Exaggerating Asymmetry to Exploit Assistance from the Treadmill during Split-belt Walking

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Introduction: The study of adaptive locomotor learning often involves use of the split-belt walking paradigm, where individuals adapt to walking on a treadmill with two belts that move at different speeds [1, 2]. During adaptation, people systematically adjust their step lengths, defined as the distance between the feet at heel strike, from one step to the next. Initially, the step length on the slow belt is longer than the step length on the fast belt, but people gradually reduce this difference in step lengths to adopt a more symmetric pattern [2]. Here, we present theoretical and experimental evidence which demonstrates that modifications of step length asymmetry influence whether people work against the treadmill or whether they exploit the treadmill to use it as an assistive device. We further show that the people use the assistance provided by the treadmill to reduce metabolic cost.

Theory: Walking at a constant speed on a treadmill requires that the legs generate braking and propulsive forces that are balanced throughout the gait cycle. Initially, when walking on a split-belt treadmill, individuals take longer steps on the slow belt and short steps on the fast belt (Fig 1A, C). However, people can choose how to distribute the braking and propulsive forces to take advantage of the difference in belt speeds. Specifically, generating more braking forces with the fast leg and more propulsion with the slow leg (Fig. 1B) allows the treadmill to perform net positive work on the person (Fig. 1D). Critically, this is not possible during over-ground walking or on a standard treadmill. The work performed by the treadmill can be used to reduce the positive work required by the leg muscles and ultimately reduce metabolic cost. One way in which people could achieve this task is by stepping further forward with the fast leg relative to the slow leg to generate more braking on the fast belt (Fig. 1B). Using this strategy, which seems to occur in multi-day split-belt adaptation studies [6], it should be possible to increase economy. If these predictions hold, our findings would demonstrate that split-belt treadmills can act as assistive devices, if people adopt appropriate coordination strategies to reduce the positive work performed by the legs.

Methods: We determined whether individuals can modify their step lengths while walking on a split-belt treadmill to gain assistance from the device, reduce positive leg work, and ultimately reduce metabolic cost. To this end, we mapped the relationship between step length asymmetry and mechanical and metabolic energetics in 16 healthy participants while walking on a dual belt instrumented treadmill. The left and right belt speeds were set at 1.5 m/s and 0.5 m/s, respectively, and participants used visual feedback to maintain step length asymmetries (Fig. 2A) of 0.00, +/- 0.05, +/- 0.10 and +/-0.15 in separate, six-minute trials presented in a random order (Fig. 2A-B). Positive asymmetries indicate longer steps on the fast belt, while negative asymmetries indicate longer steps on the slow belt. We computed the mechanical work performed by the legs and the treadmill using an extension of the individual limbs method [3, 4] and we calculated metabolic rate from expired gas analysis using the Brockway equation [5]. Lastly, we used mixed-effect regression models to determine 1) if the positive work performed by the treadmill increased as step length asymmetry became more positive, 2) if people take advantage of the positive work performed by the treadmill to reduce the positive work performed by the legs, and 3) whether reductions in positive work performed by the legs are accompanied by reductions in metabolic cost.

Results and Discussion: Consistent with our predictions, there was a ~28% increase in positive work performed by the belts on the body as asymmetry became more positive (Fig. 3A-C). In addition, participants transitioned from performing net positive work with the legs at negative step length asymmetries to performing net negative work at positive asymmetries (Fig. 3D-F). The changes in mechanical work performed by the legs were primarily driven by reductions in positive work performed by the leg on the fast belt (Fig. 4A). The relationship between work performed by the treadmill on the body and positive work performed by the legs showed that for every three Joules of work performed by the treadmill on the body, there was a one Joule reduction in positive work performed by the legs. People used the assistance provided by the treadmill at positive asymmetries to reduce metabolic cost (Fig. 5) such that participants experienced an 8 to 18% (95%CI) reduction in cost relative to a step length asymmetry of -0.15. The asymmetry that minimized metabolic cost had a 95% confidence interval of 0.06 and 0.38, which is consistent with our prediction that positive asymmetries minimize energetic cost.

Together, these results show that people can exploit assistance provided by the treadmill by modifying step length asymmetry such that the treadmill performs positive work on the body, thereby allowing the legs to perform net negative mechanical work. This can reduce metabolic cost because negative muscle work is performed by eccentric action of muscles, which are less energetically costly than concentric contractions [7]. Therefore, reductions in asymmetry during split-belt walking reveal that individuals take advantage of the work generated by the treadmill instead of resisting the assistance from the treadmill. This can aid explain the observed reductions in energetic cost observed during locomotor adaptation [8, 9].

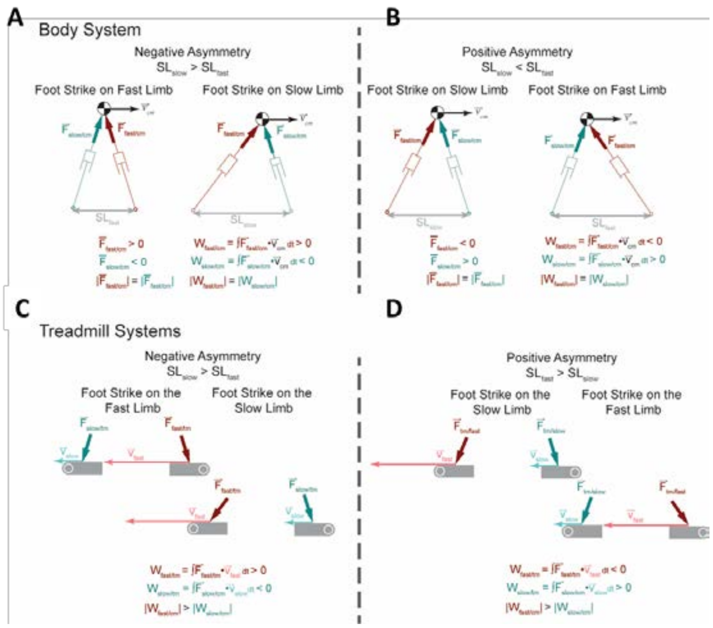

Figure 1. Mechanics of split-belt walking. A) Mechanical work performed by the legs on the center of mass and on the treadmill when the fast step length is longer than the slow step length, i.e. early adaptation, B) when the fast step is longer that the slow step. C-D) Work performed by the treadmill on the legs for the cases presented in A. We predict that long steps on the fast belt and short steps on the slow leg, which is the opposite of the pattern occurring during adaptation, will lead to net negative work performed by the legs as shown in panels B and D.

