A Collaborative Benchmark for the Validation of Hill-Type Muscle Models in Multibody Dynamics Frameworks

Sérgio B. Gonçalves*, Mariana Rodrigues da Silva#, Filipe Marques#, Paulo Flores#, Miguel Tavares da Silva*

*IDMEC, Instituto Superior Técnico
Universidade de Lisboa
Av. Rovisco Pais 1, 1049-001, Lisboa, Portugal
{sergio.goncalves, miguelsilva}@tecnico.ulisboa.pt

#CMEMS-UMinho
Universidade do Minho
Campus de Azurém, 4804-533, Guimarães, Portugal
{m.silva, fmarques, pflores}@dem.uminho.pt

Abstract

Muscle activity plays a fundamental role in human movement and constitutes a key variable for understanding neuromuscular function. Accurate knowledge of muscle behavior can contribute to elucidating the mechanics underlying movement, as well as to characterizing the muscular function of non-pathological and pathological individuals. In this context, computational modeling of muscle function has emerged as a powerful non-invasive approach to simulate skeletal muscle behavior during human motion, overcoming many of the constraints associated with experimental methodologies [1].

Within this context, multibody dynamics formulations offer a suitable and efficient solution for biomechanical simulations. Their ability to handle systems with a large number of degrees of freedom enables the modeling of partial- or full-body human representations incorporating numerous muscles, tendons, and ligaments [2]. However, although several benchmark datasets are publicly available for validating multibody formulations and numerical methods used in their resolution [3,4], to the best of the authors' knowledge, no standardized benchmarks currently exist for the validation of musculotendon unit (MTU) modeling methodologies within multibody dynamics computational frameworks. This lack of reference problems hinders the systematic validation of newly developed musculoskeletal biomechanical models. Hence, the present work addresses this gap by proposing a set of benchmark problems with increasing levels of complexity, designed to validate MTU models formulated using multibody system dynamics. These benchmarks aim to support researchers in the implementation, verification, and validation of muscle models when developing or extending computational tools for biomechanical motion analysis.

Five benchmark cases are introduced and discussed, each targeting a specific stage of MTU computational implementation. Particularly, the first benchmark consists of two rigid bodies connected by a revolute joint and actuated by two single line-of-action MTUs, and is specifically designed to assess the integration of a muscle contraction dynamics model within a multibody framework. Building upon this configuration, the second benchmark addresses the modeling of MTUs with via points by considering a different path definition for the MTUs. The third benchmark focuses on the muscle force-sharing problem by introducing two additional MTUs acting across the same joint. In the fourth benchmark, the model from the third case is modified by replacing the revolute joint with a universal joint, enabling the validation of the generation of neutralizing torques required to constrain motion within a predefined plane. Finally, the fifth benchmark introduces a new configuration comprising three rigid bodies and five MTUs, with the objective of validating the modeling of biarticular muscles (Fig. 1a). All benchmark problems are formulated using an inverse dynamics approach combined with static optimization, considering a muscle stress minimization criterion. In addition to providing the topological and anthropometric data required to implement the benchmark models, this work presents a detailed description of the methodologies used for incorporating MTUs within each multibody formulation. Moreover, the steps required to include a muscle contraction dynamics model are presented, considering a phenomenological Hill-type muscle mode with a rigid tendon assumption [1].

In order to ensure the robustness and reproducibility of the reference results, the benchmark cases were implemented in two different in-house multibody software frameworks developed in MATLAB: one based on the Fully Cartesian Coordinates with a Generic Rigid Body (FCC-GRB) formulation [5–7] and the other relying on Cartesian coordinates (CC) [8].

To facilitate the dissemination and reuse of the proposed benchmarks, they were submitted to the Library of Computational Benchmark Problems of the International Federation for the Promotion of Mechanism and Machine Science (IFToMM) [4]. Following the established format of this library, a separate *.tsv

file was generated for each benchmark case. These files contain the reference results necessary to validate MTU computational implementations, with each column corresponding to a specific modeling or simulation output. The results are provided at a sampling frequency of 100 Hz, and each file includes a header describing the stored variables. For each MTU, the reported quantities include: (1) time, (2) muscle activation, (3) MTU force, (4) contractile element force, (5) passive element force, (6) maximum contractile force for the current muscle state, (7) MTU length, (8) normalized muscle fiber length, (9) pennation angle, (10) force–length relationship, and (11) force–velocity relationship. Some of these results are illustrated in Fig. 1b-c. Additionally, six columns are included to describe the position and velocity of the center of mass of each rigid body. A supplementary PDF file accompanies the benchmark data, providing optimization performance and accuracy metrics, including computation time, number of iterations, number of function evaluations, and final constraint violations [1].

