A model-based analysis of the mechanics and energetics of walking on uneven terrain

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1 Introduction

Walking on natural, complex terrain is energetically more demanding than walking on flat, smooth surfaces. Many surface characteristics, such as compliance, damping, incline angle, friction or terrain unevenness can affect gait biomechanics and energetics. Past research has shown that surface unevenness, in particular, leads to increased energy expenditure as a result of larger positive work done at the knee and hip joints [1]. To help understand the underlying mechanisms for these mechanical and energetic changes, we examined two simple models (the rimless wheel [2] and the simplest walker [3, 4]) during walking over surfaces of varying terrain unevenness. We also looked at several types of gaits and energy input methods for both models. Comparison of model results to empirical data showed that experimental results were most with agreement with models that relied on energetically expensive hip work but still showed adaptations to the terrain by adjusting the amount of work done through push-off. We believe these findings provide a better understanding of the adaptations used by humans in natural environments. In addition, this research could potentially be useful in the design and control of bipedal robots and assistive devices.

2 Methods

Both models walked on an approximated uneven terrain surface that consisted of repeating up and down steps of equal drop height d. As a result, it was possible to find steady-state gaits on this uneven surface and we performed simulations over just two steps (one up- and one down- step). Although model forward velocity and step length could vary between steps, we constrained both models to walk analogously to human gait at an average speed of 1.0 m/s and with an average step length of 0.662 m [1]. The models had a specific initial step velocity for the up- and down- steps, termed v^{1+} and v^{2+}, respectively. By affixing v^{1+}, we could uniquely determine v^{2+}, given the desired average velocity and a drop height d. This allowed us to isolate three different *gait strategies*: gaits where v^{1+} and v^{2+} are equal, a combination of v^{1+} and v^{2+} that produce equal apex velocities for both steps, and a combination of v^{1+} and v^{2+} that produce steps of equal time durations. We presumed that humans could potentially want to utilize such gait strategies in response to uneven terrain and were interested in the difference in energy consumption of each gait type. However, past research has shown that methods through which energy is added to the system also significantly affect net energetic cost [5]. Energy transfer is most energetically efficient when positive work is done through push-off, immediately prior to heel-contact of the leading leg. However, walking on uneven terrain is likely to interrupt these timings in real-world environments, requiring for more energetically expensive work to be done at the hip. To determine how energy input timing affects net energetic cost of model locomotion, we allowed for energy to be added to the system using three different *energy input strategies*: only through impulsive push-off, only through impulsive hip work, and using a constant impulsive push-off with the remaining energy coming from the hip.

3 Results and Conclusions

For the rimless wheel, the relationship between v^{1+} and v^{2+} for any given drop height d follows a curved line segment. In contrast, the v^{1+} and v^{2+} relationships for the simplest walker are elliptical [Fig. 1A]. As a result, possible simplest walker gaits falls closely within the rimless wheel gait strategy that produces equal step durations. The rimless wheel gait strategy with equal initial step velocities v^{1+} and v^{2+} was the most energetically efficient for all energy input strategies. The gait strategy with equal step durations was the most energetically expensive. For both models, the energy input strategy that primarily relied on push-off work was the most economical. However, it is interesting to note that this strategy could only produce a selected range of v^{1+} and v^{2+} combinations for the rimless wheel before requiring additional energy to be added by the hip. Comparing model results to experimental data showed that human cost of transport on uneven terrain clearly lay above the most energetically efficient gait and energy input strategies of the models. However, it was also significantly below the most energetically expensive strategies. In fact, human cost of transport on uneven terrain lay approximately between rimless wheel gaits with equal time durations a using only a push-off impulse as energy input and gaits with equal apex velocities using a fixed push-off impulse with supplementary hip work. From this, we can infer that humans can slightly modify their push-off in response to uneven terrain but mostly rely on additional work done at the hip.

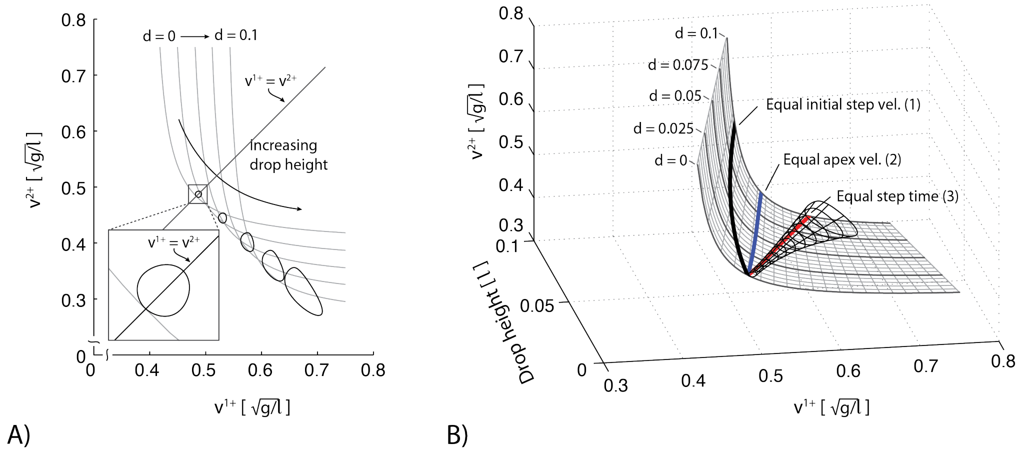

Figure 1: A selected range of initial velocities v^{1+} and v^{2+} for the rimless wheel and simplest walker models. A. Relationship between v^{1+} and v^{2+} with changes in drop height d for the rimless wheel (grey lines) and the simplest walker (black elliptical lines) B. Three-dimensional view of the v^{1+} and v^{2+} relationship for the rimless wheel (grey surface) and the simplest walker (black tube). Various gait strategies of the rimless wheel plotted with solid lines.

In summary, we characterized the effects of several different model gaits and energy input strategies on overall model energy consumption. Whereas our models relied on simple impulses as energy input, future studies could focus on using more sophisticated control to reduce energetic cost. It would also be useful to evaluate the trade-off between gait stability and energetics. Still, we believe the models presented here provide a better understanding of the mechanisms humans may adapt in response to walking on uneven surfaces. As a result, we believe these findings could potentially be useful in improving clinical rehabilitation approaches as well is in the design and control of robotic devices.

References

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