A parameter study of joint torque trajectory control during walking with bilateral ankle exoskeletons

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1 Motivation

Wearable robots for lower-limb assistance have long shown promise for improving mobility by working in parallel with biological muscle-tendon units, and thereby sharing a portion of the mechanical load of locomotion, aiding in body weight support, or restricting unfavorable kinematics [4]. In particular, ankle-assistive devices target the joint responsible for delivering half the mechanical energy used in walking, and could combat the compromising effects of aging, spinal injuries, and debilitating conditions like cerebral palsy and stroke [2,3]. However, wearable lower-limb assistive devices have rarely produced measurable benefits in key performance areas such as metabolic energy consumption, preferred walking speed, and stability, possibly because their control parameters have not yet been optimized [1,6].

2 Our Approach

We have created a flexible testbed and powerful tethered device for the rapid exploration of prospective control strategies. Our ankle-foot orthosis (AFO) consists of a lightweight, adjustable carbon fiber frame capable of applying substantial plantarflexion torque about the user's ankle joint (Figure 1). User comfort was prioritized in the design of the AFO by offboarding heavy actuators and power sources, integrating soft and flexible attachment points, and smoothing the application of rapid torques via series elastic actuation.

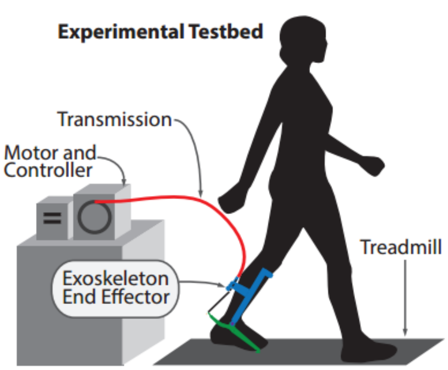

Figure 1. Depiction of experimental testbed during unilateral AFO testing. An off-board motor and controller control the exoskeleton end effector via a Bowden cable transmission. Tests are conducted with able-bodied subjects on a split-belt force-sensitive treadmill.

As one facet of a larger effort to compare the relative performance of several promising control strategies, this study focuses on sweeping relevant parameters to determine the optimal implementation of joint torque trajectory control. This method of high-level torque control consults a look-up table to generate a desired ankle torque based on a dynamic estimation of current stride phase (as a percent of the gait cycle), playing out a predefined torque trajectory in time (Figure 2).

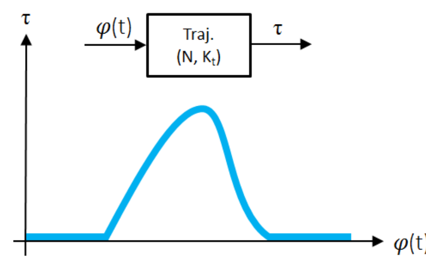

Figure 2. Control architecture of joint torque trajectory control. The torque generated is a scaled (K_t) function of current stride phase *φ(t)* normalized via a filtered average over the last *N* stride periods.

Such joint trajectory control may be summarized as:

$$\tau_d = K_t \cdot f\big(\varphi(t)\big) \tag{1}$$

where K_t is a gain parameter. $f(\varphi(t))$ is a time-series of recorded torques as a function of stride phase:

$$\varphi(t) = \frac{t - t_{hs}}{T_s} \tag{2}$$

The stride phase $\varphi(t)$ normalizes the time since last heel strike, t - t_{hs} ,by a stride period T_s which in turn is the filtered average of the last N stride periods:

$$T_s = \frac{1}{N} \sum_{i=1}^{i=N} T_i \tag{3}$$

This dynamic phasing may help to entrain synchronous behavior between the robot and the human user.

Time-based spatial trajectory control schemes – matching gait phase to desired position – have proven successful for a range of walking robots, prostheses, and rehabilitative devices. In contrast, joint torque trajectory control schemes – matching gait phase to desired joint torque - are relatively complex.

