A Comparison Between a Functional and an Anthropometric Approach to Estimate Subject-Specific Musculotendon Parameters

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EXTENDED ABSTRACT

1 Introduction

Predictive simulations of human motion have the potential to aid the design of assistive devices, foresee surgical outcomes, and analyze isolated muscular features, which would otherwise be difficult to measure experimentally. However, the actuation models employed in these predictions typically represent the muscles of an average human, rather than a specific individual [1]. In order to effectively employ these simulations in clinical applications, it is crucial to use subject-specific models, which accurately reflect the muscular properties of a patient. The most-widely used approach to represent musculotendon actuators in human motion simulations is the Hill-type model. It defines the force generating capacity of a muscle, based on five parameters: the maximal isometric muscle force, the optimal muscle fiber length (l_o^M), the tendon slack length (l_s^T), the maximal muscle fiber velocity, and the optimal pennation angle. The most-commonly adopted method to personalize these parameters is referred to as "anthropometric approach" and it consists in scaling the parameters, according to the subject-specific skeletal dimensions (e.g., [2]). However, this method can produce inaccurate results because musculotendon properties also vary with age, gender, and activity levels. Therefore, in this study, a "functional approach" is developed, relying on both skeletal dimensions and experimental measurements of daily activities. It involves the optimization of the parameters, while minimizing the difference between experimental and model-based joint moments. As a first step towards this ambitious goal, the aim of this study is to determine the subject-specific musculotendon parameters of the vastus medialis and tibialis anterior, during squat and sit-to-stand-to-sit (STSTS). Only the values of l_o^M and l_s^T are estimated since dynamic simulations of musculoskeletal models are most sensitive to those two parameters [3].

2 Methods

The following six functional motions were recorded: gait, squat, stair descent, stair ascent, STSTS, and squat jump. These activities were chosen because they encompass a wide range of contractile conditions, require a large range of joint angles and reflect various musculotendon force distributions [3]. Motion capture technology and an electromyography (EMG) system were used to record the trajectories of 38 reflective markers and measure the electrical activity of 7 muscles per leg of a healthy subject, respectively. The EMG signals were processed by band-pass filtering (20-400 Hz), full-wave rectification and low-pass filtering (10 Hz), using a fourth-order Butterworth filter. Subsequently, the data were normalized to the peak value of the activity of interest. In this specific study, only squat and STSTS were used to estimate subject-specific musculotendon parameters.

A generic musculoskeletal model [4], comprising 23 degrees of freedom (DOFs) and 54 muscles, was scaled on OpenSim 4.3. This procedure linearly scales the size of the skeletal segments and the lengths of the musculotendon actuators. Consequently, the generic l_o^M and l_s^T parameters defined in the model are also linearly scaled, based on the new musculotendon lengths. Prior to computing the subject-specific Hill-type parameters, the physiologically feasible combinations of l_o^M and l_s^T were mathematically defined for each muscle, to constrain the solution space of these two values, as described in [3].

The l_o^M and l_s^T parameters were personalized on GPOPS-ii, using the direct collocation method in a single-phase optimal control problem (OCP) and an implicit formulation of the musculoskeletal dynamics [5]. The cost function minimized i) the difference between the joint torques produced by the muscles and the corresponding torques computed through inverse dynamics; and ii) the difference between the post-processed EMG signals and the muscle excitations calculated using the Hill-type activation dynamics. In the first term, the joint torques refer to the ankle dorsiflexion and the knee extension. A constant was set as a static parameter of the OCP and was multiplied to the EMG data in the second term of the cost function, to further normalize each experimental EMG signal. The resulting parameters (hereinafter referred to as "functional parameters") were verified by estimating the muscle excitations during the two analyzed motions. To achieve this, a similar OCP as before was defined, where the moment arms and musculotendon lengths were imposed, the tendon forces of the non-personalized muscles were tracked and the excitations were set as design variables. This simulation was repeated with musculotendon parameters determined using the anthropometric approach (hereinafter referred to as "anthropometric parameters") developed in [2], to allow for comparison.

