

MECHANICAL AND METABOLIC COST AS A FUNCTION OF STEP LENGTH IN HUMAN WALKING

J. Maxwell Donelan¹, Rodger Kram², and Arthur D. Kuo³

¹Dept. of Integrative Biology, University of California, Berkeley;

²Dept. of Kinesiology and Applied Physiology, University of Colorado, Boulder;

³Dept. of Mechanical Engineering & Applied Mechanics, University of Michigan, Ann Arbor

Email: mdonelan@uclink4.berkeley.edu Web: http://socrates.berkeley.edu/~hbbiomxl/mdonelan/

INTRODUCTION

In the inverted pendulum model of walking, the center of mass moves along an arc dictated by the stance limb (Cavagna et al., 1977). While the single support phase can be nearly conservative (Mochon & McMahon, 1980), the transition from one stance limb to the next requires mechanical work to redirect the center of mass velocity from one pendular arc to the next (*stance limb transition cost*).

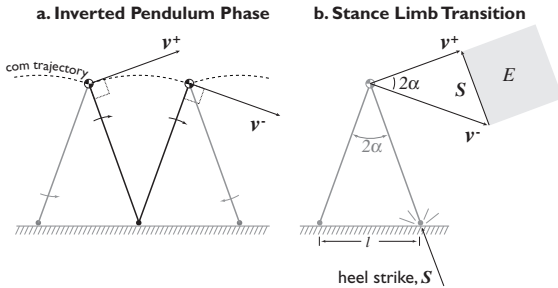


Figure 1. A simple model of bipedal walking consisting of a point mass, supported by two massless rigid legs. (a.) The direction of the center of mass velocity is perpendicular to the stance limb during inverted pendulum-like phases. (b.) Each transition to a new stance limb requires redirection of the center of mass velocity, from \mathbf{v}^- to \mathbf{v}^+ , accomplished by an impulsive heel strike ground reaction force, \mathbf{S} , acting along the leading limb. \mathbf{S} also causes an instantaneous reduction in the magnitude of the center of mass velocity requiring negative work by the leading limb; $|\mathbf{v}^+| < |\mathbf{v}^-|$ with $E \propto |\mathbf{S}|^2$ (shaded area). The magnitude of E depends on the angle between the legs, 2α , and the walking velocity, v . α is a nearly linear function of step length, l , and v is the product of l and step frequency, f .

Stance limb transition costs depend strongly on step length as illustrated by analysis of a simple bipedal model (Figure 1; Kuo, 2001). At each stance limb transition, the leading leg performs negative work to redirect the center of mass velocity. To maintain a steady walking speed, positive work is needed to replace the energy lost. The model predicts a stance limb transition cost de-

pendent upon on step length, l , and step frequency, f :

$$E \propto f^2 l^3, \quad (1)$$

where E is normalized for body weight and distance traveled to yield a dimensionless mechanical cost of transport.

We explored this theoretical stance limb transition cost by measuring the mechanical and metabolic costs of walking faster by increasing only step length while keeping step frequency fixed (*length modulation*). Based on our model's predictions (Eq. 1), and assuming constant muscular efficiency, we hypothesized that both mechanical and metabolic costs of transport will increase with the third power of step length:

$$E = Cl^3 + D, \quad (2)$$

where C and D are empirical parameters to be identified from data.

METHODS

Ten healthy subjects (5 male, 5 female; mass 68.9 ± 12.2 kg; leg length 0.93 ± 0.05 m; mean \pm S.D.) provided informed consent.

We used the external mechanical work performed by the individual limbs to estimate mechanical costs. We measured the individual limb ground reaction forces as subjects walked across two ground-mounted force platforms. The external mechanical power generated by each limb is the dot product of that limb's ground reaction force with the center of mass velocity. Center of mass velocity is calculated from the time integral of the center of mass acceleration, subject to appropriate boundary conditions. Center of mass acceleration is calculated from the resultant ground reaction force. The positive work performed by each limb is the time integral of the individual limb external mechanical power restricted to the domain over which power is positive. Total positive external mechanical work is the sum of the

positive external mechanical work generated by each limb (Donelan et al., 2001). We determined the dimensionless mechanical cost of transport, by dividing the work per step by body weight and step length. We averaged mechanical costs over three complete steps for each subject for each trial. Subjects walked at 6 speeds (0.75-2.0 m/s). At each speed, we enforced step frequency to be the frequency each subject preferred at 1.25m/s.

