INTRODUCTION

Exoskeletons have been used for human performance restoration and enhancement for many years. Due to the dynamic nature of human locomotion, torque control is widely used in lower-limb exoskeleton assistance during stance phases of walking. In these systems, series-elastic actuators (SEA) are commonly used to provide low error torque tracking in the presence of unknown and changing human dynamics. Good torque tracking performance is important to the fidelity of gait-related biomechanical experiments and the effectiveness of clinical gait recovery training. Control of lower-limb exoskeletons is normally hierarchical, with high level controllers determining behavior-related desired torques and torque control lying at a lower level. Many low-level control methods have been proposed for existing exoskeleton systems. However, relatively little has been reported on the relative performance of different torque controllers on the same platform under practical walking conditions, making differentiation among candidate methods difficult. Moreover, the interactions between high- and low-level controllers are unknown. This study aimed to compare the torque-tracking performance of prominent torque controllers, under realistic experimental conditions, with multiple high-level controllers, in a single exoskeleton platform [1]. These results are expected to help guide the selection and tuning of lower-limb exoskeleton torque controllers for locomotion assistance, which will benefit gait-related biomechanics research and clinical training.

METHODS

The ankle exoskeleton testbed used in experiments consisted of an off-board geared electric motor with real-time driver, a flexible Bowden cable transmission with series compliance, and an exoskeleton that interfaced with the human body (Fig. 1). Motor input voltage was regulated by a motor driver running in velocity control mode, which provides smoother torque tracking in series elastic actuators. Desired motor velocity was commanded to a dedicated hardware motor controller for all torque controllers investigated. Nine torque controllers, including variations and combinations of classical feedback control, model-based control, adaptive control and iterative learning, were experimentally compared in this study. Each was tested separately with four high-level controllers that determined desired torque based on time, ankle angle, a neuromuscular model (NMM), or electromyography (EMG). Under each high- and low-level controller combination, the exoskeleton was tested with one subject who walked on a treadmill with 1.25 m/s for one hundred steady-state steps on a treadmill. The root mean squared torque errors were calculated for each stride (RMSE) and for an averaged stride (RMSE-A).

RESULTS AND DISCUSSION

The best torque tracking performance was observed with the combination of model-free, integration-free feedback control and iterative learning for all high-level controllers, both in real-time and for the average stride. In this study, this type of controller was represented by proportional control and damping injection compensated by iterative learning (PDa+LRN) as described below.
\[
\dot{\theta}_{\text{m,des}}(i,n) = -K_p e_\tau(i,n) + -K_d \dot{\theta}_m(i,n) + \dot{\theta}_{\text{LRN}}^{\text{PDa}}(i+D,n)
\]

In this equation, \(\dot{\theta}_{\text{m,des}}\) is the desired motor velocity to be commanded, \(K_p\) is a proportional gain, \(e_\tau\) is torque error, \(K_d\) is a damping gain, and \(\dot{\theta}_m\) is measured motor velocity. \(\dot{\theta}_{\text{LRN}}^{\text{PDa}}\) is the compensation from iterative learning, which is updated by

\[
\dot{\theta}_{\text{m,des}}^{\text{LRN}}(i,n+1) = \dot{\theta}_{\text{m,des}}^{\text{LRN}}(i,n) - K_L e_\tau(i,n),
\]

where \(i\) is the time index (number of control cycles elapsed) within this step, \(n\) is this step and \(n+1\) is the next step, \(K_L\) is the iterative learning gain, and \(D\) is an estimate of the delay between commanding and achieving a change in motor position. Using this controller, the motor commands arose primarily from feedback control, with iterative learning compensating for consistent tracking errors. Part of the controller is labeled as 'damping injection' instead of 'derivative control' since motor velocity is used instead of the relative velocity between motor and ankle joint. This was to reduce noise while maintaining comparable control performance. The iterative learning part only acts in the next step based on the torque errors of the current one.

**Table 1:** Tracking errors with PDa+LRN torque control

<table>
<thead>
<tr>
<th></th>
<th>RMSE</th>
<th>(% \tau_{\text{max}})</th>
<th>RMSE-A</th>
<th>(% \tau_{\text{max}})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time</td>
<td>0.57 ± 0.18 Nm</td>
<td>1.3%</td>
<td>0.10 Nm</td>
<td>0.2%</td>
</tr>
<tr>
<td>Angle</td>
<td>0.99 ± 0.23 Nm</td>
<td>2.5%</td>
<td>0.11 Nm</td>
<td>0.3%</td>
</tr>
<tr>
<td>NMM</td>
<td>0.93 ± 0.32 Nm</td>
<td>2.3%</td>
<td>0.12 Nm</td>
<td>0.3%</td>
</tr>
<tr>
<td>EMG</td>
<td>2.14 ± 0.77 Nm</td>
<td>5.9%</td>
<td>0.22 Nm</td>
<td>0.6%</td>
</tr>
</tbody>
</table>

Error values for PDa+LRN and their percentage of the peak desired torque, \(\tau_{\text{max}}\), for the average step are given in Table 1. Overlapped desired and measured torque trajectories for one hundred steps with PDa+LRN are shown in Fig. 2. The high variations of torques for Angle- NMM- and EMG-based high level controllers are the result of step-to-step gait variation of the subject. Depending on high-level conditions, the real-time torque errors with this controller were 38%-84% lower than with PDa alone, and average-step torque errors were 91%-97% lower. This approach is effective since it is analogous to the classical proportional-integral-derivative control. The proportional term provides basic tracking; damping injection improves the system stability like derivative control; iterative learning, which is a step-wise integral control, eliminates steady-state errors in cyclic operations.

**CONCLUSIONS**

A systematic comparison of uni-directional Bowden cable driven exoskeleton torque controllers under walking conditions was conducted, demonstrating that proportional control with damping injection compensated by iterative learning had better torque tracking performance than any other methods tested in this study and in the literature. Implementation of this controller was straightforward, requiring sequential tuning of only four parameters. Our results suggest that this approach can be applied to multiple torque-controlled lower-limb exoskeletons used in cyclic processes like locomotion. The application of this controller in lower-limb robotic devices will improve the precision of interventions and allow better-controlled experiments.

**REFERENCES**