However, by designing a high-level torque control resistant to error resulting from erratic, atypical, and changing spatial trajectories, this strategy may prove to be particularly well-suited for rehabilitation in teaching or retraining healthy gait.

3 Methods

Experimental Setup

The experimental testbed consists of a powerful off-board motor and control hardware, a flexible tether to transmit mechanical power and sensor signals, and a lightweight instrumented exoskeleton (Figure 1). Ankle position and actuator torques are measured directly by an encoder and a load cell. Low-level torque control is achieved by controlling motor velocity as a function of the current system state and the desired ankle torque specified by the time-based look-up table.

Experimental Protocol

The performance of the torque trajectory controller will be evaluated on eight neurologically-intact subjects walking in a pair of ankle exoskeletons at 1.25 m/s on two separate days (Figure 3). The first day will acclimate subjects to the co-robot walking experience by presenting a randomized series of controller parameter combinations. These trials will last for 7 minutes each, with 5 minute rest periods in between. The second day of testing will begin with a baseline control trial, recorded while not wearing the exoskeletons, and a secondary control trial, recorded while wearing the exoskeletons but receiving no assistance. The experiment will continue by presenting the same randomized order of parameter combinations as on the first day, sweeping each parameter linearly.

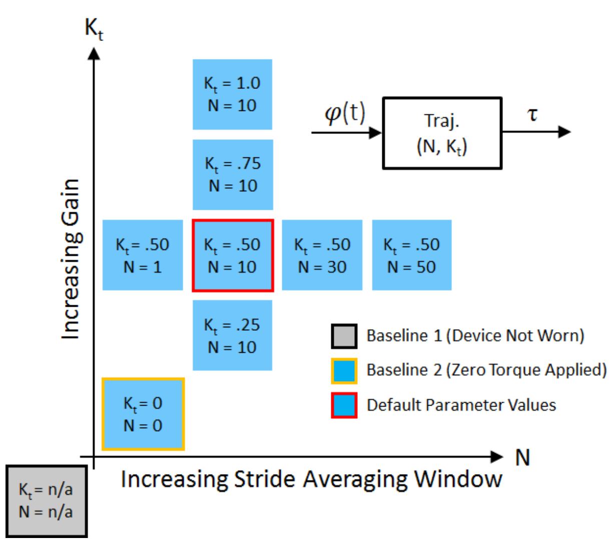

Figure 3. Experimental protocol of parameter sweep. Gain (K_t) and stride averaging window N will be independently varied from default values (outlined in red) in a randomized series of trials to determine the effects of these parameters on the controller's dynamic calculation of torque.

The subject's gait dynamics and energetics will be measured via the instrumented split-belt treadmill, indirect calorimetry, and marker-based motion capture. Using this data, the performance of the controller will be evaluated with respect to center of mass mechanics, joint mechanics (using inverse dynamics to estimate joint power), metabolic energy expenditure, and muscle activity.

4 Preliminary Results

We have previously investigated the metabolic and biomechanical effects of independently varying the average torque and net work applied to the ankle joint using our AFO unilaterally. Our primary findings were that both increased work and increased average torque reduced effort at the ankle, but while increased work also reduced metabolic expenditure, increased torque increased metabolic expenditure [5]. This study builds upon these results by fine-tuning the application of torque for optimal reductions in metabolic cost.

5 Open Questions and Possible Outcomes

The potential utility of this study is two-fold. Firstly, by measuring the performance of the joint torque trajectory control strategy for a range of users and parameter combinations, the relative efficacy of such a time-based controller may be generally compared to previously documented control strategies, either prompting or discouraging future exploration. While the robustness of joint torque trajectory control against human noise may be seen as one of its key benefits, the possibility also exists that users will perceive the device as unresponsive, difficult to anticipate, or directly interfering with their own gait control. Secondly, by methodically exploring the parameter space of the torque trajectory controller, the optimality of specific combinations of gain and stride averaging window may be determined, paving the way for future development of high-performing lower-limb assistive devices.

Acknowledgements

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