3 Results and Discussion

Table 1 compares the functional values of l_o^M and l_s^T computed for the two motions, and it includes the anthropometric parameters for reference. The optimal control problems for both activities yield similar results, thus implying that the functional musculotendon parameters depend on the individual, rather than the performed motion. Additionally, the predicted muscle excitations in both activities are closer to the experimental signals when using the functional parameters (see Figure 1). The tibialis anterior model with anthropometric parameters generates higher muscle excitations when the fiber length increases (i.e., during plantar flexion) in both motions. In fact, its anthropometric l_o^M is higher than its functional value and therefore, when stretching, the muscle produces less passive force and needs to activate more. On the other hand, the anthropometric and functional l_o^M values of vastus medialis are relatively similar and the discrepancy between the two predicted excitations of this muscle is less noticeable. Moreover, for STSTS, the average root-mean-square errors (RMSEs) between the experimental and predicted excitations of the analyzed muscles are 0.09868 and 0.05167, when using anthropometric and functional parameters respectively. Whereas for squat, the corresponding RMSEs are 0.1152 and 0.005366.

Table 1: Anthropometric (ant.) and functional musculotendon parameters for both motions.

Muscle	l_o^M *(ant., cm)*	l_o^M *(squat, cm)*	l_o^M *(STSTS, cm)*	l_s^T *(ant., cm)*	l_s^T *(squat, cm)*	l_s^T *(STSTS, cm)*
Vastus medialis	12.421	10.802	10.847	11.891	10.952	10.944
Tibialis Anterior	11.593	7.1446	8.3039	27.330	27.848	26.729

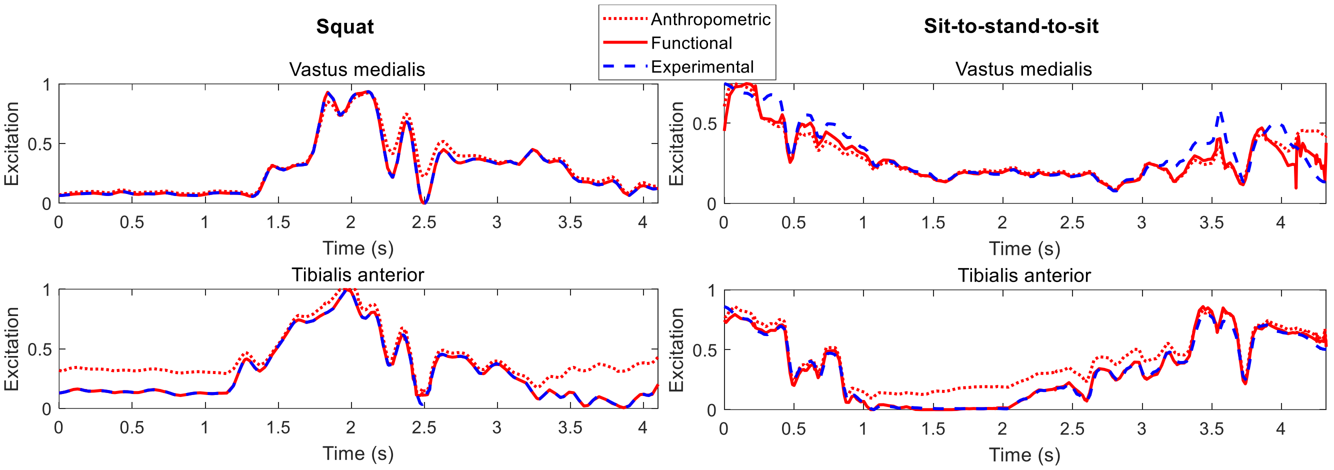

Figure 1: Comparison between the experimental and predicted excitations with functional and anthropometric parameters, for squat (left) and STSTS (right).

4 Conclusions and Future Work

This study analyzed how subject-specific musculotendon parameters can be estimated using a functional approach. As expected, when using the functional values for l_o^M and l_s^T, the computed muscle excitations matched more accurately the experimental EMG signals. This was particularly apparent for the tibialis anterior, which produced significantly higher excitations during plantar flexion when assigned the anthropometric parameters. Since this work generated promising results, it will be extended to include more muscles and motions. In addition, more DOFs affected by the studied muscles will be considered when personalizing the parameters (e.g., subtalar inversion for the tibialis anterior). The final goal will be to employ this muscle personalization technique for patients suffering spinal cord injury.

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