Can a user self-tuned exoskeleton control reduce walking metabolic cost?

Guoping Zhao[1*], Niklas Schäfer[2], Bowen Li[1,3], Martin Grimmer[1], Andre Seyfarth[1]
[1]Lauflabor Locomotion Laboratory, Techanical University of Darmstadt, Germany
[2]Measurement and Sensor Technology, Technical University of Darmstadt, Germany
[3]Department of Fluid Control and Automation, Harbin Institute of Technology, China
*guoping.zhao@tu-darmstadt.de

1 Introduction

Recent studies have demonstrated that the human-in-the-loop (HIL) optimization-based approaches can generate individualized assistance control parameters and reduce human walking metabolic cost [1–4]. However, the time-consuming optimization process of these methods makes them less practical for elderly individuals and patients. On the other hand, humans are able to adapt gait patterns with different exoskeleton assistance profiles and further reduce their metabolic costs over time [5]. This suggests that humans can potentially self-tune exoskeleton control parameters and find user-specific optimal assistance profiles. Therefore, this study aimed to investigate a user self-tuning method for the exoskeleton assistance control. We hypothesized that humans can effectively find optimal control parameters to reduce walking metabolic cost through subjective perception.

2 Methods

A hip exoskeleton (named GuroX, Figure 1A) was used for this study. It consists of two onboard electric motors which can generate extension and flexion torques on both hip joints. The power unit and the control box are off-board. Vertical ground reaction forces from an instrumented treadmill were used to detect heel-strike. A wireless joystick was used to tune the exoskeleton control parameters while walking on the treadmill (Figure 1B).

We conducted a pilot experimental study with 5 young and healthy subjects (4 females, age 22.0 ± 1.7 years, body mass 69.7 ± 2.5 kg, height 1.72 ± 0.03 m, mean ± s.e.). The study was approved by the Ethics Committee of TU Darmstadt. The exoskeleton torque profile consists of four half-cycle sinusoidal curves connected at their respective peaks (Figure 1B). The four control parameters are the timing of the transition from flexion to extension torque (t_1), the peak extension torque timing (t_2), the timing of the transition from extension to flexion torque (t_3), and the peak flexion torque timing (t_4). The exoskeleton peak hip extension torque and peak hip flexion torque were 12 N m. The treadmill speed was 1.25 m/s. After familiarizing with the setup, subjects were instructed to tune the four control parameters using the joystick and find the optimal parameters for maximum walking assistance. The self-tuning process was terminated when subjects felt that they have identified the optimal values. In order to assess the self-tuned assistance torque profile, we conducted an evaluation session for metabolic rates using indirect calorimetry (Cosmed K5, Italy) during walking with a zero-torque condition (the exoskeleton torque was set to zero) and the self-tuned assistance torque condition. Each condition lasted 4.5 min. The

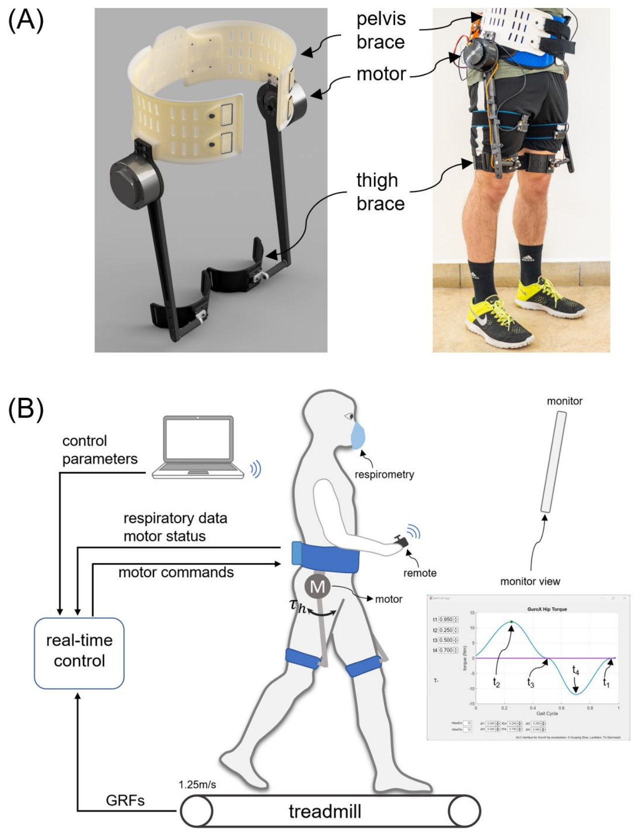

Figure 1: (A) The mechanical structure of the hip exoskeleton GuroX (left) and a subject wearing the exoskeleton (right). (B) Experimental setup. The monitor shows the subject the hip torque pattern applied by the exoskeleton. Subjects can tune the torque pattern with the joystick remote.

