Subject-Specific Calibration of Neuromuscular Models for Predictive Control of Achilles Tendon Force during Locomotion

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Summary

Developing wearable robots with predictive closed-loop control of musculotendon loads can enhance bio-protection and reduce injury risks. Model-based Predictive Control (MPC) of these devices demands computationally efficient models. Once a suitable model is developed [1], personalizing it through calibration for users is essential. This paper outlines the procedure for calibrating a personalized model of plantarflexors (PFs) suitable for hopping and walking tasks.

Introduction

Optimizing rehabilitation outcomes and preventing injuries heavily relies on effectively controlling the mechanics of the musculotendon unit (MTU). By personalizing MTU control using neuromusculoskeletal (NMS) modeling, it becomes possible to consider individual neurological and physiological traits, thereby enhancing the precision and effectiveness of rehabilitation strategies. CEINMS-RT toolbox [2] enables real-time load estimation after a calibration phase (Figure 1, Stage I), during which MTU parameters are optimized to align the predicted joint moments with joint moments derived from inverse dynamics (ID). In prior work, we showed that closed-form modeling of Hill-type muscle model [3] enable the design of MPC frameworks for controlling MTU loads in exoskeleton-assisted movements [4]. This paper outlines the steps necessary for calibrating NMS and controller models to integrate them effectively into predictive control frameworks.

Methods

Designing a predictive controller requires the algorithm to predict future states of the MTUs, such as MTU length, which plays a direct role in force generation. Thus, the model within the MPC framework should incorporate a motion-related component to predict upcoming movement kinematics. Additionally, the model undergoes a calibration phase to tailor it to the individual, ensuring accurate representation of user's unique biomechanical characteristics (Figure 1, Stage II).

Results and Discussion

To control Achilles tendon force using MPC, the triceps surae muscles are lumped into a single MTU that contributes to ankle moment production in conjunction with the ground reaction force (GRF) and a mechanical advantage (MA). The parameters of the lumped MTU are determined by calculating the weighted average of the individual parameters of the triceps-surae muscles. For personalized control, the motion-related model is calibrated by adjusting the weights, the MA value, and the slope of the linearized muscle force-velocity (F-V) relationship. For instance, during walking and running, the F-V relationship was approximated by $\tilde{F}_M^V = 2.2\dot{\tilde{L}}_M + 1$ [4]. Experimental results showed that a slope of 5 fit well for some hopping subjects. Likewise, while previous studies assumed an MA of 3, we found values up to 5 in certain subjects.

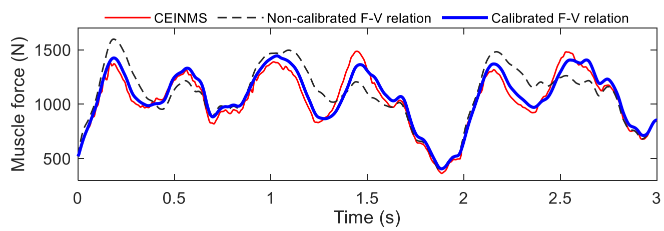

Figure 2: Impact of F-V slope calibration on MTU force estimate.

Conclusions

This study underscores the critical role of subject-specific calibration in both the NMS model and the controller's inner model to accurately capture individual biomechanics. Such personalization is essential for improving the effectiveness of MPC-based strategies.

References

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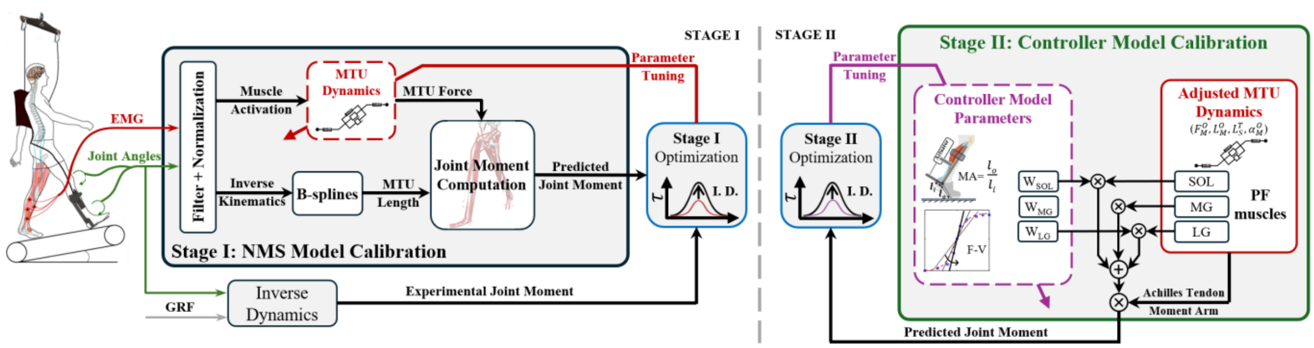

Figure 1: Calibration pipeline of for obtaining musculotendon parameters and the lumped muscle model parameters.