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Virtual muscle and reflex controllers are capable of describing human gait and responses to perturbation

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Summary

Various strategies for controlling modern prosthetic devices have been proposed, though able-bodied locomotion is usually not achieved. Spinal reflex models and virtual muscles have been demonstrated in simulation, but have not been compared to human control actions. In this study, we tuned a virtual muscle and artificial reflex controller using human walking data under the effect of mechanical perturbations. The gains of the controller, as well as muscle slack-length and muscle delay properties, were optimized using Particle Swarm Optimization, in which the multi-objective cost function minimized the difference between the predicted and experimental joint torque and the sum of the muscle activations. The results suggest that muscle reflexes can both replicate able-bodied locomotion and describe variations within and between gait cycles. This implies that such controllers are not only suitable for use in prosthetic devices, but these models may also explain key aspects of the human control system.

Introduction

The design of modern prostheses and exoskeletons is focused on developing adaptive controllers which can more closely replicate able-bodied gait. A viable control strategy is using virtual muscle models with autonomous reflex control, which has been shown to produce realistic human locomotion in simulations [1].

These reflex models have not been tuned or validated using human walking data obtained through experiments. Here, we investigate the possibility of using a Virtual Muscle Reflex (VMR) system in order to determine if muscle reflexes are not only capable of reproducing able-bodied walking, but can also sufficiently replicate the variations in human joint moments within and between gait cycles when subjected to random mechanical perturbations.

Methods

Walking data from 15 participants, including 4 females and 11 males, with an average age of 24 ± 4 years, height of 1.75 ± 0.09 m, and mass of 74 ± 13 kg was used in the study [3]. The test subjects walked for 8 minutes on an instrumented treadmill at 0.8, 1.2, and 1.6 m/s and were perturbed using random belt acceleration signals generated from discrete-time Gaussian white noise. The variance of the signal was adjusted until the perturbations were within 10% of the mean walking speed. Results from one representative subject are presented here.

Inertial artifacts in the ground reaction force data (GRF), which are introduced by accelerating the treadmill belt, rollers, and motor, were compensated using a linear, second-order, discrete-time model [2]. Joint angles and joint torques from the experiment were calculated through standard inverse 2D analysis [6], using joint positions obtained through the motion capture and the compensated GRF.

A planar, lower-leg model with three muscle groups (Gastrocnemius, Soleus, and Tibialis Anterior), representing a lower-limb prosthesis, was used to test the controller. Muscles were represented by a Hill-type model with a contractile element (CE) based on standard force-length and force-velocity properties, series/parallel nonlinear elastic elements (SEE/PEE), and a small amount of viscous damping in parallel to the contractile element. Muscle contraction dynamics and activation dynamics were formulated as a set of first-order implicit differential equations (IDE) and were simulated in MATLAB® using a first-order, implicit Rosenbrock solver [5]. Ankle torque (τ) was obtained through the VMR model by multiplying the force generated by each muscle with the moment arms.

Muscle excitation signals (u) were generated by an autonomous muscle reflex model using positive force feedback of the extensor muscles during the stance phase [1]. The control parameters were optimized in MATLAB using Particle Swarm Optimization (PSO) [4], using a multi-objective cost function. The tracking term of the cost function minimized the norm between the VMR ankle torque (τ_{VMR}) and measured ankle torque (τ_{exp}) while the effort term was modeled as the mean of the squared muscle activation (a) :

$$C = W_1\left(\sqrt{\frac{1}{N}\sum\left(\tau_{VMR} - \tau_{exp}\right)^2}\right) + W_2\left(\sqrt{\frac{1}{N}\sum a^2}\right)$$

Muscle properties, including the SEE/PEE slack-lengths and reflex time delays for each muscle, were included as parameters in the optimization. The population number and number of generations for the PSO were set to 50 and 100, respectively.

Results and Discussion

The results of the optimization suggest that muscle reflexes alone can generate realistic joint moments for use in a prosthetic device. Data from one test subject (male, age = 21, mass = 64 kg, speed = 1.2 m/s) is shown in Figure 1, where the experimental (black) and VMR (red) ankle torque are compared.

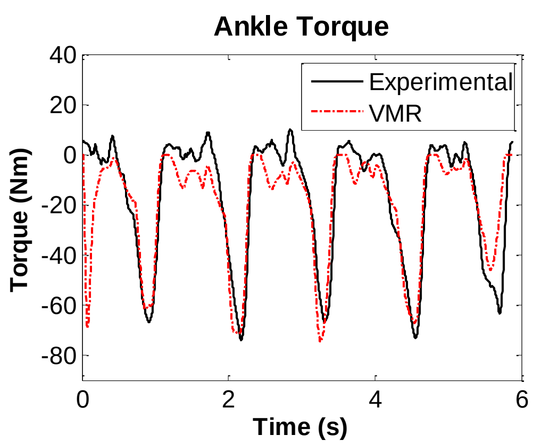

Figure 1: Experimental joint torque (black) and Virtual Muscle Reflex (VMR) joint torque using optimized reflex control parameters (red). Negative torque corresponds to plantarflexion.

The VMR system produces variations in peak moment between gait cycles and the majority of these variations correlate to the torque observed in the subject. The predicted joint torque matches the amplitude and timing of ankle push-off and mimics the shape of the experimental torque during the swing phase. Some of the discrepancies between the experimental and predicted joint moment during the swing phase may be attributed to residual errors after performing the inertial compensation on the GRF.

Additional research includes lengthening the duration of the optimization from 5 gait cycles to the entire 8 minutes of the experimental trial, as well as including the data from all 15 participants to tune the control parameters. For use in transfemoral prostheses or exoskeletons, the VMR system should be expanded to include the knee and hip. Additional control of a separate neurological process should be added to initialize the reflex controller for prosthetic or robotic devices which cannot benefit from hip actuation from the user.

Conclusion

The reflex controller of Geyer et al. [1] is capable of producing realistic joint moments in a powered prosthesis or exoskeleton. Our initial findings suggest that this reflex controller is also capable of replicating human response to perturbations and may describe important aspects of the human control system.

Acknowledgments

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