

Externally powered and controlled ankle-foot prosthesis

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1 Motivation

Due to the loss of muscle tissue and the limitations of currently available prosthetic devices¹, people suffering from unilateral transibial amputation experience a 20% increase in metabolic energy consumption during normal walking² as well as decrease in stability³. As a result of these mobility challenges, amputees experience a decrease in quality of life, particularly in areas such as recreation⁴.

A prosthesis which replaces the net positive work of the ankle joint could help reduce energy consumption⁵ and improve balance. The major energy-consuming role of the ankle during walking is to provide push-off work late in stance. Several mobile lower limb prostheses that provide push-off work are under development, some of which suggest reduced metabolic energy consumption over traditional feet in pilot studies⁶. However, it is difficult to generalize these results since the nature of the prosthesis push-off in these systems is based on what subjectively feels optimal for the amputee, given the constraints of the device. These prostheses cannot explore a breadth of possible control solutions in order to find the most efficient ones because of fundamental limitations imposed by their actuators, DC motors in parallel with a fixed stiffness springs, and their onboard power sources. Thus far, no powered devices address the issues that amputees experience with balance.

One might suspect that an equivalent to or even higher than biologically normal quantity of work provided by a prosthesis could be metabolically beneficial. However, the relationship between push-off work and metabolic energy consumption during walking is not obvious. One might also expect that modulation of push-off work on a step-by-step basis could improve the stability of the gait cycle. Thus, through experimentation with a prosthesis capable of varying the quantity of net positive ankle work, much can be done to improve walking efficiency and stability.

2 Methods

We will conduct controlled experiments with an externally powered and controlled ankle-foot prosthesis in order to understand relationships between prosthesis control parameters and performance. We suspect that push-off work, timing, and peak power will have both energetic and balance consequences. The system has the capability to provide much more power and control than previous robotic prostheses, so a wide variety of these parameters

can be tested and their effects measured, providing data for the designers of future mobile prosthesis seeking optimal control strategies.

System overview: We have developed an experimental testbed featuring a single degree-of-freedom prosthesis capable of providing powered push-off (Figure 1A).

Motor and controller: The motor and controller, a 1.61 kW 3-phase AC servomotor manufactured by the Baldor Electric Company and a DS1103 real time controller manufactured by dSPACE Inc., were selected to have an excessive amount of performance for the given task, in order to enable a wide breadth of experimentation.

Flexible transmission: The flexible transmission transfers the rotary motion of the motor into linear motion at the ankle. To do this effectively, the transmission must not impinge upon the normal gait of the test subject while also being able to withstand the loading from the motor. Two styles of transmission have been developed. The first is a Bowden-style assembly with flexible inner cable and outer conduit, as one finds in bicycle brake systems. The second system is also cable-driven, but consists of a series of rigid carbon fiber tubes connected by explicit joints. Testing will be conducted with these two systems to find an ideal cable-driven transmission.

Prosthesis: The experimental prosthesis provides up to 171 ft-lbs of push-off torque and has a range of motion of 14 degrees dorsiflexion to 29 degrees plantarflexion. Due to the compliance of the series elastic element, the minimum time to reach maximum torque from rest is 86ms. The mass of the prosthesis is approximately 860 grams. The details of the mechanical design can be found in Figure 1B.

Experiment: A subject wearing their conventional prosthesis walks at his or her comfortable walking speed on a treadmill. Ground reaction forces, body segment kinematics, and metabolic energy consumption are recorded by force plates, motion tracking, and indirect respirometry equipment respectively. The experimental prosthesis is then configured to operate in a mode that mimics the normal ankle torque-angle relationship of the average adult human, scaled accordingly for the subject's height and weight. Push-off work is then systematically varied by modulating the area within the torque-angle work loop. In doing so, a relationship between ankle push-off work and metabolic energy consumption is determined.

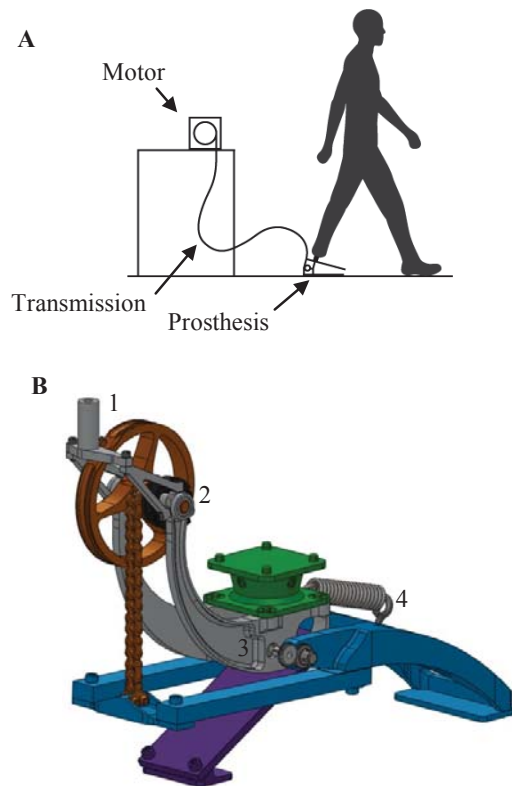


Figure 1: **A.** Schematic of the experimental testbed. The prosthesis is worn by a unilateral transibial amputee who walks on a treadmill. The motor and controller are connected to the prosthesis via a flexible transmission. **B.** CAD model of the prosthesis. The flexible transmission attaches at 1, where the inner cable continues to the pulley/sprocket (orange). A roller chain pulls on series leaf springs (blue) which deflect and rotate the toe segment (blue) about the ankle joint. Encoders at 2 and 3 measure spring deflection to enable series-elastic force control. A heel spring (purple) cushions impact at heel strike. A spring at 4 lifts toe during swing. A universal prosthesis adapter (green) attaches the device to the amputee's residual limb.

3 Future work

In addition to push-off work, timing and peak power will also be systematically varied in order to determine their effects on metabolic energy consumption as well as on balance. Simultaneously, a walking simulation will be developed with which to generate and test control ideas without requiring experimentation on human subjects.

4 Open questions

We are interested in feedback from designers of mobile robotic prostheses regarding specific relationships between control parameters and metrics of performance that we

should investigate with our experimental approach. We would also like to gauge interest in the testing of others' experimental prostheses with the testbed.

References

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