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SOLUTIONS TO THE MUSCLE REDUNDANCY PROBLEM: FROM AN UNDETERMINATE TO A DETERMINISTIC PROBLEM

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Abstract

Introduction: The muscle force quantification is still of primary importance to understand musculo-skeletal control, and is a current challenge combining closed-loop multibody dynamics and muscle physiology modeling. Indeed, at each instant *t* of a movement, the constraint (1) based on the principle of potential powers should be strictly followed to guarantee that the sum of muscle forces $F_{m,i}(t)$ times the muscle tendon potential velocities $\Delta v_i(t), \forall i = 1,\ldots, n$ muscles, should be equal to the torque at the joint *J* actuated by these muscles times the joint potential angular velocity $\Delta\omega_J(t)$ [1]. Experimentally, this could be interpreted by a necessity of consistency between kinematic and electromyographic (EMG) data, $\forall t$. And because several muscles actuate a joint, the constraint 1 consists in an undeterminate problem, for which there is an infinity of $F_{m,i}(t)$ solutions.

$$\sum_{i=1}^{n} F_{m,i}(t) \cdot \Delta v_i(t) = M_J(t) \cdot \Delta\omega_J(t) \tag{1}$$

In the literature, these forces are usually evaluated using two alternative method sets:

I. EMG-driven methods [4], based on the maximal isometric muscle force $F_{max,i}$, the muscle activation dynamics $a_i(t)$ obtained from the EMG envelop, the muscle force-length $\widetilde{F_l^{CE}}(\widetilde{l_{m,i}})$ and force-velocity $\widetilde{F_v^{CE}}(\widetilde{v_{m,i}})$ relationships [4]: $F_{m,i}(t) = F_{max,i} \cdot \left[a_i(t) \cdot \widetilde{F_l^{CE}}(\widetilde{l_{m,i}}) \cdot \widetilde{F_v^{CE}}(\widetilde{v_{m,i}})\right]$. (2)

These methods allow the quantification of muscle forces with good accuracy but are still impossible to use in clinical settings because $F_{max,i}$ is too variable to be identified in each subject.

II. Optimization algorithms defining the muscle force distribution, such as Forster's cost function:

$$\min_f \left[\sum_{i=1}^{n} \left[\frac{F_{m,i}(t)}{F_{max,i}} - x_s\right]^2\right], F_{max,i} \geq f_{m,i} \geq 0 \tag{3}$$

where x_s represents the muscle co-contraction, set to an arbitrary constant – especially equal to 0 in Crowninshield's method – which is therefore non-physiological. Based on both limited solutions, the objective of this study is to propose two novel solutions to the muscle overactuation problem.

Methods: A new multiple closed-loop dynamic model of the upper limb (Figure 1A) was developed using ROBOTRAN [3] and tested in 15 adults performing cycles of elbow flexion/extension (FE) and pronation/supination (PS). Two methods for muscle force quantification were developed:

Method 1: By replacing $F_{m,i}(t)$ from constraint (1) by Equation (2), and by considering that $a_i(t)$ is provided by the EMG data envelop, the undeterminate problem leads to a deterministic identification

process of n unknown $F_{max,i}$ (e.g. : n = 7 in Figure 1A) using a large number of t equations, i.e. at each instant t (e.g. : t = 1000 for 10s of movement recorded at 100 Hz).
Method 2 : x_s was identified by a polynomial regression based on joint angle q and velocity $\dot{q}$, so that the solution obtained by Equation (3) best fits the forces obtained by EMG in the 15 adults.

Results: During elbow FE, Figure 1B compares the results from methods 1 and 2 with solutions from EMG-driven and Crowninshield's methods. Complementary results during FE and PS will be presented at the Conference. In method 2, the identified x_s varies from 0.04 to 0.2 and is given by:

$$x_s(q,\dot{q}) = 0.512 - 2.042 \cdot \dot{q} + 2.36 \cdot \dot{q}^2 - 3.78 \cdot 10^{-4} \cdot q - 0.22 \cdot 10^{-4} \cdot q^2 + 0.15 \cdot 10^{-4} \cdot q \cdot \dot{q} \quad (4)$$

A Tukey's post hoc test was performed to determine that no significant difference was observed between the results from three methods: EMG-driven, 1, and 2.

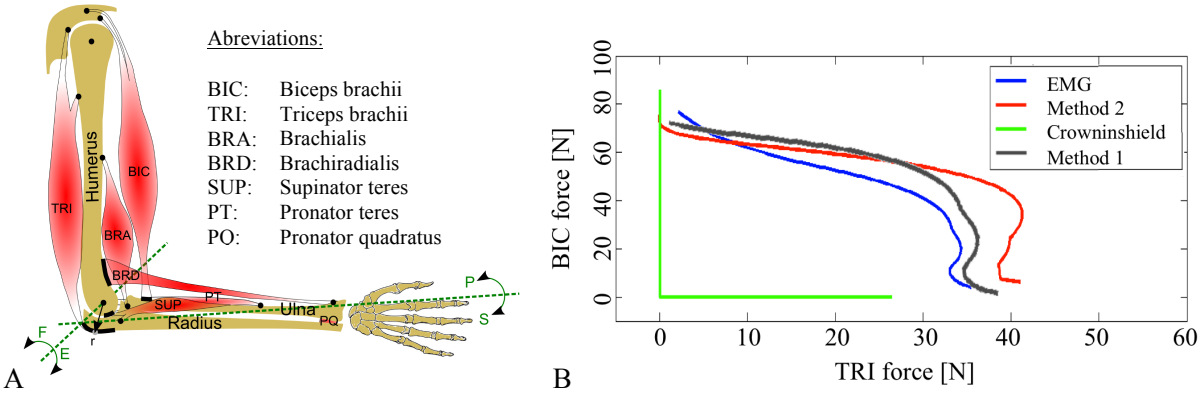

Figure 1. A. Musculo-skeletal model including seven muscles acting in elbow FE and PS.
B. Results of muscle antagonistic forces during FE using four methods.

Discussion: As illustrated in Figure 1B, the post hoc test shows that the results from methods 1 and 2 are globally close to the EMG-driven solution. Relatively to the EMG-driven methods: method 1 has the advantage of identifying $F_{max,i}$ in experimental dynamic conditions and not from tables or in static conditions; method 2 has the advantage of predicting the muscle forces by identifying x_s with no other information than kinematics, independently from EMG data. Both methods 1 and 2 enable to simplify the muscle overactuation problem from an undeterminate to a deterministic problem. At each instant t, at least one of the muscle forces obtained from Crowninshield's method tend to zero, as previously demonstrated by [2], as a result of Equation (3) when x_s=0.

Conclusion: Methods 1 and 2 are promising methods to solve the muscle force redundancy. Both methods could be further analyzed to improve the physiological interpretation, and extended to include more joints and pluri-articular muscles, involving more complex musculo-skeletal models during more complex movements. The incentive of this project is based on the actual need for dynamic muscle force modeling, to understand healthy and pathologic musculo-skeletal control.

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