Analysis of the musculotendon dynamics influence on the shoulder muscle force sharing problem using a fully inverse dynamics approach

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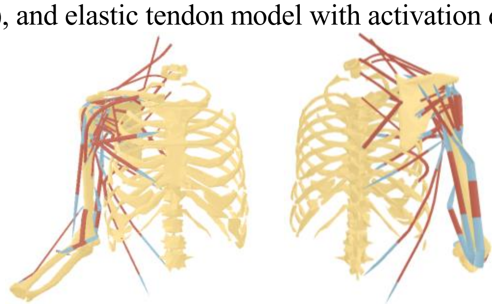
Most computational simulations of human movement are based on inverse dynamics because of its computational efficiency [1, 2]. However, the muscle dynamics, i.e. the activation dynamics and the muscle-tendon contraction dynamics, are rarely considered due to numerical challenges related to the optimization methods applied. The static optimization, the most commonly applied method in inverse dynamics, solves each instant of time independently, which precludes the simulation of the time-dependent physiological nature of the muscles [3, 4], while the global optimization and the extended inverse dynamics methods are limited by the number of muscles and instants of time that can be considered since the increasing size of the optimization problem rapidly prevents the convergence of the methods [4]. Recently, a novel method, named window moving inverse dynamics optimization (WMIDO), was proposed to overcome these limitations and allow the analysis of complex biomechanical models including the activation and muscle-tendon contraction dynamics [4].

Considering the WMIDO, the aim of this study is to evaluate the influence of the muscle dynamics on the muscle force sharing problem of the shoulder using a musculoskeletal model of the upper limb [1, 5]. A fully inverse dynamics approach, of both skeletal and muscular systems, is followed considering four musculotendon models that differ in the simulation of the activation and muscle-tendon contraction dynamics [4].

The musculoskeletal model of the upper limb applied is composed of the thorax, rib cage, clavicle, scapula, humerus, ulna and radius, as depicted in Fig. 1. Excluding the degrees-of-freedom of the thorax, the biomechanical model presents 9 degrees-of-freedom, particularly 4 at the shoulder girdle, 3 at the shoulder, and 2 at the elbow. The muscular system includes 22 muscles, described by 74 muscle bundles [1, 5]. A three-element Hill-type muscle model is used to describe the mechanical behavior of muscles. Depending on the simulation of the activation and muscle-tendon contraction dynamics, four musculotendon models are modelled: rigid tendon model without activation dynamics (Hm_{RT}), rigid tendon model with activation dynamics (Hm_{RT+Act}), elastic tendon model without activation dynamics (Hm_{ET}), and elastic tendon model with activation dynamics (Hm_{ET+Act}).



(a) (b)

Fig. 1: Musculoskeletal model of the upper limb: (a) anterior view and (b) posterior view

Kinematic and EMG data were acquired synchronously at the Laboratory of Biomechanics of Lisbon for unloaded and loaded abduction and anterior flexion motions of the upper limb. A 2-kg weight was used in the hand during the loaded motions. The optimization problem associated with the solution of all muscle and joint reaction forces for all instants of time, in which the kinematic data are known, was formulated as the minimization of the muscle metabolic energy consumption subjected to the boundary constraints of the muscle activations, to the equilibrium of the equations of motion, and to the stability of the shoulder and scapulothoracic joints [1, 5]. For the simulations including activation dynamics, with the muscle models Hm_{RT+Act} and Hm_{ET+Act}, boundary constraints on the muscle excitations were also considered. The inverse dynamics optimization was solved in Matlab (MathWorks, Natick, MA, USA) using the WMIDO with a window size of 10 instants of time and a marching step of 4 instants of time [4]. To compare the solutions obtained for the four musculotendon models considered, cross-correlations between the processed EMG signals and the estimated muscle activations were computed using the *xcorr* function of Matlab with the normalization option *coef* and a maximum delay of 50 ms.

The muscle activations and glenohumeral joint reaction forces were similar for all four muscle models applied in this work, as illustrated in Fig. 2 for the middle deltoid muscle during unloaded abduction in the frontal plane. The simulation of the activation dynamics produced only a limited smoothing effect on the muscle activations, not noticeable in Fig. 2, to avoid fast, unphysiological, variations. The activation dynamics is likely to be more critical for explosive movements [4], but here only slow-speed movements were studied. The tendon elasticity resulted only in small differences, particularly for muscles whose ratio of tendon slack length to optimal muscle length was larger than 1. Since among the 74 muscle bundles of the biomechanical model applied, only 15 have ratios larger than 1, and most of these muscles act mainly on the forearm, the simulation of the tendon elasticity also had a limited impact on the muscle activations of the shoulder. The comparison between the muscle activations and EMG signals showed high cross-correlations, above 0.8, for all muscle models, which provides confidence in the application of the musculotendon models considered.

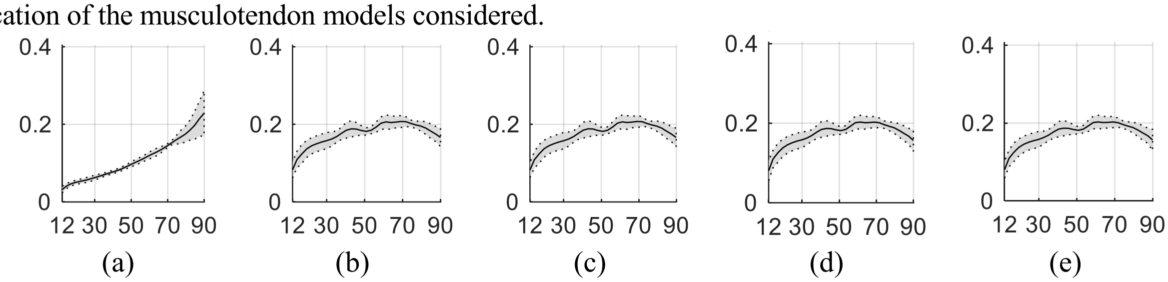


Fig. 2: Activation of the middle deltoid during unloaded abduction in the frontal plane versus the humeral elevation with respect to the thorax, in degrees: (a) normalized EMG signal, (b) Hm_{RT} model, (c) Hm_{RT+Act} model, (d) Hm_{ET} model, and (e) Hm_{ET+Act} model. The solid line represents the average of the 5 repetitions studied and the grey shaded area indicates the corresponding standard deviation. For comparison purposes, each EMG signal is normalized to have the maximum amplitude similar to the maximum muscle activation estimated

Considering that no major differences were observed between the four musculotendon models applied, the activation and muscle-tendon contraction dynamics can be neglected without compromising the solution of the muscle force sharing problem if similar conditions are considered, i.e., if slow-speed, standard movements of the upper limb are studied. Other, more explosive, motions and other musculoskeletal systems need to be studied further in the future to evaluate the influence of the muscle dynamics under different conditions.

References

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