Impact of Personalized Musculoskeletal Modeling Workflows on Triceps Surae Muscle Forces

Elias Wallnöfer [1,2,3], Willi Koller [1,2,3], Robert Csapo[1,2], Arnold Baca[1,2], Hans Kainz[1,2,3]
[1]Centre for Sport Science and University Sports, University of Vienna, Vienna, Austria
[2]Vienna Doctoral School of Pharmaceutical, Nutritional and Sport Sciences, University of Vienna, Vienna, Austria
[3]Neuromechanics Research Group, Centre for Sport Science and University Sports, University of Vienna, Vienna, Austria
Email: elias.kaj.wallnoefer@univie.ac.at

Summary

This study evaluated how personalization techniques in musculoskeletal modelling affect estimated muscle force share during plantarflexion – an insight of high relevance for research on Achilles tendinopathy. Model calibration and muscle recruitment estimation should use combined electromyography (EMG) and dynamic ultrasound (US) data. Personalized maximum isometric muscle forces from 3D freehand ultrasound (3DfUS) are recommended.

Introduction

Accurate estimation of muscle forces during dynamic tasks is critical for understanding musculoskeletal function and overuse such as Achilles tendinopathy. Subtendon shear forces resulting from unfavorable recruitment of soleus (SOL) and gastrocnemius medialis (GM) and lateralis (GL) muscles are among the contributors to this injury [1]. Musculoskeletal models are widely used to estimate muscle forces but are mostly scaled to generic data. This may restrict insights into the interaction between muscle recruitment and muscle architecture, particularly when conducting research on athletes or populations with musculoskeletal disorders. The study aimed to evaluate how different personalization techniques affect the estimation of the relative distribution of muscle forces during plantarflexion.

Methods

OpenSim 4.5 [2] was used to create twenty-four differently personalized models of one female dancesport athlete (22 years, 1.65m, 62 kg). Lower limb muscle parameters were individualized to varying degrees using combinations of three techniques: (1) 3DfUS, to derive maximum isometric force of GM, GL, SOL and tibialis anterior (TA) from measured fascicles lengths, pennation angles, volumes and a specific tension of 60 N/cm²; (2) ParamOptimizer [3], to adjust optimal fiber length and tendon slack length; and (3) calibration algorithms [4], to estimate optimal fiber length, tendon slack length and Achilles tendon stiffness using dynamic US of GM fascicles and/or EMG data of GM, GL, SOL and TA during maximum voluntary contraction (MVC) plantar flexion on a dynamometer in isokinetic condition at 90°/s. These models were tested on maximal isokinetic (120°/s) and isotonic (resistance of 25% bodyweight) contractions with four dynamic optimization approaches: US-informed, EMG-informed, US&EMG-informed or uninformed [4]. 96 workflow combinations (personalized models x optimization approaches) were ranked based on normalized root mean square errors (NRMSE) between measured and estimated GM fascicle length as well as EMG and estimated muscle excitations. Deviations above 5% between tracked moments of subtalar or ankle joint and estimated net joint moments from muscle forces were considered as invalid. Personalization techniques were evaluated based on feature importance of the top twenty ranked workflows and their coefficients in a regression model.

Results and Discussion

Measured fascicle lengths ranged from 22 to 52 mm. The most important features of the twenty best-performing workflows were US&EMG-informed calibration and US&EMG-informed dynamic optimization. ParamOptimizer and 3DfUS were also more present among the better ranked workflows. Model calibrations based solely on EMG information tended to worsen NRMSE and result in high moment residuals. 14 workflows were considered invalid because of that. The remaining ones still showed high variability in their effect on estimated muscle force share (Figure 1). This suggests open potential for studies on individual force sharing strategies in different populations [4]. But it also underlines the importance of extensive workflow tests to avoid overfitting and detailed method descriptions for standardization and reproducibility.

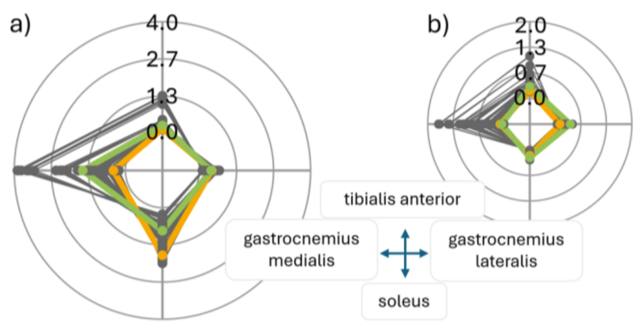

Figure 1: Mean muscle force in BW during plantar flexion cycle analyzed by 96 different workflows (gray) highlighting the generic one (yellow) and the one including all inspected tools/information (green). a) isokinetic MVC at 120°/s, b) isotonic, 25% bodyweight

Conclusions

Model calibration and estimation of muscle recruitment are suggested with a combination of EMG and US data, followed by extensive tests to avoid overfitting and high residuals. We furthermore recommend ParamOptimizer and 3DfUS model personalization regardless of optimization approach.

References

[1] Hug et al. 2017. *Exercise Sport Sci. Rev.* **45** (4): 201-8
[2] Delp et al. 2007.*IEEE Trans.Biomed.Eng*. **54**(11):1940-50
[3] Modenese et al. 2016. *J. Biomech*, **49** (02): 141-148
[4] Delabastita et al. 2020. *Ann.Biomed.Eng.*,**48**(02): 722-33