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A patient-specific EMG-driven neuromuscular model for the potential use of human-inspired gait rehabilitation robots

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ABSTRACT

A patient-specific electromyography (EMG)-driven neuromuscular model (PENm) is developed for the potential use of human-inspired gait rehabilitation robots. The PENm is modified based on the current EMG-driven models by decreasing the calculation time and ensuring good prediction accuracy. To ensure the calculation efficiency, the PENm is simplified into two EMG channels around one joint with minimal physiological parameters. In addition, a dynamic computation model is developed to achieve real-time calculation. To ensure the calculation accuracy, patient-specific muscle kinematics information, such as the musculotendon lengths and the muscle moment arms during the entire gait cycle, are employed based on the patient-specific musculoskeletal model. Moreover, an improved force–length–velocity relationship is implemented to generate accurate muscle forces. Gait analysis data including kinematics, ground reaction forces, and raw EMG signals from six adolescents at three different speeds were used to evaluate the PENm. The simulation results show that the PENm has the potential to predict accurate joint moment in real-time. The design of advanced human–robot interaction control strategies and human-inspired gait rehabilitation robots can benefit from the application of the human internal state provided by the PENm.

1. Introduction

Clinical evidence supports the proposal that *gait rehabilitation robots,* which conduct task-oriented repetitive training [1–3], can improve motor performance for patients with neurological disorders or orthopaedic lesions [4–16] based on the *activity-dependent neural adaptation model* [17–19]. Preliminary studies found that individuals who received robotic gait rehabilitation demonstrated improved EMG activity during locomotion [20], walked more symmetrically [21], were able to bear more weight on their legs [5], and experienced higher returns in functional walking ability when compared to patients who received conventional gait training [6]. However, there is also evidence that the robotic training paradigms that enforce a fixed kinematic control are suboptimal [13,22] or even counter-productive [23] for rehabilitative training because they do not account for the intrinsic property of neuromuscular control, which is likely to reduce the activity of the spinal neural control circuits that control locomotion [24–26]. Therefore, *compliant control paradigms* [2] or *assist-as-needed control paradigms* [13] have been developed to incorporate patients' intentions and to activate the muscle contribution [27]. Currently, the leading methodologies for realizing these control strategies are through the compliant behaviour of the robots based on kinematic information, kinetic information, or impedance patterns [28–31]. The main limitations of these control strategies are, firstly, that they cannot assess the patients' dysfunctions at muscle level and, secondly, that the anatomical and anthropometric or muscle-related parameters, which are essential for the robotic control algorithm, are not patient-specific.

A logical solution is to develop a *patient-centred controller* based on the patient's own musculotendon system, which models the human accurately and incorporates the human's intention. For patients with neurological disorders, electromyography (EMG) signals are one of the most effective ways to identify the errors in neurological control, muscle weakness, voluntary substitutions or obligatory posturing through the altered timing and intensity [32]. Thus, EMG-driven models with or without an appropriate musculoskeletal model have been used to represent a patient's own neuromuscular effort in gait rehabilitation robotic control schemes [33].

Previous *EMG-driven lower limb models* are usually used to predict *joint kinematics* [34,35] and *joint kinetics* [36] in the area of biomechanics, based on the Hill-type model and the iterative algorithm. For instance, Lloyd et al. [34] estimated knee joint moment based on a generic 3D anatomical model, which included 10 and 13 muscles around the knee joint respectively. They also

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included 18 adjustable parameters to ensure good moment estimation via an optimisation algorithm. The muscle mechanics model they employed is a separated force–length (FL) and force–velocity (FV) relationship. The model is processed offline using numerical iterative algorithms. One problem with these physiological models is that they aim to diagnose or manage neurological or orthopaedic conditions or to study human neurological control in clinical applications. Such EMG-driven models cannot be used to control gait rehabilitation robots. Firstly, a large part of the muscle mechanics models treat the FL and FV relationship separately [34–37]. However, it is not physiologically meaningful to use the FL and FV relationships separately because, when the FL property is defined, the FV equation only describes the FV relationship when the muscle is at its optimal length (l_m^0) [38,39]. Therefore, the *Hill-type muscle mechanics* should be described by a *combined FLV relationship*. Secondly, the current iterative algorithms such as the Runge-Kutta-Fehlberg algorithm cannot realise in real-time, which is one of the main requirements for the rehabilitation robotic application [40]. Thirdly, the majority of the applications of previous EMG-driven models are in the area of biomechanics instead of rehabilitation robots. They tend to include as many muscles as possible [41] around each joint with a large number of adjustable parameters to ensure good prediction (such as joint moment). This leads to a longer calculation time or a poor prediction ability for novel data [42].

