# Metabolic Cost of Walking Varies with Foot Roll-Over Radius

[1]Peter Gabriel Adamczyk, Kaitlin A. Schneider, Arthur D. Kuo
Department of Mechanical Engineering
University of Michigan, Ann Arbor, MI USA
[1]email: padamczy@umich.edu

## INTRODUCTION

Humans perform simultaneous positive and negative work during the double support phase of walking [1]. In order to redirect the body center of mass (COM) velocity between steps, the leading leg performs negative work on the COM as the trailing leg pushes off with positive work. A simple passive dynamics-based model of walking predicts that the mechanical work required at push-off should decrease quadratically as the effective roll-over radius of the feet increases [2]. Because mechanical work requires metabolic energy, we hypothesize that a similar trend should appear in metabolic rate with variation in roll-over radius. We artificially varied the effective shape of subjects' feet by attaching cylindrical arc-soled boots to the lower leg. We measured metabolic rate while subjects walked on arcs of several sizes. We found that metabolic rate decreased substantially with higher radius of curvature, suggesting that simultaneous positive and negative work during double support is a major contributor to the total metabolic cost of walking.

## METHODS

We measured metabolic energy consumption as human subjects walked on different-sized wooden arcs. The experimental setup consisted of a speed-controlled treadmill, a breath gas analyzer, and seven pair of wooden arc shapes used to give the subject a specific foot roll-over radius (arcs' radii of curvature were 2, 5, 10, 15, 22.5, 30, and 40 centimeters). These arcs were attached to the legs of the subject through a pair of Aircast PneumaticWalker boots modified to allow the interchange of foot shapes (Figure 1a). The boots immobilized the ankle, causing the subject's leg to function much like that of the passive walking model. When standing upright, the contact point of the arcs with the ground was about 7.6 cm in front of the tibia, near the metatarsal head.

Ten healthy young adults (five male, five female) were recruited to perform this study. Each subject's rate of oxygen consumption was measured during treadmill walking at 1.3 meters per second using each of the wooden arcs in random order. Step frequency was held constant across all trials in order to eliminate possible energetic variation due to swinging of the legs; frequency was set to the subject's preference when walking on the largest (40 cm) arcs. Average metabolic rate was estimated in Watts, and then non-dimensionalized using the subject's mass ($m$) and leg length ($L$) and the gravitational acceleration ($g$). Collision losses experienced by passive walking models decrease with increasing radius of curvature [3], because roll-over arcs greatly affect the change in COM velocity during double support. The theoretical relationship between mechanical work ($W_{\mathrm{mech}}$) per step and radius of curvature $R$ is given by [1, 3]

$$W_{\mathrm{mech}}/\mathrm{step} = \alpha^2\left(1-\left(R/L\right)\right)^2, \qquad (1)$$

where $\alpha$ is the half-angle between the model's legs at heel strike. We hypothesized that this mechanical work would exact a proportional metabolic cost [1]. At constant step frequency, the relationship between mechanical work per step and the hypothesized metabolic rate $P_{\mathrm{met}}$ has an unknown constant of proportionality [2]. Allowing for different offsets above basal metabolism, data were therefore fit to the curve

$$P_{\mathrm{met}} = C*\left(1-\left(R/L\right)\right)^2 + D. \qquad (2)$$

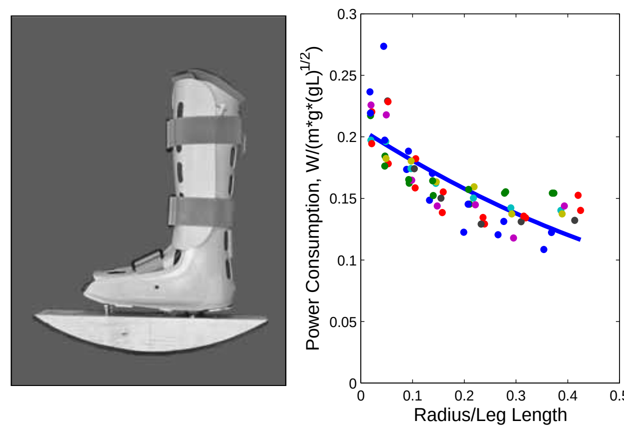


**Figure 1:** (a) One of the experimental boots, with 40 cm radius attachment. Metabolic rate decreased substantially with increasing radius of curvature. (b) Metabolic power vs. radius of curvature, with theoretical curve fit (Eq. 2).

## RESULTS AND DISCUSSION

Average net metabolic power expenditure decreased significantly with radius of curvature (Fig. 1b). Net metabolic rate was highest at the smallest radius of curvature. Expenditures using the smallest arcs averaged 218% greater than normal walking (511 vs. 203 W above resting); expenditures using the 30 cm arcs averaged only 46% greater (296 W above resting).

The results indicate that metabolic rate roughly followed the trend predicted theoretically. Fig. 1b also shows the best fit of these data to the theoretical curve of Eq. 2: $C$ = .134, $D$ = 0.072, $R^2$ = 0.79. There are several reasons why the results do not agree entirely with the theoretical curve. Visually, it appears that the best quadratic fit to the data is not the theoretical curve, but rather one centered around $R/L$ = 0.3. This early upturn suggests that phenomena not included in the simple model may cause humans to expend more energy when the radius of curvature causes the effective foot length to be greater than normal. An explanation noted by McGeer [3] is that in the models, bipeds with mass distributed near the feet have lower efficiency than those with mass closer to the hip (as used to derive Eq. 1). Early simulation results suggest that anthropomorphic mass distribution may explain the optimum roll-over radius observed here.

## REFERENCES

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3. McGeer T. *Int. Journal of Robotics Research* **9(2)**, 62-82.

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