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

Guillaume Gaudet\textsuperscript{1,2}, Maxime Raison\textsuperscript{1,2,⋆}, Sofiane Achiche\textsuperscript{1}, Fabien Dal Maso\textsuperscript{2,3}, Grégoire Musy\textsuperscript{1,2}, Mickael Begon\textsuperscript{3}

\textsuperscript{1} Department of mechanical engineering, École Polytechnique de Montréal, 2500 Chemin de Polytechnique Montreal, Canada
\textsuperscript{2} Research center Ste-Justine UHC, 5200 Bélanger, H1T1C9, Montreal, Canada
\textsuperscript{3} Department of kinesiology, Université de Montréal, 2100 Edouard Montpetit, Montreal, Canada
mickael.begon@umontreal.ca, fabien.dalmaso@gmail.com

Key Words: Overactuation, Closed-loop, Multibody, Dynamics, Muscle force, Electromyography

Abstract

Introduction: The muscle force quantification is still of primary importance to understand musculoskeletal 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:

\textit{I. EMG-driven methods} [4], based on the maximal isometric muscle force \(F_{\text{max},i}^\text{t}\), the muscle activation dynamics \(a_i(t)\) obtained from the EMG envelop, the muscle force-length \(F_{\text{p},i}^\text{LE}(l_{m,i})\) and force-velocity \(F_{\text{p},i}^\text{VE}(v_{m,i})\) relationships [4]:

\[
F_{m,i}(t) = F_{\text{max},i}^\text{t} \cdot \left[ a_i(t) \cdot F_{\text{p},i}^\text{LE}(l_{m,i}) \cdot F_{\text{p},i}^\text{VE}(v_{m,i}) \right]. \tag{2}
\]

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

\textit{II. Optimization algorithms defining the muscle force distribution}, such as Forster’s cost function:

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

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:

\textit{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 \( F_{\text{max},i} \) (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:

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

(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.

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 \( F_{\text{max},i} \) 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.

References


