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Neural network–derived musculotendon kinematics for simulating muscle force and fatigue during training

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INTRODUCTION:

Muscle force simulation is fundamental in sports science and biomechanics, enabling the estimation of internal muscle loads that cannot be measured directly in vivo. These simulations support training optimization, performance enhancement, injury risk reduction, and technique analysis by linking movement kinematics to neuromuscular demands. Modeling muscle fatigue is also essential for understanding performance decline, workload accumulation, and recovery. However, conventional musculoskeletal and fatigue models are computationally intensive, limiting their use in real-time applications. Previous work demonstrated the feasibility of real-time muscle-level biofeedback for load management and injury prevention [1], but was limited in range of motion and did not account for muscle wrapping or fatigue. This work aims to integrate efficient musculotendon kinematics and muscle fatigue modeling into a unified framework for future real-time biofeedback in sport.

METHODS:

An extended Kalman filter (EKF) framework was used for whole-body motion capture, kinematic reconstruction, and inverse dynamics computation [1]. For this preliminary study, the framework was implemented offline to assess feasibility and accuracy. Reconstructed kinematics were used as inputs to a neural network trained on 1,000 scaled musculoskeletal models posed across 500 joint coordinates, yielding 500,000 input vectors, to estimate muscle moment arms, muscle–tendon lengths, and contraction velocities [2]. This surrogate model accounts for muscle wrapping. A four-compartment muscle fatigue model was integrated to represent metabolic and non-metabolic fatigue effects and optimize muscle load-sharing [3]. The framework was evaluated using three cycles of three sets of ten squat repetitions with 90 s rest. After each cycle, two maximal voluntary contractions (MVCs) of the quadriceps were performed. Kinematics were recorded using 18 OptiTrack cameras (100 Hz), ground reaction forces using two AMTI force plates (1000 Hz), and MVC forces using a strain gauge (100 Hz).

RESULTS:

The unified framework was successfully implemented with high computational efficiency. Neural network–derived musculotendon kinematics required 2.8 ms per frame, while the integrated fatigue model required 4.7 ms per frame, both implemented in Python. These processing times enable real-time compatibility of the unified framework at 100 Hz when implemented in C++. Estimated muscle fatigue showed good agreement with MVC force decay (<15%). Subject-specific calibration using an isokinetic dynamometer is expected to further improve estimation accuracy.

CONCLUSION:

Integrating efficient musculotendon kinematics with muscle fatigue modeling advances the state of the art and enables intelligent training systems capable of delivering real-time, muscle-level feedback to optimize performance, manage fatigue, and reduce injury risk.

[1] Lugrís 2024
[2] Cornish 2024
[3] Michaud 2024

Topic:	Biomechanics
Presentation	Oral