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

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I. Introduction

The success of assistive devices relies on users learning to take advantage of this assistance [1]. In everyday walking, the nervous system is faced with the dilemma between exploiting previously learned, perhaps suboptimal, 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.

II. Methods

We performed a post-hoc analysis of data from a study by Poggensee et al. that was originally designed to understand the benefits of training over multiple days with generic and customized exoskeleton assistance [3]. In this study, 15 participants completed a training session on each day for a total of 5-6 days, where they walked on a treadmill while wearing a bilateral, tethered, torque-controlled ankle exoskeleton emulator. On each day, participants completed a validation trial where they experienced a generic assistance controller for 6-minute double reversal trials. Participants also completed an adaptation trial from the second day 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 analyzed how users learned to walk with 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 influence the torque timing by varying their step frequency, as well as 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. We quantified this as the step-to-step variability along gait dimensions of step frequency, ankle kinematics, and total ankle extensor muscle activity. We then determined how this exploration changed over multiple days, as well as how the final variability compared to the variability in normal walking, or zero-torque mode for measures that we approximated using the exoskeleton. Finally, we sought to determine if this exploration resulted in systematic changes along these gait dimensions.

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.*

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III. 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. In all gait dimensions that we measured, we observed high variability at the beginning of the multi-day protocol ($p=1.0\times10^{-5}$, Figure 1A; $p=4.9\times10^{-11}$, Figure 1B; $p=7.7\times10^{-6}$, Figure 1C; $p=9.1\times10^{-7}$, Figure 1D).

The nervous system reduces this exploration as it gains experience. Participants reduced their step frequency variability ($p=1.6\times10^{-6}$) and ankle angle variability ($p=0.038$) with time constants of 106.7±98.7 and 163.9±189.3 minutes, respectively (mean±SD). We also observed reduced variability in total Soleus ($p=9.6\times10^{-5}$) and Medial Gastrocnemius activity ($p=9.9\times10^{-5}$). These time constants of variability in gait dimensions are similar to that by which users reduced their metabolic cost [3].

With experience, variability along some gait dimensions converges on baseline variability without exoskeleton assistance, suggesting that exploration was in part purposeful. Participants' variability converged on their average variability in normal walking for step frequency ($p=0.16$) and total Soleus activity ($p=0.10$). However, the variability in total Medial Gastrocnemius activity ($p=1.1\times10^{-4}$) and ankle angle ($p=1.8\times10^{-4}$) remained elevated, suggesting that some learning may still be in process 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 adapt their step frequency ($p=0.43$, Figure 2A) or average ankle angle ($p=0.10$, Figure 2B); however, they did learn to adapt their total Soleus ($p=0.075$, Figure 2C) and Medial Gastrocnemius activity ($p=3.2\times10^{-5}$, Figure 2D). These findings suggest that, to customize each user's training time, we may use exploration as an indicator of when people begin to exploit a strategy that reduces their biological torques and metabolic cost [3].

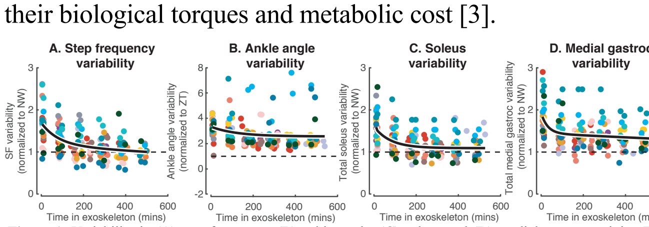

Figure 1: Variability in **(A)** step frequency, **(B)** ankle angle, **(C)** soleus and **(D)** medial gastroc activity. Each colour represents each subject. Solid black lines are fitted double exponentials. Dashed black lines indicate average normalized normal walking (NW) or zero torque (ZT) values.

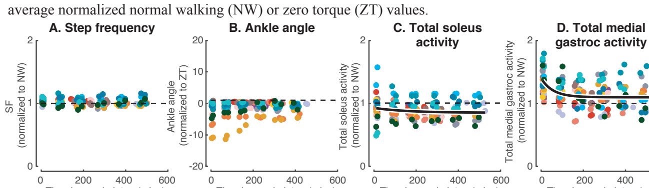

Figure 2: Adaptation in **(A)** step frequency, **(B)** ankle angle, **(C)** soleus and **(D)** medial gastroc activity.