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FES-INDUCED MUSCULOSKELETAL TRAJECTORY OPTIMIZATION WITH AN ADAPTED MUSCLE MODEL

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Introduction: To increase efficiency in Functional Electrical Stimulation (FES) assisted activities, simulation can be used to explore optimized stimulation patterns and predict muscle forces and joint kinematics. In this sense, trajectory optimization can efficiently manage biomechanics and FES related constraints, ensuring the optimal activation of required muscles for specific tasks. However, the intricate mechanisms from calcium ions regulation to cross-bridge mechanics, muscle contraction and multibody systems lead to complex system's dynamics. Here, we first demonstrate the feasibility of using trajectory optimization with an FES-stimulated muscle model to optimize a biomechanical task in simulation.

Methods: We adapted the nonlinear model of [1] by truncating the existing summation in the activation dynamics to account for the effect of the last p stimulation pulses before time t . We defined $n(t) = \lfloor t/T \rfloor$ to represent the largest integer n , such that $n \leq t/T$, where T represents a constant pulse period. The activation dynamics was approximated by:

$$\frac{dC_N}{dt} = \frac{1}{\tau_c} \sum_i^{n(t)} \alpha_i R_i e^{-\frac{t-t_i}{\tau_c}} - \frac{C_N}{\tau_c} \quad (\text{Eq. 1})$$

where $i = \max(1, n(t) - p)$ is the truncated train of pulses containing the history of the last $p = 5$ pulses with states defined by $\alpha_i = \{0, 1\}$. The model parameters were set with the average values reported in [1], where their respective notations can be found. A 1-degree-of-freedom leg model with 3 muscles (*rectus femoris*, *vastus lateralis* and *vastus medialis*) (Fig. 1a) was used in a two phase problem to first reach a target torque of 12.5 Nm at the knee, in which an isometric contraction was performed with the tibia locked by a contact force (Fig. 1a, #3), and then a reaching task to align two markers: target (Fig. 1a, #1) and shank (Fig. 1a, #2) markers, using numerical optimal control [2]. Pulse width was optimized as a piecewise constant control variable within $350 - 800\mu\text{s}$ at a frequency of 50Hz.

Results: Fig. 1b shows the optimized muscle forces in the two different objective-oriented tasks and the contact force produced on the tibia. Fig. 1c demonstrates that torque produced on the knee achieved the torque target expected in the 1st phase and that the shank successfully reaches the target point in the 2nd phase with final distance between markers equal to 0.59cm.

Discussion and conclusion: We adapted the model of [1] to account for non-consecutive trains of pulses and demonstrated the potential of the proposed method to be used in trajectory optimization problems. Although the results are consistent with the literature [1], experimental validation is necessary to confirm the parameters used in the model and reevaluate the predicted forces. Future work should improve our model to account for muscle fatigue and force-velocity relationships. It is of our interest to use the proposed methodology to explore optimal control in FES-cycling stimulation.

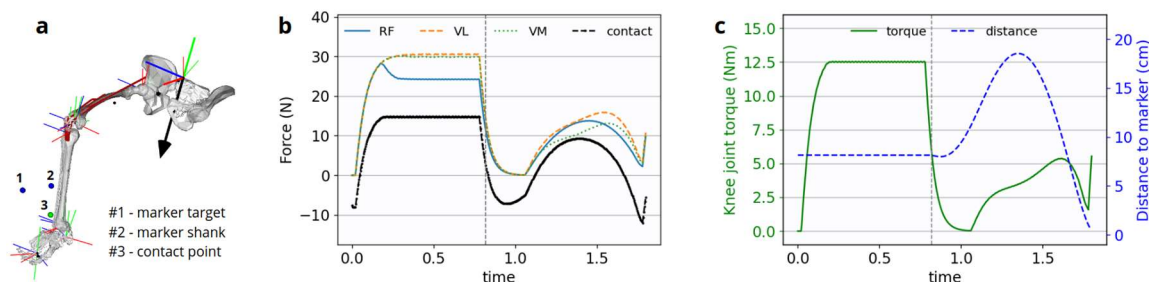


Figure 1: a) Biomechanical model; b) Optimized muscle forces; c) Optimized knee torque and distance between markers. The vertical dashed lines represent the phase transition.

References

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