# Modified Muscle Fatigue Model to Enhance the Simulation of Intermittent Short-Duration High-Intensity Exercises

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## Abstract

Computer modeling and simulation of muscle forces have been extensively explored, dating back to Hill's early models over half a century ago [1]. These simulations offer valuable alternatives for estimating muscular forces [2] during human activities, particularly due to the invasive nature of in vivo experimental measurements, challenges in obtaining muscle electromyography (EMG) data for deep muscles, and the inconsistent relationship between muscle force and EMG signals [3]. Muscle force capabilities change dynamically over time due to mechanical and physiological variations such as moment arms, tendon lengths, muscle activation patterns, and muscle fatigue, which can make their modeling challenging.

Until now, there has been limited consideration of muscle fatigue when applying mathematical muscle models. For tasks involving low-force or infrequent muscle activations, this omission might not be critical. However, for activities with high-intensity demands where muscle fatigue and the loss of muscle force are anticipated, the integration of muscle fatigue models with muscle force and load-sharing paradigms becomes increasingly important. These simulations hold potential value in applications such as functional electrical stimulation (FES), motor control and prediction, and ergonomic scenarios where estimating muscle force over time is pertinent. This need arises in various contexts, including rehabilitation, injury prevention in sports and workplaces, and surgical planning for the reconstruction of diseased joints.

Muscle fatigue cannot be modeled as a single universal mechanism, since it follows nonlinear behavior, is task-related, and can vary across muscles and joints [4]. Various fatigue modeling approaches have been presented in the literature. One of them, the three-compartment controller (3CC) model marked an improvement over an earlier model that could only represent maximum activation. Xia and Frey-Law introduced this model equipped with a feedback controller to match target loads within a single muscle or at joint level, thus allowing it to handle any time-varying force profile [5]. Consequently, this fatigue model offers a relatively straightforward and adaptable solution for various applications.

In their recent publication [6], the authors integrated multi-level models to account for redundant muscle forces within a multibody environment, along with the 3CC muscle fatigue model. They assessed the methodology necessary to generate time-varying muscle force predictions for a high-intensity dynamic task by merging different modeling approaches into a comprehensive, subject-specific multi-level muscle model. While their results provided reasonable estimates, they observed that the 3CC model did not accurately capture the expected force decay during the training session. Consequently, it suggested that the training activity could be sustained indefinitely. This observation appears to be unrealistic and contradicts findings from other muscle fatigue studies.

In this study, to enhance the simulation of intermittent short-duration high-intensity exercises, the authors opted for modifying the 3CC muscle fatigue model. Specifically, they introduced a four-compartment model (Figure 1) that distinguishes between the short-term fatigued state (corresponding to metabolic inhibition) and the long-term fatigued state (simulating central fatigue and potential microtraumas). Through new experimental measurements during short and long-duration exercises, they introduced a

new methodology to estimate the subject-specific fatigue parameters for their model. These experimental data were used to calculate the root-mean-square error (RMSE) with the simulated results, in order to quantitatively compare the 4CC and 3CC approaches. In this work, the authors validated their approach and also demonstrated the limitations of the classic 3CC in matching target loads, highlighting its inability to handle any time-varying force profile.

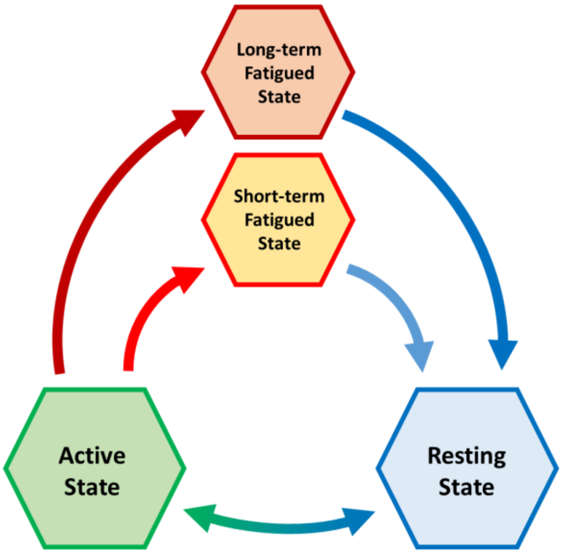


Figure 1: Schematic representation of the novel four-compartment controller.

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**References**

[1] M. G. Hoy, F. E. Zajac, and M. E. Gordon, “A musculoskeletal model of the human lower extremity: The effect of muscle, tendon, and moment arm on the moment-angle relationship of musculotendon actuators at the hip, knee, and ankle,” *J. Biomech.*, vol. 23, no. 2, pp. 157–169, Jan. 1990, doi: 10.1016/0021-9290(90)90349-8.

[2] F. Michaud, M. Lamas, U. Lugrís, and J. Cuadrado, “A fair and EMG-validated comparison of recruitment criteria, musculotendon models and muscle coordination strategies, for the inverse-dynamics based optimization of muscle forces during gait,” *J. Neuroeng. Rehabil.*, vol. 18, no. 1, 2021, doi: 10.1186/s12984-021-00806-6.

[3] J. L. Dideriksen, D. Farina, and R. M. Enoka, “Influence of fatigue on the simulated relation between the amplitude of the surface electromyogram and muscle force,” *Philos. Trans. R. Soc. A Math. Phys. Eng. Sci.*, vol. 368, no. 1920, pp. 2765–2781, 2010, doi: 10.1098/rsta.2010.0094.

[4] R. M. Enoka and J. Duchateau, “Muscle fatigue: What, why and how it influences muscle function,” *J. Physiol.*, vol. 586, no. 1, pp. 11–23, Jan. 2008, doi: 10.1113/jphysiol.2007.139477.

[5] J. M. Looft, N. Herkert, and L. Frey-Law, “Modification of a three-compartment muscle fatigue model to predict peak torque decline during intermittent tasks,” *J. Biomech.*, vol. 77, pp. 16–25, 2018, doi: 10.1016/j.jbiomech.2018.06.005.

[6] F. Michaud, L. A. Frey-Law, U. Lugrís, L. Cuadrado, J. Figueroa-Rodríguez, and J. Cuadrado, “Applying a muscle fatigue model when optimizing load-sharing between muscles for short-duration high-intensity exercise: A preliminary study,” *Front. Physiol.*, vol. 14, Apr. 2023, doi: 10.3389/fphys.2023.1167748.