For the purpose of developing a *patient-specific biological command-based rehabilitation robot controller*, we present a *patient-specific EMG-driven neuromuscular model* (PENm). Besides the inherent requirement for an EMG-driven method, the PENm aims to modify the current EMG-driven models for the potential use of gait rehabilitation robots by decreasing the calculation time and preserving the prediction accuracy. To decrease the calculation time as far as possible, this model is designed to incorporate EMG channels from two muscles around each joint and minimum physiological parameters. Furthermore, a *dynamic computation model* is developed based on Zajac's computation flowchart [43]. To preserve the prediction accuracy while the PENm is based on a simplified musculoskeletal model, accurate patient-specific muscle kinematics information such as the musculotendon lengths and the muscle moment arms during the entire gait cycle are employed based on the musculoskeletal model. An improved FLV relationship is implemented to generate accurate muscle forces. Kinematic data, kinetic data, as well as EMG signals of knee joint muscles, from six healthy subjects [44] are used as the case study to evaluate the effectiveness of the PENm.

2. The patient-specific EMG-driven neuromuscular model

The PENm has been developed for the control of human-inspired gait rehabilitation robots. According to the robotic application requirements, the proposed model has been modified in terms of minimised subject-specific parameters and muscle channels, modified muscle mechanics relationships and calculation strategy. A Hill-type muscle mechanics model combined with a 3D motion capture technique and 3D musculoskeletal model were employed to meet these requirements.

As depicted in Fig. 1, the PENm consists of four parts: musculoskeletal model, EMG-torque modelling, inverse dynamics and the parameters optimisation algorithm. The EMG-torque modelling covers the process from neural excitations of muscles to musculotendon force generation and the resultant joint moment; the inverse dynamics modelling aims to estimate the reference joint moment based on the kinematic data and external loads, and the optimisation algorithm is used to determine a set of patient-specific parameters, which ensure good joint moment

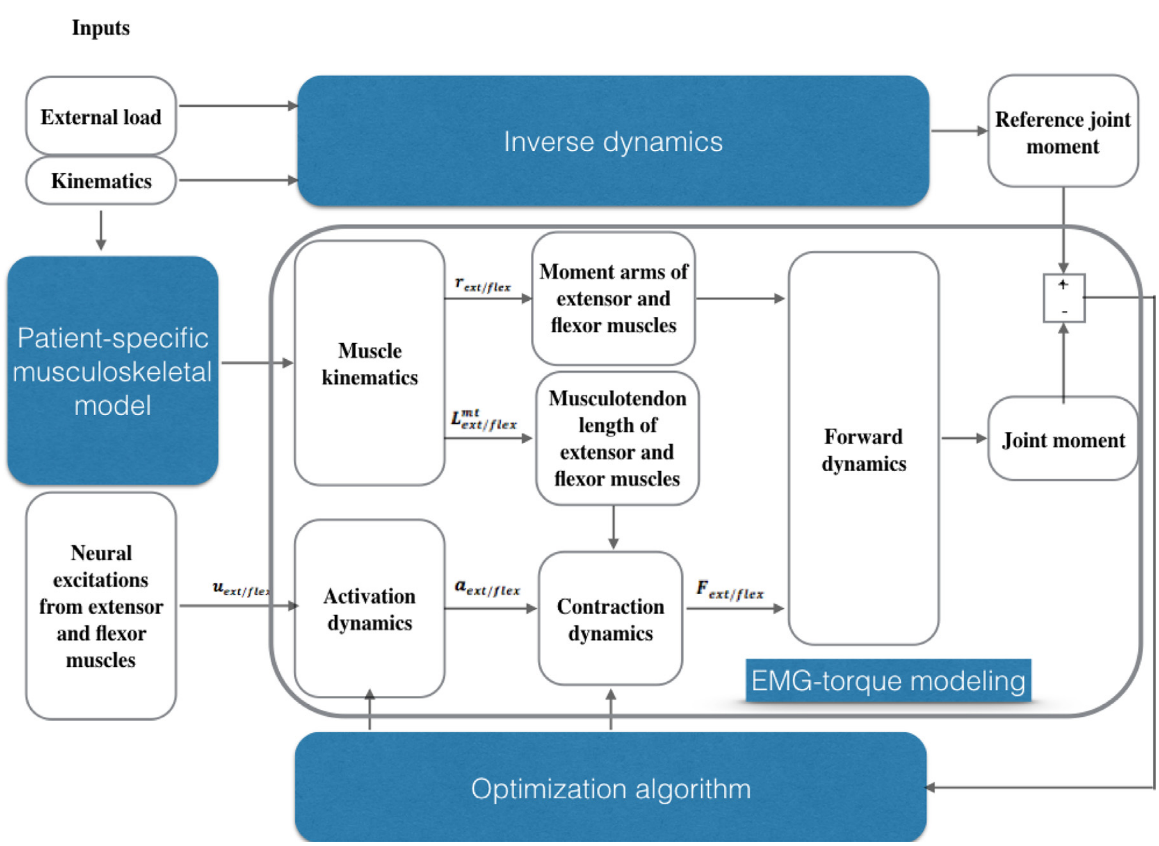

Fig. 1. The patient-specific EMG-driven neuromuscular model (PENm).