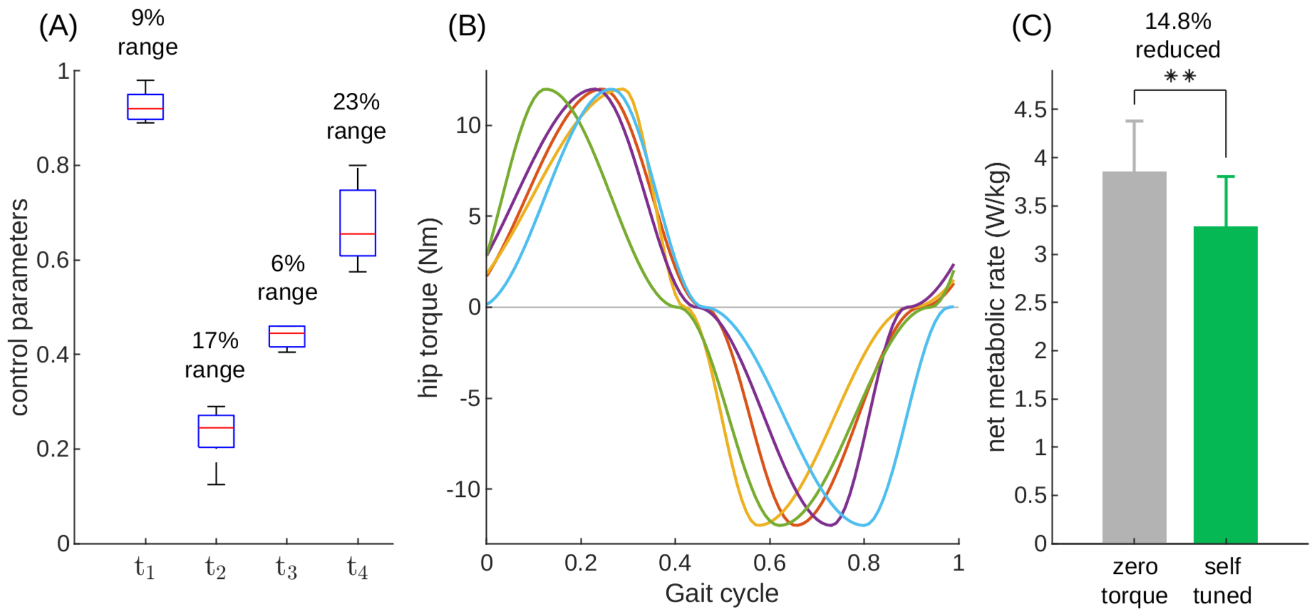

Figure 2: (A) Subject self-tuned control parameters. Red lines, boxes and whiskers indicate the medians, the 25th to 75th percentile, and the range, respectively. (B) Self-tuned optimal hip torque pattern for each subject. Different line colors indicate different subjects. (C) Net metabolic rate of walking with zero-torque condition and self-tuned optimal assistance torque condition. Double asterisks denote statistical significance ($P < 0.001$).

metabolic rate was estimated by fitting a first-order dynamic model to the breath-by-breath data measured in each condition. The standing metabolic rate was computed by averaging over 3 min of standing data which was performed before walking.

3 Results and discussions

All subjects found their optimal assistance torque patterns within 13 min (9.9 ± 0.8min, mean $\pm$ s.e.). The net metabolic rate with the self-tuned optimal pattern (Figure 2A,B) was significantly reduced by $14.8 \pm 1.2\%$ (mean $\pm$ s.e., $P < 0.001$) compared to walking with the zero-torque condition (exoskeleton turned off, Figure 2C). Our approach produces a comparable level of metabolic reduction to previous hip exoskeleton studies [2, 4] while it is more than two times faster than state-of-the-art HIL optimization approaches. For instance, it took on average 21 min for optimizing 2 control parameters of the hip extension torque profile with respiratory data based HIL optimization in [2], while an online metabolic estimation approach took 24 min for optimizing 4 control parameters of a hip exoskeleton [4].

Similar to HIL optimization-based studies [1–4], we also found that the optimal torque patterns vary widely across subjects (Figure 2A,B). This indicates that users are able to find individualized assistance profiles. Interestingly, the variations in zero-crossing timings (i.e., t_1 and t_3) are much smaller than those of the peak timings (i.e., t_2 and t_4). This suggests that a narrow parameter value range can be used for t_1 and t_3 to further reduce the self-tuning duration.

4 Conclusions

The results of this preliminary study support our hypothesis that humans can determine individualized assistance profiles through self-tuning of control parameters, guided by their subjective perception of walking effort. It provides a new and significantly faster way of finding personalized exoskeleton assistance profiles compared to existing state-of-the-art methods. Future work with more subjects is required for further investigating the effectiveness of our method on different type of exoskeletons and different locomotion tasks.

References

[1] Juanjuan Zhang, Pieter Fiers, Kirby A. Witte, Rachel W. Jackson, Katherine L. Poggensee, Christopher G. Atkeson, and Steven H. Collins. Human-in-the-loop optimization of exoskeleton assistance during walking. *Science*, 356(6344):1280–1284, 2017.

[2] Ye Ding, Myunghee Kim, Scott Kuindersma, and Conor J. Walsh. Human-in-the-loop optimization of hip assistance with a soft exosuit during walking. *Science Robotics*, 3(15):eaar5438, 2018.

[3] Patrick Slade, Mykel J. Kochenderfer, Scott L. Delp, and Steven H. Collins. Personalizing exoskeleton assistance while walking in the real world. *Nature*, 610(7931):277–282, Oct 2022.

[4] Daniel F. N. Gordon, Christopher McGreavy, Andreas Christou, and Sethu Vijayakumar. Human-in-the-loop optimization of exoskeleton assistance via online simulation of metabolic cost. *IEEE Transactions on Robotics*, 38(3):1410–1429, 2022.

[5] Katherine L. Poggensee and Steven H. Collins. How adaptation, training, and customization contribute to benefits from exoskeleton assistance. *Science Robotics*, 6(58):eabf1078, 2021.