To estimate metabolic cost, we measured metabolic rates of subjects as they walked on a treadmill. We averaged steady-state O₂ and CO₂ flow rates from minutes 3-6 of the 7 minute trials. We calculated metabolic power (W) for each trial using standard metabolic equations (Brockway, 1997). We subtracted the metabolic power for standing from all walking values and then normalized these net values for body weight and walking velocity to yield a dimensionless metabolic cost of transport. Subjects walked at 4 speeds (1.25-1.90 m/s) using the same fixed step frequency as in the mechanics trials.

RESULTS AND DISCUSSION

In support of our hypotheses, mechanical and metabolic cost of transport increased with the third power of step length (Figure 2). Nonlinear regression yielded the coefficients $C_{\text{mech}} = 0.012l^{-3} \pm 0.001$ (95% confidence interval) and $D_{\text{mech}} = 0.033 \pm 0.004$ for the mechanical cost. For metabolic cost the coefficients were $C_{\text{met}} = 0.060l^{-3} \pm 0.007$ and $D_{\text{met}} = 0.120 \pm 0.028$. Metabolic cost increased in direct proportion to stance limb transition cost as a result of their same cubic dependence on step length.

Our length modulation results suggest that stance limb transition costs are an important biomechanical determinant of the metabolic cost of walking. But if this were the only cost to walking, then taking very short steps very quickly would minimize metabolic cost. Humans increase their step length and step frequency in almost equal proportion as they walk faster suggesting a substantial cost

to swinging the limbs. In normal walking, there is likely a tradeoff between stance limb transition costs and the cost of swinging the limbs (Kuo, 2001).

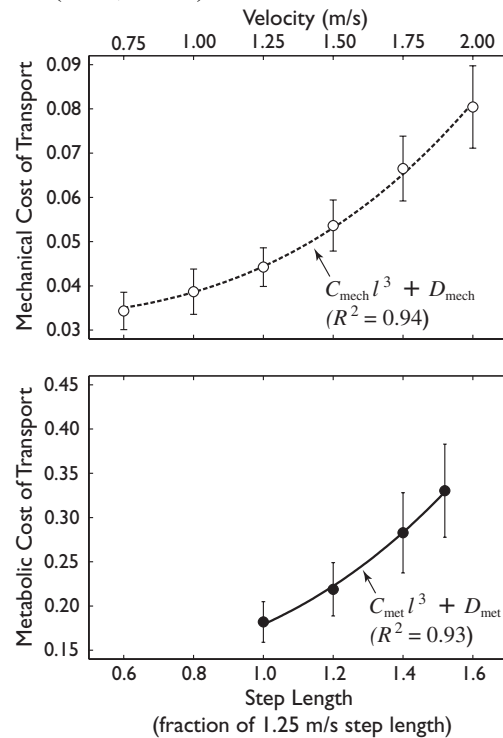


Figure 2. Mechanical and metabolic dimensionless cost of transport required for length modulated walking. Error bars are S.D.

SUMMARY

Theoretically, stance limb transitions require mechanical work, and thus metabolic energy, to redirect the center of mass velocity. These costs increase with step length. We explored stance limb transition costs by measuring the mechanical and metabolic costs of step length modulated walking. Our results suggest that stance limb transitions costs are an important biomechanical determinant of the metabolic cost of walking.

REFERENCES

- Brockway, JM (1987) *Hum. Nutri. Clin. Nutri.* **41C**, 463.
- Cavagna et al (1977) *Am. J. Physiol.*, **233**, R243.
- Donelan et al (2001) *J. Biomech.* conditionally accepted.
- Kuo, AD (2001) *J. Biomech. Engin.*, in press.
- Mochoch, S and TA McMahan (1980) *J. Biomech* **13**, 49.

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