Selecting the Best Series Stiffness and Iterative Learning Gain for Exoskeleton Torque Control

Juanjuan Zhang and Steven H. Collins
Carnegie Mellon University, Pittsburgh, PA, USA
juanjuanzhang@cmu.edu; *stevecollins@cmu.edu*

1 Introduction

Series elastic actuators have been widely used in human-robot interactive systems due to their high controllability and improved human experience. One such system is the powered ankle exoskeleton. In [1], the torque control of a tethered ankle exoskeleton with a coil spring (Fig. 1) was investigated, which showed that the combination of model-free, integration-free feedback control and iterative learning resulted in the best tracking performance. During these torque control experiments, interesting interactions were observed between the exoskeleton hardware, the high level controller that determines desired torques and the low level controller that tracks torques. In this study, we focus on the interactions between three stiffness or stiffness-like values in ankle exoskeleton torque control: the desired stiffness K_{des} defined as the slope of desired torque τ_{des} and ankle angle θ_{a} relationship, the passive stiffness K_{t} defined as the relationship between the torque τ and angle θ_{a} while the motor position is fixed, and the iterative learning gain K_{l}. Hypotheses based on symbolic analysis are made and tested through walking experiments. The results of this project are expected to answer these questions: What is the optimal hardware compliance for a fixed control objective? What is the optimal iterative learning gain for a fixed combination of system compliance and control objective?

2 Hypotheses

From the previous experiments and theoretical analysis, two hypotheses were made: A. For a fixed desired stiffness $K_{\text{des}} = d\tau_{\text{des}}/d\theta_{\text{a}}$ of the ankle exoskeleton tracked by proportional control with damping injection under optimal control gains, the torque error is minimized when the passive stiffness of the testbed transmission $K_{\text{t}} = d\tau/d\theta_{\text{a}}$ matches K_{des}; B. For a fixed passive stiffness K_{t} and a fixed desired stiffness K_{des} to be tracked by iterative learning, the torque error is minimized when the learning gain K_{l} is chosen to be $K_{\text{opt}} = 1/K_{\text{t}}R$, in which R is the total effective gear ratio from the motor to the ankle position.

3 Experimental Methods

All the experiments are conducted with one healthy subject, who walks on a treadmill with a fixed speed of 1.25 m/s while wearing the tethered ankle exoskeleton on the right leg. The exoskeleton is controlled by an off-board motor system through a Bowden cable transmission [1]. For testing of both hypotheses, the passive stiffness of the transmission system is varied by changing the the coil spring of the device (Fig. 1).

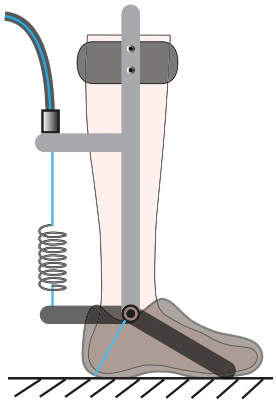

Figure 1: The tethered ankle exoskeleton with series elastic actuation

For hypothesis A, with each spring installed on the exoskeleton, we prescribe five different desired stiffnesses K_{des}. For each stiffness, the torque error using proportional control and damping injection under optimal gains is achieved through experiments. Relationships of the five torque error values and their corresponding relative desired stiffnesses, $K_{\text{des}}/K_{\text{t}}$, is investigated. The torque error is expected to be minimized when $K_{\text{des}}/K_{\text{t}}$=1.

For hypothesis B, with each spring, we identify multiple desired stiffnesses K_{des} . For every K_{t} and K_{des} combination, multiple gains for iterative learning are tested. Relationship between the torque errors and their respective relative learning gains, which is defined as $K_{\text{l}}/K_{\text{opt}}$=$K_{\text{l}}K_{\text{t}}R$, is investigated. We expect minimized torque error at $K_{\text{l}}K_{\text{t}}R$=1.

4 Preliminary Results

Fig. 2 shows the preliminary experimental data with one specific spring for both hypotheses. For this specific passive stiffness and transmission system, the data agree with the hypotheses well. However, more data from different springs and Bowden cables are needed to make a firm conclusion.

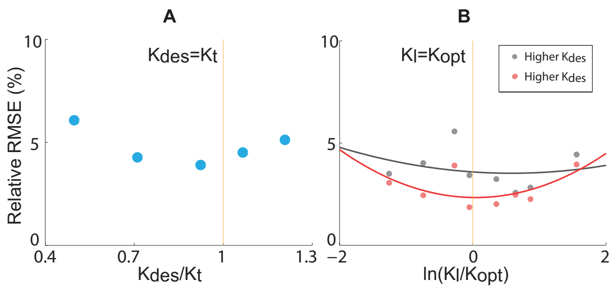

Figure 2: Test results for one spring. (A) Hypothesis A: Best PD control test results versus $K_{\text{des}}/K_{\text{t}}$. (B) Hypothesis B: Learning control gains versus $\ln(K_{\text{l}}K_{\text{t}}R)$ for various desired stiffness K_{des}. Data agree with hypotheses well.

References

[1] J. Zhang, C. C. Cheah, and S. H. Collins. Experimental comparison of torque control methods on an ankle exoskeleton during human walking. In *Proc. Int. Conf. Rob. Autom.*, 2015.