Development of a Musculotendon Model within the framework of Multibody Systems Dynamics

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Abstract

Despite being performed since birth, human movement is the result of an intricate process involving the musculoskeletal and the central nervous system (CNS). A complex pattern of electric signals, generated at CNS level, results in a synergetic contraction of muscle fibers, which induces forces that are transmitted by tendons to the skeletal system, causing its movement or maintaining a given pose. As such, the study of muscle activity is of great interest for the scientific and medical community alike, as it allows for better understanding the contribution of a specific muscle to a given movement [1], providing insight to the design of fully-customized prostheses, orthoses, functional neuromuscular stimulation systems and other assistive devices [2], among other applications.

An important aspect of the musculotendon complex arises from the viscoelastic properties of the tendon, which allow for a dynamic interaction between the muscular and skeletal system, influencing the force transmission, energy storage, joint control and movement accuracy [3]. Hence, the development of non-invasive methods based on musculoskeletal modelling and computer simulations is of particular interest, since these methodologies allow to understand the dynamics underlying these interactions and their influence on movement.

The main objective of this work is the development of a musculotendon model within the framework of multibody systems dynamics that takes into account the influence of tendon in muscle contraction. The methodology applied in the solution of the problem should be robust enough, enabling its application both in forward and inverse dynamics simulation of large biomechanical systems. The proposed model is based on the work developed by Zajac [2], in which the musculotendon unit is described by a Hill-type muscle model in series with an elastic element that depicts the physiological properties of the tendon (Fig. 1).

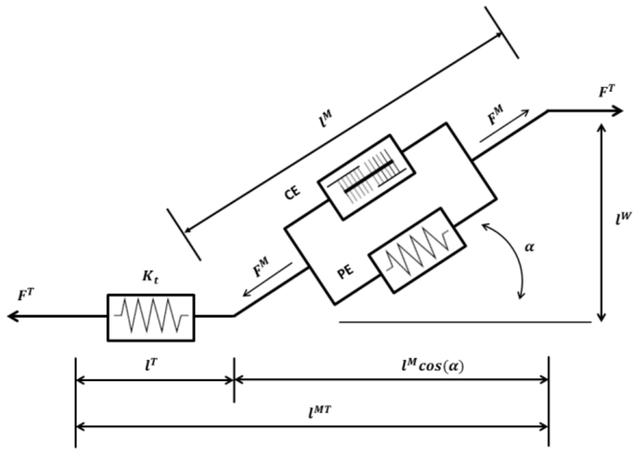

Figure 1: Musculotendon Model. Adapted from Zajac [2].

The dynamic contraction of the musculotendon is characterized by a first order differential equation (Eq. 1) that will be integrated numerically to ensure the calculation of the normalized musculotendon force for a fully-activated muscle state $\left(\tilde{F}_a^T\right)$ throughout the analysis for the prescribed movement:

$$\frac{d\tilde{F}_a^{MT}}{dt} = \tilde{K}_t \left(\frac{v^{MT}}{v_0} - \frac{v^M}{v_0 cos(\alpha)} \right) \quad (1)$$

where $\widetilde{K}_t$ is the tendon stiffness calculated according to Zajac [1] as ($\widetilde{K}_t = {}^{30}/_{\tilde{l_s}^T}$), in which $\tilde{l}_s^T$ is the normalization of the tendon slack length l_s^T by the optimal fiber length l_0^M. v^{MT}, v^{MT} and v_0 represents respectively the musculotendon and muscle velocity and the maximum shortening velocity and α is the pennation angle.

The analysis of the human movement depends greatly on the use of multibody formulations as a kinematic or dynamic analytic tool. The developments occurred in multibody dynamics allowed it to become an essential methodology in the mechanical design field, due to its natural ability to analyze and simulate articulated mechanical systems in great detail [4]. Therefore, the methodology required to compute the variables of the model was embedded in the simulator APOLLO [5], a built-in three-dimensional multibody dynamics software with natural coordinates. The model is developed in such a way that it enables the solution of the equations of motion of the system both in forward and in inverse dynamics. In the former case the motion of the system is simulated for a given set of prescribed muscle activations, and in the latter the analysis provides the muscle activations, and consequently the musculotendon forces, that are needed to execute a prescribed movement considering a given cost function. The inclusion of musculotendon actuators in the system leads to a problem of muscle redundancy that is solved through the use of optimization tools.

The assessment of the model was performed by applying it in the study of three daily activities with different levels of tendon recruitment: walking, running and jumping. The acquisition of the experimental data was performed at the *Laboratório de Biomecânica de Lisboa* (LBL) at IST and made use of a common motion capture system. For this purpose a human biomechanical model (lower limbs and HAT), with 43 musculotendon unities per leg, was applied. The influence of the tendon in the muscle contraction dynamics is analysed by comparing the obtained results (activations, muscle/tendon forces and lengths) with a musculotendon model in which the tendon is modelled assuming stiff properties, i.e. the length of the tendon is considered constant and equal to the respective slack length [6].

The results showed that the tendon has a significant influence in certain muscle groups for all of the movements analyzed. The major differences are found in the amount of force produced by the muscle passive component that is lower when the musculotendon model is considered. It was observed that the insertion of the tendon in the model ensures that the muscle works near its optimal zone, i.e., close to its optimal fiber length and maximum shortening velocity, allowing the muscle to develop the required muscle force with lower levels of activation, therefore bringing the simulation results closer to what is physiologically expected.

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