A Split-Belt Rimless Wheel Can Passively Walk Steadily on a Split-Belt Treadmill

Julia K. Butterfield[1], Surabhi N. Simha[2], J. Maxwell Donelan[2], and Steven H. Collins[1]
[1]Department of Mechanical Engineering, Stanford University, Stanford, California, USA
[2]Department of Biomedical Physiology and Kinesiology, Simon Fraser University, Burnaby, British Columbia, Canada
Email: *jbutterf@stanford.edu

Introduction

Split-belt treadmills are commonly used for motor learning experiments [1] and stroke rehabilitation [2], but we are still learning how people adapt to the two belts moving at different speeds. For example, Sánchez et al. [3] recently showed that after sufficient exposure, participants will self-select a gait with wider leg angles and longer steps onto the fast belt, rather than a gait with equal angles and step lengths as had previously been observed. People can extract positive work from a split-belt treadmill [3], and this may be driving split-belt adaptation. But how do choices like leg angles and treadmill belt velocities affect how energy is harvested from the treadmill?

We used a split-belt rimless wheel model to further explore the mechanics and energetics of split-belt walking. A rimless wheel loses energy during its collisions with the ground so must successfully harness energy from the treadmill to walk steadily, an impossible task if the belts are tied. We explored how treadmill conditions and leg angles affect the passive wheel's ability to extract enough energy from the treadmill to walk steadily.

Methods

We simulated a split-belt rimless wheel (Fig. 1A), two identical sets of spokes that are rigidly attached and offset by a small angle. The spokes are arranged such that only one spoke is ever in contact with the ground, and the wheel alternates contacting the fast and slow treadmill belts. The angular offset results in different inter-leg angles at collision onto the fast and slow belts, just as humans adjust their step lengths during split-belt walking to have different leg angles during the fast and slow steps.

We tested combinations of inter-leg angles and belt speed differences to find initial velocities corresponding to steady walking. If a solution existed, we calculated the wheel's average velocity in the slow belt reference frame, which is the slow belt velocity required for the wheel to station-keep.

We designed and built a physical prototype (Fig. 1B) to demonstrate that the simulation model was physically realistic. For the sets of spokes, we used plates with evenly spaced toes. We added stabilizer wheels to the front to prevent leaning and a rudder to prevent turning.

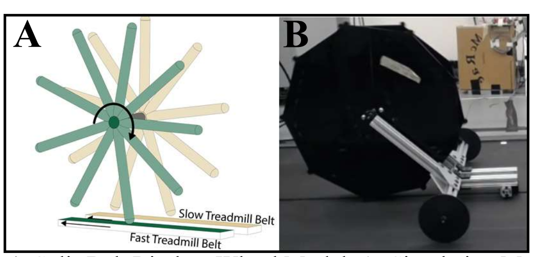

Figure 1: Split-Belt Rimless Wheel Model. **A**: Simulation Model **B**. Physical Prototype

Results and Discussion

We found a wide range of inter-leg angles and belt speed differences for which the split-belt rimless wheel could harness enough energy from the treadmill to walk. During steady walking, energy lost in step-to-step transitions is recovered as energy gained during rotation on the fast belt.

Two asymmetries in the system, the difference in belt speeds and the difference in inter-leg angles at collision, enable energy harvesting during the fast belt rotation. Because of the belt speed difference, the foot has non-zero velocity when viewed from the slow belt reference frame. The contact force on the foot then results in work being done on the wheel. Having a wider inter-leg angle at fast collision ensures the net work done is positive by enabling the wheel to primarily rotate upward during this rotation, with the contact force aligned with the foot's velocity.

A counterintuitive result is that increasing the fast belt's backward velocity increases the wheel's forward velocity in the slow belt reference frame (Fig. 2). With complicated underlying mechanics, the wheel travels further backward while on the fast belt but rotates faster through both steps, thereby achieving a greater forward gain per unit time.

The physical model, with radius 0.25 meters and fast and slow belt collision angles of 31 and 9 degrees, walked steadily for belt speed differences from 0.2 to 1.1 m/s and achieved a maximum speed of 0.2 m/s in the slow belt reference frame.

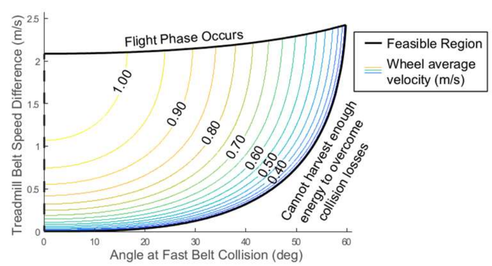

Figure 2. With an infinitesimally small angular offset between the plates such that collision onto the slow belt occurs at nearly vertical, the model can walk steadily with a large range of inter-leg angles and treadmill speed differences. Results look similar as the offset increases as long as the fast collision angle remains significantly wider.

Significance

These results confirm observations from human experiments that extracting positive work from a split-belt treadmill is possible when a wider step is taken onto the fast belt [3]. The belt speed difference, rather than the speeds themselves, is the crucial element contributing to the model's energy-free solutions. Improvements in human split-belt energy economy may be possible, and these results help us understand the limitations of humans' ability to harness energy from a split-belt treadmill.

Acknowledgments

This research is supported by the NSF Graduate Research Fellowship program and NSF Award No. 1734449.

References

1. Malone, et al. (2010) *J. of Neurophys.* **103**:1954-1962.
2. Reisman, et al. (2013) *Neurorehabilitation and Neural Repair* **27**:460-468.
3. Sánchez, et al. (2019) *J. of Physiology* **597**:4053-4068.