People explore gait dimensions, and reduce this exploration, as they learn to walk with exoskeleton assistance.

Sabrina J. Abram[1], Katherine L. Poggensee[2], Max Donelan[1], and Steven H. Collins[2]
[1]Department of Biomedical Physiology and Kinesiology, Simon Fraser University, Burnaby, Canada
[2]Department of Mechanical Engineering, Stanford University, Stanford, USA
Email: *sabram@sfu.ca

Introduction

The success of assistive devices relies on users learning to take advantage of the assistance [1]. In everyday walking, the nervous system is faced with the dilemma between exploiting, perhaps erroneously, previously learned strategies and exploring new, unknown strategies that may improve its objective [2]. Here we aim to understand how people balance this trade-off when learning to walk with ankle exoskeleton assistance. First, we hypothesized that people explore many candidate gait dimensions as they determine which dimensions are relevant to their objective. Next, we hypothesized that people reduce this exploration with experience as they learn to exploit new strategies.

Methods

We performed a post-hoc analysis of data from Poggensee et al. [3]. In this study, ten participants completed a training session per day for a total of 5-6 days, where they walked on a treadmill while wearing a bilateral, tethered, torque-controlled ankle exoskeleton emulator. Participants completed a validation trial each day where they experienced a generic assistance controller for two, 6-minute trials. They also completed an adaptation trial from Day 2 onwards, where they periodically experienced 2 minutes of generic assistance during a protocol that otherwise differed according to how Poggensee et al. randomly grouped participants. In our current study, we analysed how users learned to walk with this repeated exposure to the generic assistance controller.

In this experimental setup where the pattern of assistive torque was controlled on a step by step basis, users could 1) influence the torque timing by varying their step frequency, and 2) influence the power and work applied to the ankle by varying their ankle kinematics. We determined exploration at the level of the whole movement, the joint, and the muscle by quantifying step-to-step variability along gait dimensions of step frequency, ankle kinematics, and total ankle extensor muscle activity. In all gait dimensions that we measured, we tested how variability changed over multiple days by comparing average variability in the final 3 minutes of the 6-minute validation trial between the first and last day. We also normalized this variability to participant's average variability in normal walking (or zero-torque for ankle angle that was approximated using the exoskeleton) across all days. Finally, we tested for systematic changes along gait dimensions by comparing average adaptation in the final 3 minutes of the 6-minute validation trial between the first and last day.

Results and Discussion

When the nervous system has minimal experience walking with exoskeleton assistance, it explores along many gait dimensions in search of new strategies. We observed higher variability than normal walking at the beginning of the multi-day protocol ($p=6.6 \times 10^{-5}$, Figure 1A; $p=8.0 \times 10^{-8}$, Figure 1B; $p=3.6 \times 10^{-4}$, Figure 1C; $p=1.2 \times 10^{-4}$, Figure 1D).

The nervous system reduces exploration with experience. Participants had lower step frequency variability ($p=2.0 \times 10^{-5}$) and ankle angle variability ($p=2.1 \times 10^{-5}$) on the last day compared to the first day, and reduced this variability with time constants (τ) of 107.8±107.1 minutes and 162.0±204.7 minutes, respectively (mean±SD). They also reduced their total soleus ($p=8.0 \times 10^{-4}$, τ=20.2±46.1 minutes) and medial gastrocnemius ($p=2.3 \times 10^{-3}$, τ=25.9±45.9 minutes) variability.

With experience, variability along some gait dimensions converges on the baseline variability observed in the absence of exoskeleton assistance, suggesting that exploration was in part purposeful. Participants' variability converged on their average variability in normal walking for step frequency (p=0.38) and total soleus activity (p=0.68). However, variability in ankle angle ($p=8.0 \times 10^{-6}$) and total medial gastrocnemius activity ($p=2.2 \times 10^{-4}$) remained elevated, suggesting that some learning may still be in progress or that there is some added experimental variability.

Exploration only results in systematic changes along some gait dimensions, suggesting that the nervous system did not know a priori which dimensions to adapt. Participants did not have large adaptions in their step frequency (p=0.073, Figure 2A) or ankle angle range during stance (p=0.053, Figure 2B) on the last day compared to the first day; however, they did learn to adapt their total soleus ($p=4.6 \times 10^{-4}$, Figure 2C) and medial gastrocnemius activity ($p=9.5 \times 10^{-4}$, Figure 2D).

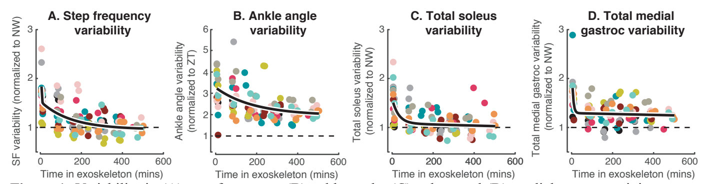

Figure 1: Variability in **(A)** step frequency, **(B)** ankle angle, **(C)** soleus and **(D)** medial gastroc activity. Each colour represents each subject. Solid black lines are fitted double exponentials.

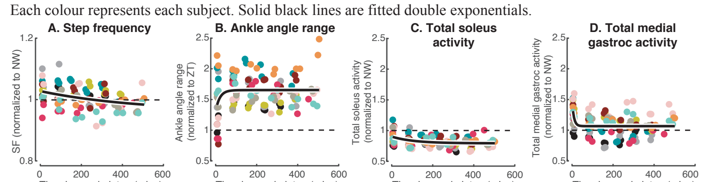

Figure 2: Adaptation in **(A)** step frequency, **(B)** ankle angle range, **(C)** soleus and **(D)** medial gastroc activity.

Significance

Our findings suggest that people balance an explore-exploit trade-off along many gait dimensions as they learn to reduce their metabolic cost of walking with exoskeleton assistance [3]. These insights into the nervous system's algorithms may be beneficial for training older adults and clinical populations to walk with assistive devices. That is, we may customize, and perhaps lower, training time by using baseline variability as a benchmark to indicate when people begin to exploit new strategies.

Acknowledgements

NSERC Michael Smith Foreign Study Supplement (SJA)

References

[1] N. Sanchez, et al. *J Physiol* **597**, 4053-4068, 2019.
[2] R.C. Wilson, et al. *J Exp Psychol Gen* **143**, 2074–2081, 2014.
[3] K.L. Poggensee, et al. *In Prep*.