Innovative muscle control for *in vitro* gait simulation

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Summary

A novel three-stage cascade muscle force control system was designed and tested on a five-segment, nine-muscle phantom foot model. Accurately recreating *in vivo* kinematics gives insights into improved orthotic design and surgical interventions. Kinematics of the tibiotalar, talocrural and metatarsophalangeal joint of the hallux were prescribed. The controller tested showed high accuracy and repeatability, with < 0.66° mean error for all joints and motions.

Introduction

In vitro gait simulators are important tools for quantifying the internal kinetics and kinematics of the joints within the foot and ankle. Their goal is to recreate the motions of *in vivo* data, giving an insight into how the body works. They are used to improve orthopedic surgical interventions, and orthotic and ankle joint replacement designs. Previous simulators have focused on controlling vertical ground reaction force and, therefore, leave kinematics of the foot and ankle joints unconstrained. Unconstrained kinematics have resulted in strong linear kinematic correlations, > 0.87, but with no mention of error magnitudes [1]. The aim of this study was to improve the biofidelity of *in vitro* gait simulators through the design of a kinematics driven control system.

Methods

A five-segment, nine-muscle biofidelic phantom foot model was designed, using joint axes and tendon pathways from [2]. Two control methods were tested. The first was a three-stage cascade controller. Stage one used a PID controller to find the torques required to move the tibiotalar, subtalar and the first metatarsophalangeal joints to the desired positions. Three torques were then input into a muscle stress minimization algorithm to calculate muscle force. The muscle forces were input into the third stage where PID controllers generated actuator positions that resulted in the intended muscle forces. The second control strategy was force control in which muscle forces from a cascade control trial were directly input into the actuator PID controls to create the desired forces.

The systems were tested with two motions. The first was a sinusoidal range of motion study for flexion/extension (FE): 20° to -20°, inversion/eversion (IE): 4° to -4°, and hallux FE (Hal-FE): 20° to -20°. The second set of kinematics was the typical kinematics of the stance phase of gait. Ten repetitions of each motion were performed for each control strategy.

Accuracy and repeatability were assessed by the mean and standard deviation (SD) of the difference between the desired and actual kinematics achieved for each frame of a repetition. Additionally, the SD of each muscle force across repetitions was averaged over all frames for each motion.

Results and Discussion

Small errors and SD's demonstrate the repeatability of the motions (Table 1; Figure 1). Kinematic correlations were > 0.98 for all joints in all trials. Muscle force SD was < 6.9 N and < 0.96 N for cascade and force controllers, respectively.

Table 1: Average errors for the four trial scenarios.

	FE (°)	IE (°)	Hall-FE (°)
ROM Cascade	0.27 ± 0.01	0.12 ± 0.01	0.23 ± 0.09
ROM Force	0.55 ± 0.09	0.13 ± 0.02	0.64 ± 0.21
Stance Cascade	0.16 ± 0.00	0.13 ± 0.01	0.24 ± 0.02
Stance Force	0.38 ± 0.06	0.16 ± 0.01	0.66 ± 0.11

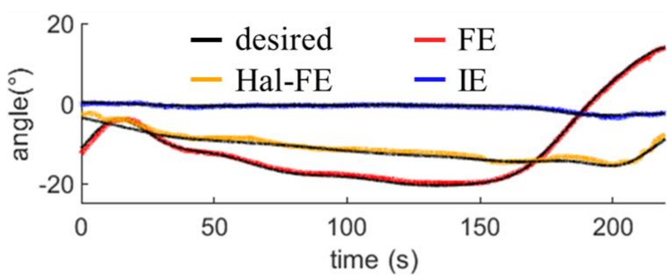

Figure 1: FE, IE and Hal-FE for 10 repetitions of the force control system replicating typical kinematics of the stance phase of gait.

Repeatability is very important for *in vitro* simulation. Maintenance of minimal variability across repeated trials means that, when comparing different simulated conditions, it is definitive that the controlled variable is causing the resultant change in kinematics. Consistency of the errors across different motions means that the simulator will continue its high performance regardless of the desired kinematics.

Conclusions

The proposed control method is more accurate and repeatable than previous simulation methods. The next step will be to include ground reaction force into the simulator.

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References

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