Presented at Dynamic Walking conference, June 4-7, 2016, Camp Ohiyesa, MI.

Simultaneous Optimization of Design and Control Parameters in a Powered Prosthesis with Energy Regeneration

Farbod Rohani, Hanz Richter, Antonie J. van den Bogert

Mechanical Engineering, Cleveland State University

f.rohani@csuohio.edu

Summary

The performance of powered prostheses is limited by energy requirements and battery capacity. To overcome this problem we consider an electro-mechanical transfemoral active prosthesis with energy storage and regeneration. The system consists of two DC motors, two controllable power converters, and an ultracapacitor. Simulation results show that we can reduce the energy consumption of the system dramatically by allowing some deviation from able-bodied movement. With further design improvements, self-powered operation may be possible.

Introduction

Currently available prosthetic legs for above-knee amputees are passive and require compensatory gait strategies which can cause adverse ancillary health conditions [1]. Powered prostheses are being developed, but these consume energy and battery life is a limitation. During normal walking, there are periods of the gait cycle that knee, ankle or both perform negative work [2]. It should be possible to store this energy and release it to either joint whenever it requires positive work. We propose an ultracapacitor as the storage element because it can charge and discharge faster than a battery and has better efficiency.

The goal of this study is to design a powered prosthesis that can operate with minimal or possibly zero use of external energy and with a least trajectory error for the knee and ankle. An optimal control approach is used to simultaneously optimize design parameters and joint motions and to determine how the energy use depends on how closely the device tracks able-bodied gait kinematics.

Methods

The schematic of the energy regenerative system is shown in Fig. 1. The inputs of the system are the knee torque (M_K) and the ankle torque (M_A) which were obtained from normal gait data. Two geared DC motors actuate the knee and ankle, assisted by springs and dampers (included in the model but not used in the present study). A single ultracapacitor is used to supply and store energy for the two-joint system. The voltage supplied to each motor is controlled by a four-quadrant power converter between capacitor and motor. The dynamic model of the system has five state variables: position and velocity in each joint (knee and ankle), and the capacitor charge. The two control inputs are the transformer ratios u_K and u_A.

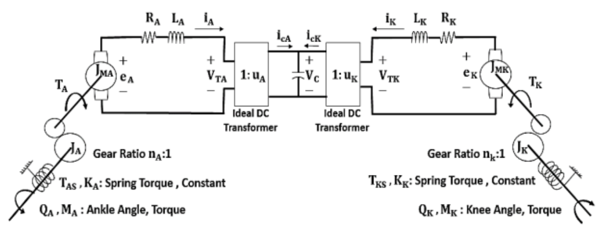

Figure 1: Schematic diagram of the electromechanical prosthetic system with motors at ankle (left) and knee (right).

The fixed model parameters included the torque constant, electrical resistance, and moment of inertia of a 24V DC motor (Pittman, 14201 series). The capacitance of the ultracapacitor was 100F. An open loop optimal control was used to simultaneously optimize the gear ratios and determine the controls that minimize a two-part cost function, consisting of tracking error and energy loss over one gait cycle:

$$F = W_1 \int_0^T \left[\left((\theta_K(t) - \theta_{K,0}(t))/\sigma_K \right)^2 + \left((\theta_a(t) - \theta_{a,0}(t))/\sigma_a \right)^2 \right] dt + W_2 \frac{Q(0)^2 - Q(T)^2}{2C}$$

Tracking error was defined as the difference between simulated joint angles θ(t) and able-bodied joint angles θ_0(t) divided by their standard deviation (σ_k *and* σ_a). Energy loss was computed from the capacitor charge (Q), and the capacitance (C). Similar to [3], the optimal control problem was transcribed using direct collocation, using the midpoint Euler discretization. The gear ratios (n_k and n_a) were added as additional unknowns to the resulting nonlinear program (NLP). Grid refinement showed that 50 time nodes per gait cycle was sufficient. The NLP was solved by IPOPT. Pareto-optimal solutions were obtained by performing optimizations with different cost function weights W_1 and W_2.

Results and Discussion

By choosing proper weighting factors for scaling different parts of the cost function, a good compromise between tracking error and energy loss can be produced by the optimal solution. Fig. 2a and Fig. 2b show how joint angles track able-bodied data. In this case, the joints have a small amount of root-mean square (RMS) tracking error (4.5°), and the energy loss in the capacitor is 17.2 J (Fig. 2c). There is a trade-off between the tracking objective and the capacitor energy, as shown by the Pareto optimizations (Fig. 2d). At one extreme (case 1), the tracking error was nearly zero, and the associated energy loss was 74.9 J. At the other extreme (case 3), more than enough energy is harvested to operate the system without external energy, but the tracking error of 14° is unacceptably large. The middle solution (case 2) is the compromise shown in Figures 2abc. Table 1 shows the energy balance of the system in each of the three solutions, separated into the work delivered by the prosthetic system, the heat generated in the motors, and the change in stored energy.

In the solution with perfect tracking (case 1), energy is harvested from the knee, but not sufficient to power the ankle and compensate for energy dissipated as heat. The system uses about 75 J of energy in each gait cycle. In the intermediate solution (case 2), RMS tracking error is 4.5°, which is an acceptable performance, and external energy use is reduced to 17.2 J. In this solution, the joint movements were subtly altered, resulting in a 77% reduction in energy use. However, a significant amount of energy is lost as heat in the motor. While the tracking error is small, the knee motion after heel strike is in the wrong direction which may be a problem.

The Pareto plot shows that self-powered operation would be possible at a tracking error of about 7°, which is probably too large. We plan to improve performance by adding optimally designed passive springs and dampers to assist the motors, using the same optimization techniques.

Table 1: Work-energy values and optimized gear ratios for the three Pareto-optimal solutions.

	W_{knee} (J)	W_{ankle} (J)	*Heat* (J)	ΔE_{cap} (J)	n_{knee}	n_{ankle}
1	-14.7	18.6	66.7	- 70.1	115.9	193.4
2	-30.9	13.2	35.1	-17.2	150.2	438.9
3	-65.2	0.7	30.8	33.4	111.2	600

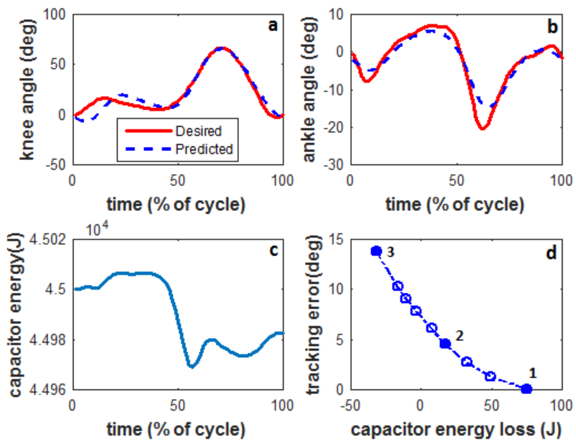

Figure 2: Joint angles (a,b) and capacitor energy (c) for a typical simulation. The Pareto front (d) shows the tradeoff between energy cost and RMS tracking error.

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ACKNOWLEDGEMENTS

We thank Poya Khalaf for providing the motor parameters. Financial support was received from NSF under grants No. 1344954 and 1544702.