Dynamic optimization clearly shows the determinants of bipedal gaits: reduced gravity predictions and verification

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In spite of the strong connection of legged locomotion to our daily life the governing principles determining effective legged locomotion are not well understood. Different hypothesis address different factors as the main determinant of legged locomotion, chief among them are energy recovery, momentum loss and cost of work, etc. Experimental robots and computer-based models can improve our knowledge of legged locomotion by serving as a means to evaluate theories of how humans and animals move. Although organisms are generally multi-purpose and highly complex systems, investigating locomotion using simple models can provide insight into the factors influencing their fundamental behavior. To this end we devise a simple planar rigid-joint biped model that has no elastic components. It consists of an upper body, two telescoping straight legs, and horizontal feet (Fig. 1). Some simpler versions of this model have shown good success in explaining some aspects of human and animal locomotion. The effectiveness of the model can be verified by comparing its predictions of changes in locomotion adaptation under novel conditions, for example different gravity levels, with experimental observations.

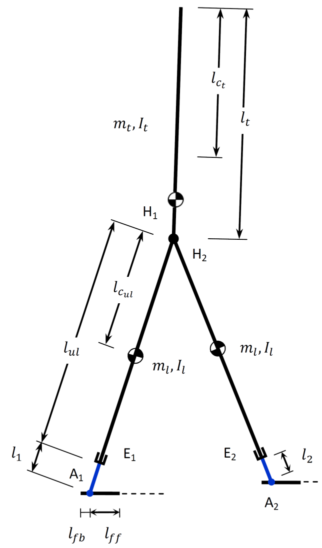

Figure 1: Biped Model

Farley and McMahon [1] have shown that the rate of metabolic energy consumption in running decreases with decreasing gravity more dramatically than in walking. They hypothesized that the difference in dependency of walking and running energetics to gravity is due to the different energy-saving mechanisms associated with each of these gaits. We have previously shown that the optimal gaits of the model of Fig. 1 exhibit the same energetic characteristics [2]. The lack of elastic elements in this model directly challenges the hypothesis that recovery is the origin of different gait characteristics. In fact, the results are better explained by momentum loss minimization at support transfer and cost of swinging the leg.

The energy optimal gaits of the biped model in Fig. 1 also predict the most effective kinematics of walking and running in reduced gravity conditions. At any given forward speed the step length and step period of the optimal gaits increase with reduced gravity. This increase is more dramatic in running than in walking due to the almost-free-of-cost flight phase in running. In walking the frequency of ballistic motions of the swing leg and inverted-pendulum like motions of the stance leg decrease with decreasing gravity, and the balance between the collision loss and the swinging cost occur at slightly longer step lengths. To verify this prediction we monitor spontaneous gait of human subjects in simulated reduced gravity. The simulation harness is based on the zero-length spring, a mechanism developed for long period seismometers [3]. The design applies a constant upward force over a reasonable range of vertical center or mass oscillations during locomotion. The timing of steps is accurately collected by electronic sensors, and are verified by measurements extracted from high-speed video recordings. The results show strong agreement with the model predictions.

The agreement between the optimization and experimental results without implicitly relying on energy recovery suggest that the cost of support transfer and leg swing cost combined with the geometry of each gait are the main factors influencing these gaits, and therefore the balance between these costs is the main determinant of legged locomotion. Minimization of the total cost of locomotion results in a bang-coast-bang type control in which quasi-passive phases of motion connect phases of concentrated work. In walking, due to the geometry of the gait which requires at least one leg to be in contact with the ground, the quasi-passive phases naturally resemble the motion of an inverted pendulum which inherently involves exchange between potential and kinetic energy, and thus implies recovery as a natural outcome. The cost per step is determined by the swing cost and the collision loss that occurs at unavoidable support transfers, both are correlated with the step geometry. Collision losses can be avoided by doing more work with the swing leg, but the total cost will be higher. Increasing the progression speed in walking requires increasing the step length, step frequency, or both; all result to an increase in the locomotion cost. At some speed it becomes more economical to do more work to lift the entire body from the ground, but instead benefit from a longer step at a lower collision cost. This reduction in collision cost is made possible by ability to land on an almost vertical leg which is possible only through a non-contact flight phase. Landing requires contracting of the leg to actively absorb the impact energy. To compensate for the lost vertical momentum during impact an accelerating phase with extending stance leg is required before the next take-off. The optimality of concentrating the intervals involving active work implies that the extension phase immediately follows the contraction phase, resembling the bouncing motion of a spring. In this case the built-in passive compliance can further reduce the cost by elastic energy storage-recovery.

The same factors influence the optimization of locomotion under reduced gravity conditions. In running the quasi-passive flight phase is not directly constrained by the geometry of the legs and steps, so the flight time and consequently the step length can increase in reverse proportion to g without affecting the collision loss and swing cost (due to the almost vertical landing leg). Therefore the cost of transport (COT) in running shrinks linearly with g. Decreasing the gravity increases the swing cost which can be compensated by increasing the swing angle. However, in walking step length is completely correlated with the step geometry, and has a theoretical upper bound of twice a leg length. Even prior to this limit increasing step length directly increases the collision loss, so in walking the increment of step length and decrement of COT cannot take place in low gravity levels as much as in running.

Although our rigid model has been successful in explaining some aspects of human locomotion and predicting the energetics and kinematics of walking and running, this doesn't imply that elastic energy storage and recovery is not important. As it is stated above, it is the automatic consequence of energy optimality, and is a good strategy for further decrease the cost of locomotion. The question remains regarding which aspects of human locomotion mainly rely on passive compliance and elastic energy return. Also, our optimization-based predictions of kinematics of walking under reduced gravity conditions and their experimental verification are in contradiction with a previous study [4] which has rejected the dynamic similarity hypothesis based on kinematics of human walking in simulated reduced gravity. Our results raise questions regarding those conclusions as well, and suggest further studies on the role of dynamic similarity in locomotion.

Keywords: dynamic optimization, reduced gravity, energetics and kinematics

Preffered Format: Poster

Note: The first author is a PhD student, and would like to apply for a travel grant.

References

[1] C.T. Farley, and T.A. McMahon, "Energetics of walking and running: insights from simulated reduced-gravity experiments," *J. Appl. Physiol.*, 73(6): 2709-2712, 1992.

[2] S.J. Hasaneini and C.J.B. Macnab and J.E.A Bertram and H. Leung, "Gravity effects on energetics and kinematics of walking and running using dynamic optimization," in *Proc. of Dynamic Walking Conference 2011*, pp. 101-102, July 2011.

[3] L.J.B. LaCoste, "A new type long period vertical seismograph," *J of Applied Physics*, vol. 5, pp. 178-180, July 1934.

[4] J. Donelan and R. Kram, "The effect of reduced gravity on the kinematics of human walking: a test of the dynamic similarity hypothesis for locomotion," *J Exp Biol*, vol. 200, pp. 3193-3201, December 1997.