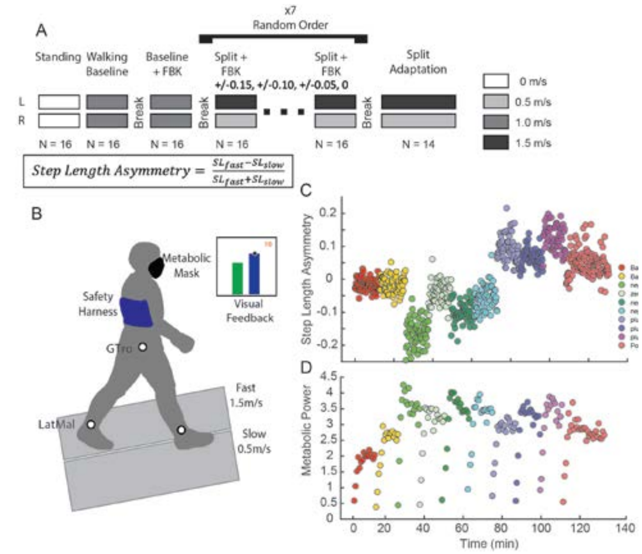

Figure 2. Methods. A) Experimental Protocol. B) Experimental Setup. C-D) Raw step length asymmetry and metabolic data for a single participant.

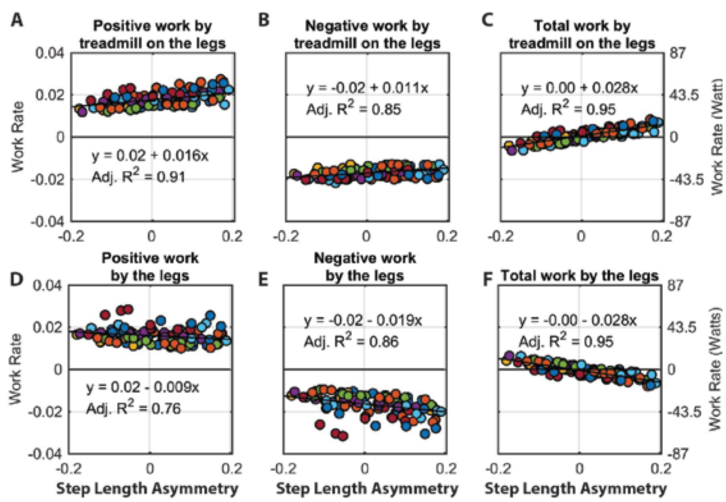

Figure 3: Average rate of work performed by the treadmill and legs across levels of step length asymmetry. A-C) Positive/negative work performed by the legs decreased/increased as step length asymmetry became more positive, leading to net negative work. D-F) The positive work performed by the treadmill on the legs increased. Each color represents a different participant.

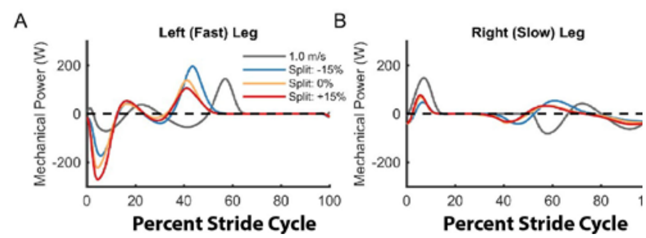

Figure 4. Mechanical power generated by the A) fast leg, B) slow leg throughout the stride cycle for baseline (gray) and step length asymmetries of -0.15 (blue), 0 (yellow) and 0.15 (red). Mechanical work corresponds to the area under the curve of the mechanical power. As asymmetry becomes more positive, for the fast belt, the area under the negative portion of the power curve increases and the area under the positive portion of the power curve decreases. We did not observe any systematic changes in positive work in the slow leg.

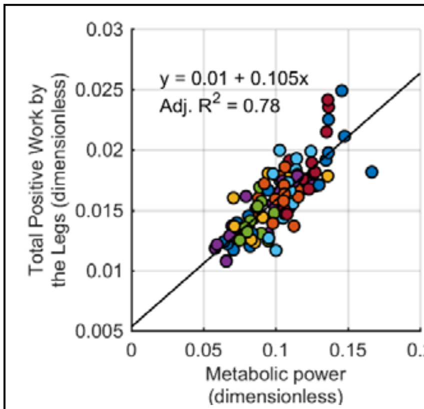

Figure 5. Relationship between positive work by the legs and metabolic power. Reductions in metabolic power were associated with reductions in positive work. Each color represents a different participant.

REFERENCES 1. Dietz, et al., 1994. **2.** Reisman, et al., 2005. **3.** Selgrade, et al., 2017. **4.** Donelan, et al., 2001. **5.** Brockway, 1987. **6.** Leech, et al., 2018. **7.** Herzog, 2018. **8.** Finley, et al., 2013. **9.** Sánchez, et al., 2017.

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