyographic (EMG) activity to infer estimates regarding the underlying physiological properties.

Rehabilitation robotics is an area of growing interest in both research and commercialization. There is an increasing demand for physical rehabilitation and a need to increase accessibility to therapy. The ability to provide patients with in-home physical rehabilitation and automatically monitor their progress is highly sought after [10]. To our knowledge, the use of robotic exoskeletons as a supplementary tool for characterizing muscle properties has yet to be explored. Previous integration of robotic exoskeletons with musculoskeletal modeling has focused on the development of control strategies for rehabilitative training [11–13].

This paper proposes a novel approach to assess an individuals neuromuscular characteristics through the use of rehabilitative robotic exoskeletons (including HD-sEMG) and computational neuro-musculoskeletal modeling. A neuro-musculoskeletal model for the elbow, in combination with an upper arm exoskeleton, has been implemented to evaluate neuromuscular characteristics for the biceps and triceps muscle groups. An overview of the proposed technique is illustrated in Fig. 1.

The aim of this study was to conduct a pilot trial on a healthy population to investigate the efficacy of our technical approach and evaluating neuromuscular characteristics using a Hill-based neuro-musculoskeletal model. The objectives were (1) to validate the ability to obtain subjects neuromuscular characteristics that predict/replicate human dynamics; (2) evaluate the reliability of the subject specific assessment; (3) determine the feasibility of using robotics with neuromuscular modeling as an assessment tool.

2. Methods

2.1. Robotic exoskeleton

An upper limb robotic exoskeleton designed for rehabilitation therapy was used for the experiments [14]. The exoskeleton has one active degree-of-freedom (DOF), driven by a series elastic actuator, for flexion/extension at the elbow joint, and two passive DOF to account for pronation/supination of the forearm as well as humeroulnar articulation. Hall effect sensors at the active joint accurately track elbow angle and torque. A robust, low-level sliding-mode controller is implemented to control human-robot interaction torques, allowing the exoskeleton to carry out assistive and resistive rehabilitation exercises.

2.2. EMG acquisition and processing

EMG activity was captured using high density surface electromyography, or HD-sEMG. Compared to traditional single channel electrodes, this multi-channel system provides additional redundancy to increase measurement robustness. A recent study has also shown HD-sEMG can improve muscle force estimation accuracy [15].

An ActiveTwo HD-sEMG system (*BioSemi B.V., Amsterdam, Netherlands*) was used to record EMG from the biceps and triceps brachii. In total, 64 channels were recorded, 32 per muscle. A 16-by-2 electrode array was placed on each muscle, with both rows aligned parallel along the muscle fiber direction. The center of the electrode arrays was placed on the biceps brachii and triceps long head according to the well-established recommendations given by Ref. [16]. This follows the assumption that the activation in each head is indicative of the activation of the entire muscle [17,18].

All channels were sampled at 2048 Hz. The raw EMG signal was first band-pass filtered through a fourth-order Butterworth filter with cut-off frequencies at 10 Hz and 512 Hz. A 50 Hz notch filter removed mains noise, followed by a smoothing RMS filter. Using a monopolar configuration, a composite signal was generated by applying a moving maximum filter across all channels, capturing the true skin potential while accounting for poor electrode-skin contact. This filtered EMG signal was normalized for each muscle group using the maximum recorded peak during maximum voluntary contraction.

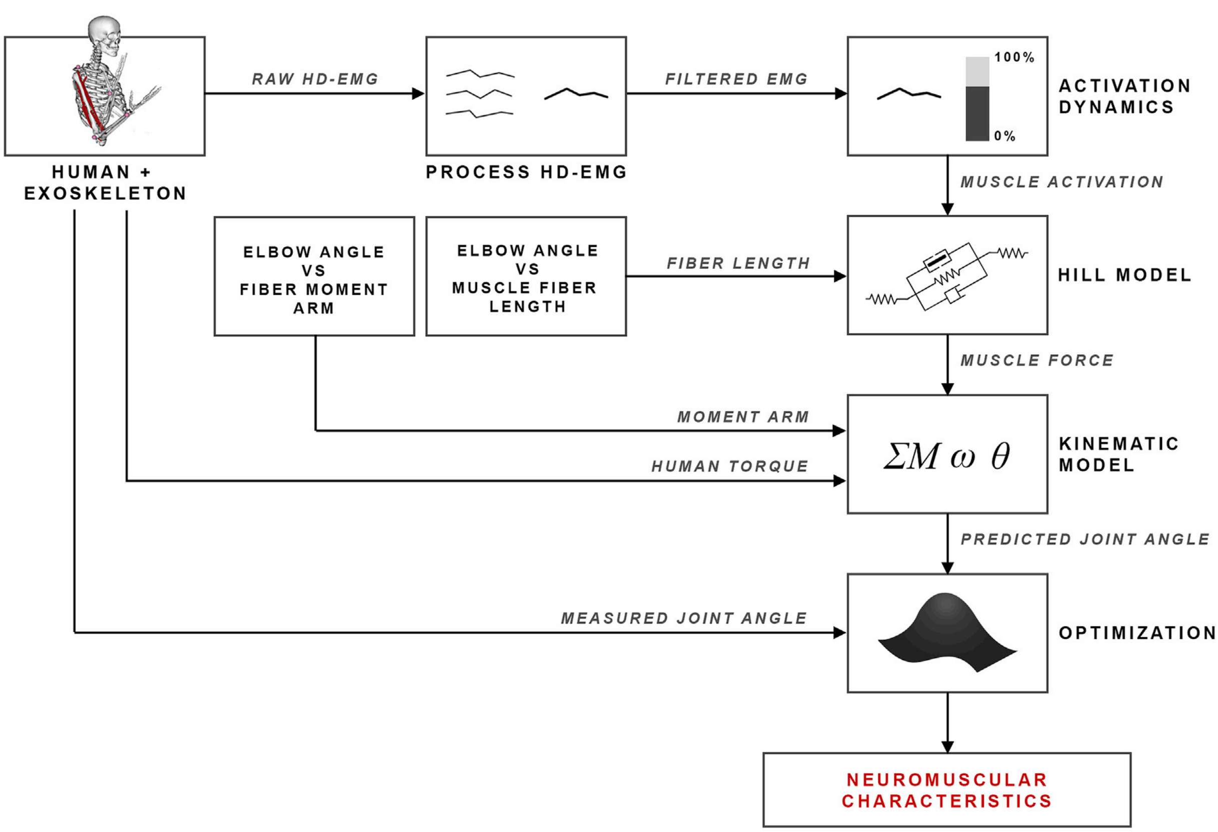

Fig. 1. Non-invasive in-vivo neuromuscular characterization using neuro-musculoskeletal modeling techniques.