Beware of the bump: Optimal strategy to traverse a step height perturbation

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1 Introduction

Humans often negotiate uneven or bumpy terrain such as uneven sidewalks or natural trails, typically using vision to plan compensatory motions. Compensations can enhance stability, but less recognized is their role in planning for economy. A small bump in the road is not necessarily destabilizing, but it will tend to slow a person down. If a fixed average speed is to be maintained, one compensation may simply be to momentarily speed up after the bump. But there may be preparatory compensations that are more economical, involving speed changes before and/or after the bump. We used a simple, rimless wheel model to consider the ideal compensations. We asked what the most economical strategy should be, how far in advance one should pre-compensate, and how far after the bump the compensation should continue. We also conducted a human subject experiment that suggests that humans do pre- and post-compensate for economy.

2 Methods

We modeled the bump as a small, vertical height discrepancy for one step. The walking model was a rimless wheel (figure 1) [1], with pre-emptive push-off to provide power just before each leg's collision which is the sole form of energy dissipation. An optimization was performed to determine the push-off sequence, in terms of positive work per step, to most economically negotiate the bump while maintaining average speed. We also posed an additional compensation constraint in the number of allowable step adjustments before and after the bump, to determine how far ahead one should plan for a bump.

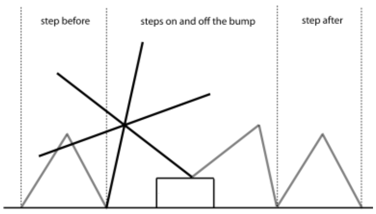

Figure 1: Rimless wheel traversing a single bump. This sample path involves 1 step before and 1 step after, 1 step on and 1 step off the bump. The legs having ground contact are shown.

The optimization was defined as follows. Push-off compensations occurred before and after the bump, which two perturbed one step onto and then one step off of the bump, designated steps $i = 0$ and 1 respectively. We considered four compensation constraints, limiting adjustments to $N = 1$, 2, 6, or 10 additional steps before and after the bump. For example, 1 step before and after, plus the on and off-bump steps, yield a total of four steps that could be adjusted, denoted steps $i = -1$ through 2 (Figure 1). While minimizing overall work, the model was given a nominal initial and final speed, plus an overall trial time to constrain average speed and restore nominal gait. In other words:

$$\text{minimize} \sum_{i=-N}^{N+1} W_i^+$$

$$\text{subject to} \sum_{i=-N}^{N+1} t_i = (2N+2) \cdot t^*$$

$$v_{-N} = v_{N+1} = v^*$$

where $W_i^+ = \frac{1}{2} P_i^2$ is the push-off work preceding step i, with impulsive push-off P_i, t_i the duration of that step, v_i the speed of that step's stance phase evaluated after the heel strike, collision, and t^* and v^* the nominal values.

For human experiments, we used a foam block 0.15 m high as the bump, and asked (a total of four) healthy adult subjects to walk and step on it. To constrain the average speed, subjects walked with a pacer, another person whose step frequency was constrained by metronome to maintain an approximately constant speed. To constrain the adjustment period, a tarp was used as a dividing wall to separate the subject and pacer for a given distance before and after the bump, with the subject's goal being to match their pacer by the end of the tarp (Figure 2), despite the bump. Each trial constrained subjects to the nominal gait at beginning and end, but with freedom to adjust their steps for a set distance. It was not important to match the precise number of steps of the model's adjustments, and so the dividing wall had lengths of 2.4m, 3.6m and 7.2m. We measured the walking speeds with inertial measurement units on both feet for the subject and for the pacer [2].

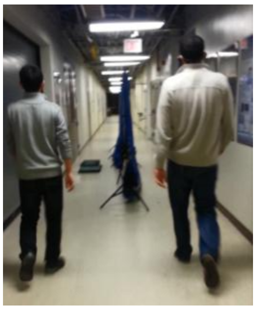

Figure 2: A test subject (left) and their pacer on the right are walking towards a dividing wall (a tarp) 7.2m long. The test subject encounters a bump in the road, but the pacer does not.