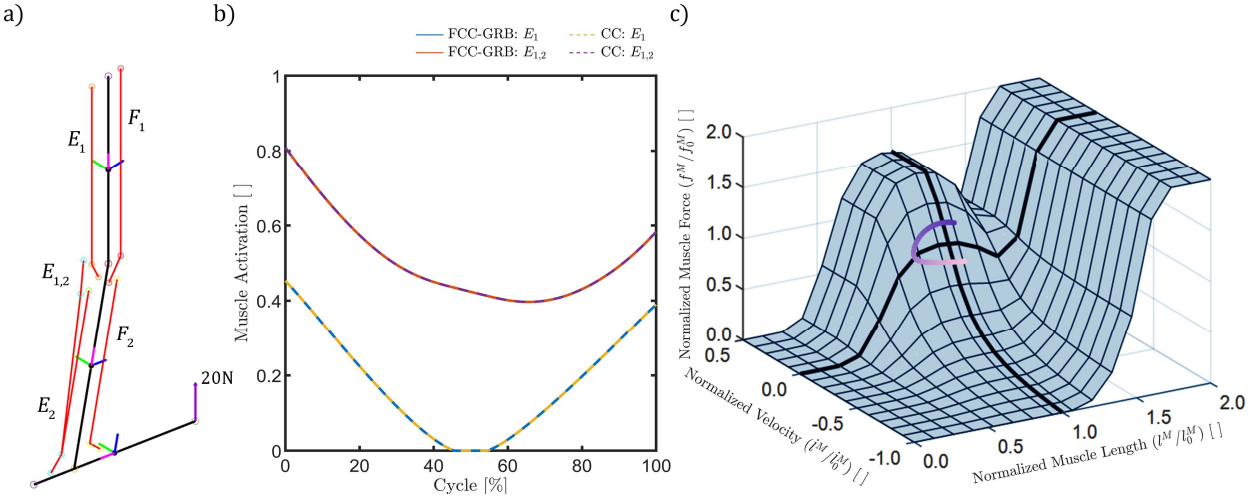


Figure 1: a) Representation of the biomechanical model and the external force applied (purple) used in benchmark 5; b) Comparison of muscle activation for MTUs E_1 and $E_{1,2}$ obtained using the two multibody; formulations; c) Carpet plot of the normalized force of the MTU $E_{1,2}$ fully activated, illustrating the evolution of the muscle state over the cycle (*adapted from* [1]).

Acknowledgments: The authors acknowledge Fundação para a Ciência e a Tecnologia (FCT) for its financial support via LAETA project (https://doi.org/10.54499/UID/50022/2025) and CMEMS project (https://doi.org/10.54499/UID/04436/2025).

References

[1] Gonçalves, S.B.; Silva. M.R.; Marques F.; Flores, P.; Silva, M.T.: Validation of Skeletal Muscle Models in Multibody Dynamics: A Collaborative Collection of Benchmark Cases, Multibody Syst Dyn (2025). https://doi.org/10.1007/s11044-025-10096-8.

[2] Roupa, I.; Silva, M.R.; Marques, F.; Gonçalves, S.B.; Flores, P.; Silva, M.T.: On the Modeling of Biomechanical Systems for Human Movement Analysis: A Narrative Review, Archives of Computational Methods in Engineering 29 (2022) 4915–4958. https://doi.org/10.1007/S11831-022-09757-0.

[3] González, M.; González, F.; Luaces, A.; Cuadrado, J.: A collaborative benchmarking framework for multibody system dynamics, Eng Comput 26 (2010) 1–9. https://doi.org/10.1007/s00366-009-0139-0.

[4] IFToMM Technical Committee for Multibody Dynamics, Library of Computational Benchmark Problems, (2022). https://www.iftomm-multibody.org/benchmark (accessed December, 2025).

[5] Gonçalves, S. B.; Roupa, I.; Flores, P.; Silva, M. T.: Kinematic and Dynamic Analysis of Spatial Multibody Systems with Fully Cartesian Coordinates and a Generic Rigid Body, Mech Mach Theory 209 (2025) 1–35. https://doi.org/10.1016/j.mechmachtheory.2025.105955.

[6] Gonçalves, S.B.; Roupa, I.; Flores, P.; Silva, M.T.: Kinematic and Inverse Dynamic Analysis using Mixed and Fully Cartesian Coordinates with a Generic Rigid Body, Mech Mach Theory 214 (2025) 1–25. https://doi.org/10.1016/j.mechmachtheory.2025.106080.

[7] Gonçalves, S.B.; Flores, P.; Silva, M.T., Musculotendon Modeling with Fully Cartesian Coordinates and a Generic Rigid Body (submitted to Mechanism and Machine Theory), 2026.

[8] Nikravesh, P.: Computer-aided analysis of mechanical systems, 1st ed., Prentice Hall, New Jersey, 07632, 1988.