Universal Optimization-based Controller for Replicating Loaded Closed-Chain Activities on an *in vitro* Knee Simulator

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Summary

Physiological *in vitro* simulators replicate natural joint kinematics and kinetics on cadaveric specimens. To achieve more physiologically realistic joint control, a novel optimization-based control strategy, which controls both agonist and antagonist muscles to track real-time *in vivo* vertical ground reaction force, was developed and implemented on a custom-built knee simulator to replicate the squatting motion on a phantom knee. This controller demonstrated better physiological realism when compared to existing control strategies, and could be adapted to simulate other daily activities involving knee motions.

Introduction

Physiological knee simulators, capable of replicating joint kinematics and kinetics *in vitro*, are widely used to quantify knee joint biomechanics during squatting, by applying passive or active quadriceps loads to maintain constant setpoint vertical ground reaction force (vGRF) [1,2]. Most simulators actively actuate only the quadriceps tendon while passively loading the hamstrings, limiting their application to tasks requiring muscle co-contraction. Simulators replicating motions other than squatting employ other strategies, thereby lacking a universal controller, and seldom comparing outputs to *in vivo* literature [3]. The aim of this study was to test a versatile optimization-based controller on a custom in-house physiological knee simulator, comparing the resulting kinetics with established *in vitro* and *in vivo* data in the literature.

Methods

A 3D-printed, Asian-sized phantom knee (adapted from SynBone, Switzerland) was mounted on a custom *in vitro* physiological knee simulator. Linear actuators (Ewellix, Germany) were connected via steel cables to the insertions of the quadriceps and the medial and lateral hamstrings. In-line S-beam load cells measured muscle forces. Knee squatting was replicated by moving the ankle inferosuperiorly and anteroposteriorly using two linear actuators, while optical encoders at the hip and ankle were used to track knee flexion.

Three control strategies were compared – a proportional-integral (PI) feedback controller for vGRF tracking using dynamic quadriceps and constant hamstring forces [2], a combination of PI controller with feedforward control (PI-FF), and a novel optimization-based controller (Optim) consisting of position controllers to track hip and ankle flexion angles from *in vivo* data [5], an optimization block to compute quadriceps and hamstring muscle forces by minimizing muscle fatigue while maintaining torque equilibrium with *in vivo* vGRF data, and force controllers with feedforward block to track these optimized forces (Figure 1). Squatting (20°-105°) was performed in triplicate using each control strategy.

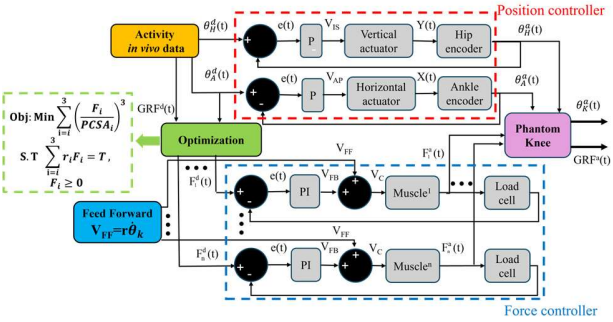

Figure 1: The novel optimization-based controller

Results and Discussion

The feedforward block in PI+FF strategy used muscle velocity compensation to reduce vGRF tracking error to 2.1N±0.9N from 5.7N±1.5N observed in PI. While Optim showed comparable quadriceps force to the *in vivo* data [4] during descent, it exhibited premature force generation during ascent (Figure 2), which could be improved by integrating the excitation-activation time delay in the optimization routine.

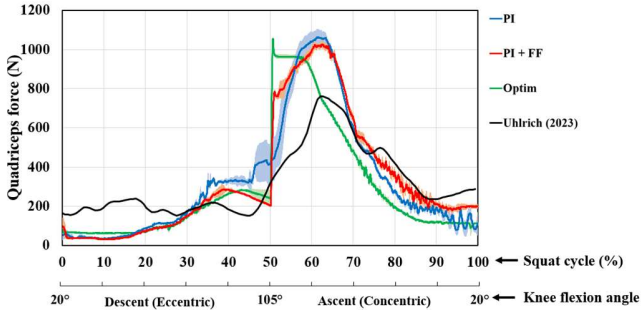

Figure 2: Quadriceps force comparison across control strategies

Optim demonstrated multi-muscle control capability for various kinematic inputs, suggesting potential adaptability for simulating other loaded closed-chain activities of the knee.

Conclusions

PI-FF control outperformed PI control in vGRF tracking, while Optim achieved physiological realism by controlling multiple muscles comparably to *in vivo* data.

Acknowledgments

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References

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