Investigating Energy and Stability Dependent Objectives During Locomotion with Vestibular Disruption

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Summary

When the vestibular system is disrupted, such as in vestibulopathy, individuals often adopt wider step-widths, which may offer greater stability [1, 2]. It remains unclear whether these wider step-widths come at the expense of higher metabolic energy expenditure or if they remain energy optimal. Here, our general aim was to investigate how stability and energy dependent objectives trade-off during locomotion with vestibular disruption. As expected, we found that participants preferred wider step-widths when walking with vestibular disruption. Interestingly, our data suggests that these preferred wider widths may improve stability without incurring a clear energetic penalty—suggesting minimal trade-off exists.

Introduction

The vestibular system plays an important role in locomotor balance and stability. With vestibular disruption, people tend to adopt wider step-widths. It is often assumed that these wider widths are selected to improve stability in the face of this sensory disruption, likely at the expense of increased metabolic energy expenditure. However, to our knowledge this trade-off has not been experimentally tested or quantified. Here, our general aim was to investigate how stability and energy dependent objectives trade-off during locomotion with vestibular disruption (**Figure 1A**). Our primary hypothesis (H1) was that the wider step-widths adopted during vestibular disruption improve stability but result in the selection of an energetically suboptimal gait. An alternative hypothesis (H2) is that the wider widths adopted during vestibular disruption improve stability and remain energy optimal, suggesting both objectives can be satisfied with minimal trade-off.

Methods

Fifteen healthy participants (11F, 4M) walked on a treadmill at 1.0 m/s while instrumented with lower limb reflective markers to capture preferred step-width and step-width standard deviation (SD) using optical motion capture (Opus 300+, Qualisys, Sweden; **Figure 1B).** We then used real-time visual feedback to command 5 step-widths (preferred, narrower: preferred – 3SD and –5SD, and wider: preferred +3SD and +5SD). Participants walked at these widths without (natural) and with electrical vestibular stimulation (EVS), which we applied using binaural stochastic stimulation (0-25Hz; ±5mA; BIOPAC, USA). We measured metabolic energy expenditure at each walking condition using indirect calorimetry (K5, Cosmed, Italy), and fit these data (for both natural and EVS conditions) with a second-order polynomial to solve for energy optimal step-widths. We used paired t-tests to compare participant's preferred and energy optimal step-widths between natural and EVS conditions. Although directly assessing whole-body gait stability is complex, we chose a measure of residual kinematic head variability (Vres, linear and angular) [3], which we captured using a forehead mounted inertial measurement unit (IMU; Delsys, USA). We used a repeated measures ANOVA to compare Vres across step-widths for natural and EVS conditions.

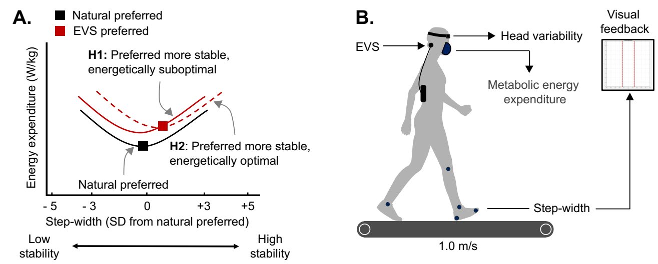

Figure 1: Experimental hypotheses (A) and instrumentation (B).

Results and Discussion

As expected, walking with EVS tended to increase both linear and angular Vres compared to natural walking ($p < 0.001$), suggesting compromised stability. Walking with wider step-widths reduced both linear and angular Vres ($p < 0.001$) compared to narrower steps, suggesting improved stability (**Figure 2A**). When exposed to EVS, participants preferred wider step-widths (0.76SD ± 1.17SD, $p = 0.01$), and displayed an increase in metabolic energy expenditure (8.89% ± 12.52%, $p = 0.02$), compared to natural walking (**Figure 2B**) We did not find a significant change in the energy-optimal step-width (Δ1.27SD ± 4.86SD, $p = 0.33$). However, in 9 of 15 participants the energy optimum shifted wider with EVS.

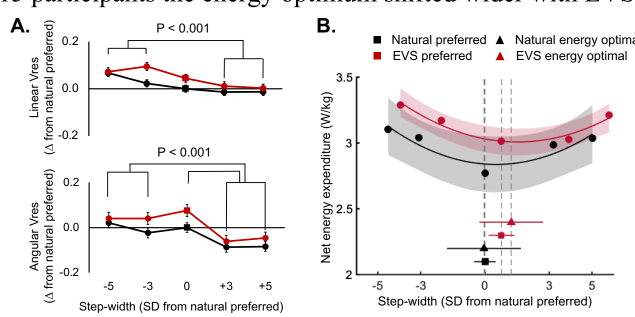

Figure 2: Changes in residual kinematic head variability (A) and preferred and energy optimal step-widths (B) for both natural (black) and EVS (red) conditions.

Conclusions

Our data align more closely with H2, where both preferred and energy optimal step-widths appeared to increase with EVS. This suggests that, contrary to prior assumptions, wider step-widths adopted when stability is challenged may remain energetically optimal.

References

[1] Magnani et al. (2022). *Exp Brain Res.*
[2] Donelan et al. (2001). *Proc. R. Soc. Lond.*
[3] MacNeilage et al. (2017). *Front. Comput. Neurosci.*