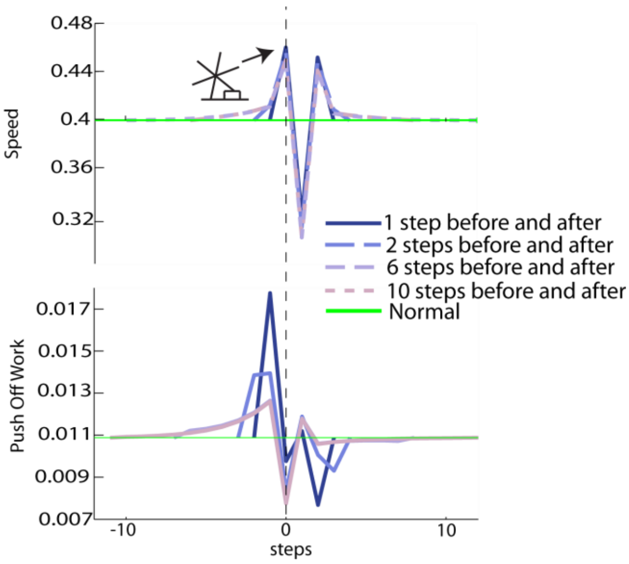

Figure 3: Rimless wheel optimally traversing a bump in the road. Shown are (top) walking speed for each step, and push off work (bottom) for each step. The step numbered zero (vertical dashed line) represents the heel strike onto foam, and speed is defined as the average speed for the preceding stance phase. The curves show optimal trajectories allowing 1 step, 2, 6 steps and 10 steps before and after the bump.

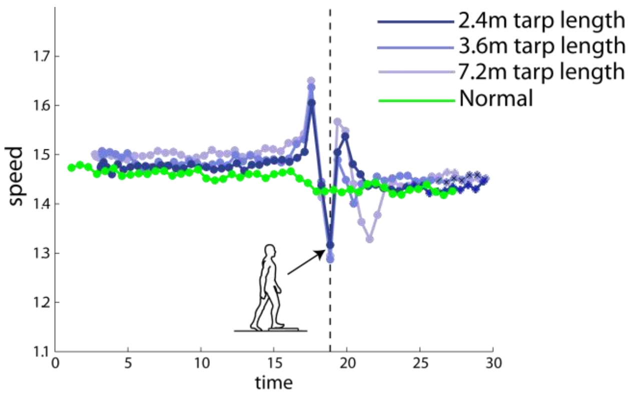

Figure 4: Average walking speeds of the test subjects for 2.4m, 3.6m and 7.2m adjustment distances (tarp lengths). The vertical dashed line represents the heel strike onto the foam.

4 Results and Discussion

Model simulations show that the most economical strategy is to speed up just before the bump, experience a slower step going over the bump back onto level ground, and then speed up again briefly before returning to nominal speed (Figure 3). The optimum sequence is nearly symmetric about the bump, and the brief speed-ups are limited to one (and to lesser degree two) steps before and after. The optimization discovered that pushing off harder yields a lower collision, but a high sustained speed is costly due to repeated collisions. It is therefore economical to speed up only briefly, and to do so only for the steps surrounding the bump. The dynamics of the rimless wheel are symmetric in time, contributing to nearly-symmetric adjustments about the bump. For any surrounding steps beyond one or two, there were smaller adjustments to reach the desired state in time. This model does not have ability to adjust step length, and so step time changed accordingly with step speed.

With fewer adjustment steps to overcome the bump, the model must concentrate the push-off increases, with a greater speed change before the foam. But the effect is small, meaning that the optimal trajectories are quite similar for any number of steps preceding the bump. Nevertheless, there is a small, but non-zero advantage to be gained by having any number of additional steps to adjust.

Human subjects showed a similar pattern of adjustments (Figure 4). They first sped up just before the bump, slowed down going over it, and then sped up again to meet their pacer. With more room to adjust, subjects barely altered their steps. There was also more variability in speed due to the lack of visual feedback of the pacer's speed.

There are a number of limitations to this study. The rimless wheel model is extremely simple, and does not predict how a swing leg could be modulated to adjust step length. Humans may adjust other parameters as well which cannot be predicted with our simple model. Additional data would be necessary to characterize more detail about how humans compensate. A more complex model might explain how those compensations. Nevertheless, an extremely simple model of collisions appears to predict the basic features of the adjustments humans make to economically traverse a bump in the road.

References

[1] McGeer, T., 1990, ''Passive Dynamic Walking,'' Int. J. Robot. Res., 9, pp. 68–82.

[2] John R. Rebula, et al., ''Measurement of Foot Placement and its Variability with Inertial Sensors'', Gait & Posture, Volume 38, Issue 4, September 2013, Pages 974–980.