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Validation of an artificially activated mechanistic muscle model by using inverse dynamics analysis

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ABSTRACT

The objective of this work is to validate a mechanistic muscle model by using inverse dynamics analysis. To do so, an artificially activated Hill-type muscle model is used. Compared to the traditional physiologically activated muscle model, an artificially activated model must take into account an additional set of parameters and dynamics that can affect the resulting force. To validate the model, the ankle dorsiflexion activated by functional electrical stimulation (FES) is subjected to an inverse dynamic analysis (IDA). The resulting values of the net joint torques are used to estimate first the muscle forces, and second, by inversion of the proposed artificially activated model, the stimulation profile that produces the recorded motion. The results are then compared with the stimulation profile applied to the subject, and the model parameters are adjusted correspondingly. Once the model has been validated, the methodology could be used to design rehabilitation programs based on electrical stimulation or to prescribe FES actuation in the design of hybrid orthoses or neuroprostheses to achieve a given movement.

1. Introduction

Multibody dynamics has been widely used either to simulate human movement in a forward approach [1] using as inputs the neural excitations or in an inverse perspective to obtain the muscle activations that define the recorded movement [2]. In both cases a mechanical model of muscle tissue is needed to ensure the physiological meaning of the obtained results. The Hill-type muscle model [3,4] has been extensively applied in Biomechanics [5–9] to reflect the mechanical behaviour of muscle tissue. Nevertheless the validation of the model is far from possible as the system inputs (neurological signals) cannot be controlled nor measured directly. The solution to this problem may be found in the use of functional electrical stimulation (FES) to activate muscle tissue. By applying electrical stimuli to the muscle, the input is controlled and the output, i.e. the movement, is still measurable.

Classical muscle models based on Zajac's work [4] divide muscles' mechanical behaviour into activation and contraction dynamics. While the former describes the time lag between a neural signal and the corresponding muscle activation, the latter corresponds to the transformation of muscle activation into muscle force (see Fig. 1a). For an artificially activated muscle, contraction dynamics is basically the same as for physiologically activated muscles [10]. Nevertheless activation dynamics must take into account the stimulation parameters, i.e., intensity (regulated by the amplitude and/or pulse width) and frequency, and nonlinearities of the artificial activation process (Fig. 1b). The traditional identification of these parameters has been made by optimization as, e.g., in Kim et al. [11], or identification methods [12]. In the literature there are artificially activated muscle models that consider the amplitude or pulse width parameters [13], frequency [14], or a combination of the two [13,10]. The purpose of these studies was to identify muscle

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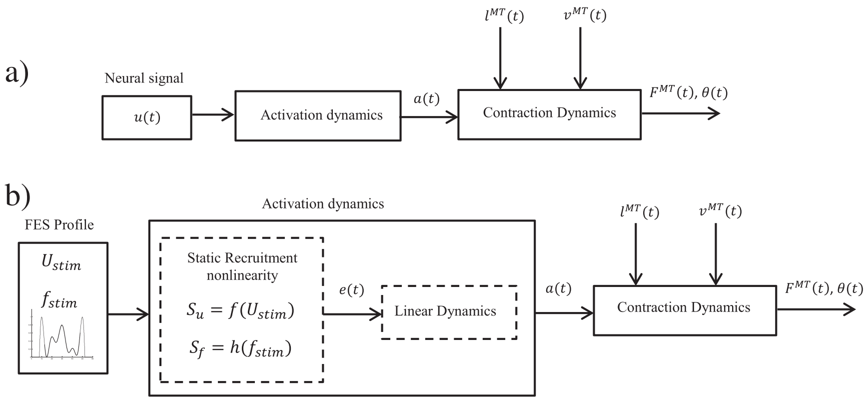

Fig. 1. Schematic representation of the process leading to a muscle contraction. (a) Physiologically activated muscle. (b) Artificially activated muscle.

parameters usually to design control strategies. Ferrarin et al. [15] went further and proposed a method based on IDA to obtain the FES profiles, however this method requires an identification phase and artificial activation was applied to a moment–angle relationship at joint level.

