Ankle-Foot Prosthesis Testbed
An Experimental Approach to the Development of Effective Assistive Devices

Joshua M. Caputo*, Steven H. Collins
Carnegie Mellon University, Mechanical Engineering
*Email: jmcaputo@andrew.cmu.edu

Methods
We have embodied experimental testbed approach with an externally powered and controlled ankle-foot prosthesis.

Electromechanical (Fig. 1)
- Off-board AC servomotor and real-time controller
- Flexible Bowden-style transmission with synthetic cable
- Lightweight ankle-foot prosthesis provides ankle torque

Sensing and Control
- Ankle torque deflects series leaf springs
- Measurement of spring deflection measures torque
- Proportional control on torque error regulates torque

Performance Evaluation
- Torque measurement and closed-loop frequency and step response tests were conducted on the benchtop
- Walking trials were performed in which a piecewise linear impedance profile was matched (Fig. 2)

Introduction
Over 1/2 a million Americans are currently affected by major lower limb amputation [1]. Existing technology falls far short of fulfilling the full functional need, resulting in reduced walking performance (20% increased energy expenditure) [2,3], 25% lower preferred walking speed [4], and 1.7 times higher incidence of falling [5] and thus ultimately, reduced quality of life [6]. Improvements to the biomechanical performance of assistive devices are undoubtedly an important part of regaining mobility for the affected population. Mobile robotic devices that hope to address these deficiencies are currently in development and show promise [6]. However, development time for these devices has been long and the breadth of application that can be done with them is quite limited. Thus, it is impractical to systematically explore assistance with these devices, limiting our ability to learn from them. We propose an experimental testbed approach in which control parameters, or even control architectures, can be easily and systematically adjusted to measure their effect on gait performance. While deepening our understanding of walking results will feed directly into the hands of developers of mobile devices seeking answers to design questions.

Results
Benchtop Tests
- Ankle torque measurements are accurate to ±3.3 Nm (Fig. 3A)
- Closed-loop step response rise time is 64 ms (Fig. 3C)
- Peak torque, closed-loop torque control bandwidth, device mass, and peak power output are superior to comparable devices in the literature (Table 1).

Walking Tests
- RMS tracking error in time was 9.9 Nm (Fig. 4A)
- Tracking in angle space difficult to quantify (Fig. 4B) but was sufficient to deliver push-off work to an accuracy of ±8.7 J
- Push-off work was systematically varied from -3.3 to 8.8 J (Fig. 5)

Conclusion
Lower limb amputees walk with higher energy consumption and lower stability at lower preferred speeds compared to their able-bodied counterparts. Next generation prosthetic limbs that address these performance limitations will help these people regain their mobility. Towards understanding the complex tradeoffs in amputee gait we have developed an experimental prosthesis testbed with which systematic studies investigating the effect of control decisions on walking performance will be conducted. Here we present the results of benchtop and walking tests which indicate the device’s performance exceeds that previously seen in the literature and is capable of providing a breadth of ankle impedance behaviors to a subject walking a subject walking.

References

Abstract
Improvements to assistive technologies are a key part of reversing the severe mobility limitations faced by amputees. Towards this end, we have developed an experimental prosthesis testbed which side-steps the challenges associated with designing a mobile device for near future consumer use to instead focus solely on developing controllers with features that are beneficial to human walking. The system consists of a powerful off-board servomotor and real-time controller, which connect to a lightweight 1 DoF series elastic torque controlled prosthesis via a flexible Bowden-style transmission. We demonstrated device performance through a series of benchtop and walking tests. The prosthesis weighed 568 kg and exhibited a closed loop torque control bandwidth of 17 Hz, a peak torque of 1.75 Nm, and a peak power of 175 W. During walking, peak RMS tracking error was 9.9 Nm, sufficient for demonstrating systematic variation of push-off work from -3.3 to 8.8 J.

Figure 1: A) Schematic of the prosthesis testbed during use in an amputee walking experiment on a treadmill (top) with detailed free body diagram schematic of the prosthesis undergoing stance phase force conditions (bottom). B) Schematic of the prosthesis and effect of the transverse elements (orange) cause loading on the series elastic springs and leaf segment (blue) to generate ankle plantarflexion torques while dorsiflexion torques are provided by passive springs. inset is a photograph of the current prosthesis prototype.

Figure 2: Example control law used here during walking. Given current ankle position and gait phase, a desired torque is commanded.

Figure 3: A) Torque measurement accuracy, quantified in a static loading test using known weights applied at different device configurations. B) Closed-loop frequency response, determined in a benchtop test with the device toe segment held in a fixed position while a step up, followed by a step down, in desired torque is commanded.

Figure 4: A) Ankle torque during normal walking at 1.25 m/s on a treadmill (6 steps = 267). Step-averaged torque displayed on axis normalized to % stance. B) Ankle torque during the same trial plotted in ankle position, the clockwise loop indicates positive work provided.

Figure 5: Systematic variation of ankle push-off work, A) through E) indicate different experimental conditions where desired work is scaled from that seen during normal walking. Ankle torque-angle work loops (bottom) are shown with corresponding push-off work value (top).

Table 1: Comparison of joint torque control systems capable of ankle-like torques for adult male subjects, approximately 100 Nm. Peak torque, closed-loop torque bandwidth (< 88 g), mass seen by the human subject, and peak joint mechanical power are compared to experimental data from the proposed device. When possible, experimental results were used in favor of proposed performance figures. The abbreviations n/a and n.r. indicate not applicable and not reported, respectively. Source from [2].

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