The objective of the present work is twofold. On the one hand, the artificially activated muscle model is used to validate the Hill-type muscle model. On the other hand, the model, once validated, can be used to determine the FES stimulation profiles to produce a given movement. The model is validated by comparing the input signal with the obtained by means of an IDA of the recorded movement. The effects of the artificial activation in an FES-induced movement are simulated by using a modification of the artificially activated muscle presented in [10]. That model was used to predict muscle forces, and thus movement, from a given profile of artificial activations. In the present paper, the model is used backwards, i.e., the aim is to estimate the artificial actuation profile that produces a given movement using FES. The two approaches are represented in Fig. 2. Both are useful for the design of FES rehabilitation programs. The forward dynamics model has been extensively applied in the literature to simulate motion in rehabilitation routines, and can be applied in hybrid orthoses design to improve control schemes or energy requirements. The inverse approach proposed here is different in that it can be used to obtain a set of electrical stimuli to apply to the subject so as to attain a prescribed functional motion.

The use of the artificially activated muscle model from an inverse perspective may help to obtain patient-specific stimulation profiles, and therefore to design precise FES rehabilitation programs. Moreover, the estimated FES profiles can be applied to the design of hybrid orthoses as feed-forward patterns, i.e., they can be used in closed-loop control systems in the context of a feed-forward controller. It is expected that the results of the present work will be used in a following stage to improve the functional efficiency of hybrid orthoses by optimizing the co-actuation of FES and mechanical actuators.

2. Methods

The methodological approach we followed to validate the mechanical muscle model and to obtain the FES profiles from a given motion is shown in Fig. 3a. Briefly, from an FES-induced movement, an IDA analysis is performed to obtain net joint torques and net joint reaction forces. Then, by applying a static optimization scheme, it is possible to obtain the muscle forces and activation patterns [6,9,16]. Next, IDA activations are transformed into activations for the FES model using a set of calibration coefficients, obtained by an optimization process between the latter ones and the predicted by the artificial activation dynamics (Fig. 3b). Lastly, FES activation profiles are obtained by inverting the model's excitation-to-activation dynamics. With the completion of this step, FES profiles are obtained in terms of amplitude, frequency, or pulse-width.

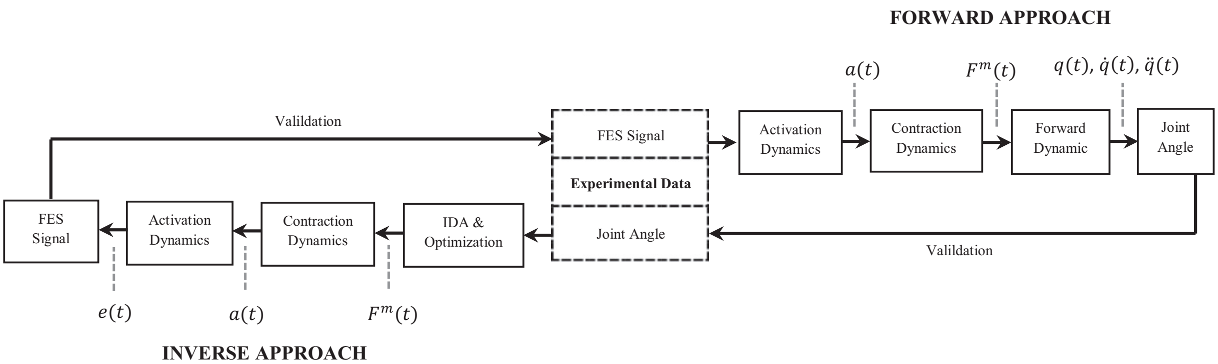

Fig. 2. Inverse and forward approaches to determine the FES signal from the kinematic data and/or the kinematic data from the FES signal, respectively.