Swing limb moment explains high cost of circumduction

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Introduction: Humans prefer to walk with step lengths and widths that coincide with minimum metabolic cost. The cost of walking with a wider than preferred step width is explained by the mechanical work performed to redirect the body center of mass (COM) [1]. However, this model fails to predict why narrower steps are also metabolically costly. A possible cost is from swing limb circumduction—movement of the swing leg laterally—to avoid the stance leg. To date, the link between energetics and the biomechanics of circumduction have not been established. We therefore seek to test how circumduction could explain the high cost of narrow steps.

The metabolic cost of walking increases approximately quadratically with amount of swing limb circumduction [2]. Leg, arm and torso motion and, to a lesser degree, stance leg moment in the vertical plane, also all increase. This indicates that circumduction may be costly, perhaps because the swing limb must be accelerated on a curved path, requiring a moment about the vertical axis, and a counter-moment on the rest of the body.

Here we investigate the contributions of COM work, lower limb joint work, and rate of change of angular momentum to the increased cost that results from circumduction. Circumduction requires muscular effort to move the leg and a counter-moment acting on the body. The aggregate effect may be summarized by the rate of change in leg angular momentum about the COM and in the vertical direction, equivalent to a moment acting on the entire swing limb. If circumduction is costly, it is potentially not reflected in common gait measures, such as lower limb work or COM measures. We therefore tested whether work and counter-rotation measures can explain cost of circumduction.

Methods: Metabolic energy expenditure along with gait kinematics and kinetics were measured during treadmill walking from seven healthy subjects. To create controlled circumduction, subjects walked at a constrained step width with foam fin obstacles mounted to each shank, directed medially, so that circumduction was necessary to avoid mid-swing contact between fins. Foam fin lengths ranged from 0 to 0.127 m (termed 0, 2, 3, 4, and 5 in). During each condition, subjects walked for approximately 6 minutes at a constant speed of 1.25 m/s.

Results: The increased circumduction created by the constraints resulted in large changes to the vertical angular momentum rate of the leg about the body COM (Figure 1). Circumduction seemed to affect peak rate about the vertical axis the most and in the sagittal plane the least. The small rate change observed in the sagittal plane suggests natural forward and aft swing dynamics were relatively unaffected. In the lateral plane, peak rate increased at 2.84 N·m per 0.1 m of circumduction. Peak vertical-axis angular momentum rate increased proportionally at 4.13 N·m per 0.1 m of circumduction, leading to an increase of 56.6% from 0 in to 5 in fin condition.

In contrast, measures of COM and lower limb joint work do not appear to explain the observed increase in metabolic cost. Positive and negative COM work were only slightly affected by circumduction, with very small increases in collision work for example. Nor did circumduction substantially affect joint work, with slightly more positive knee and negative hip work. These small magnitude changes indicate that the cost of circumduction may not be explained well by more traditional gait measures.

Discussion: Circumduction during walking is an energetically costly task, and compensatory motion in response to increased vertical angular momentum rate appears to be a main contributor to this cost. A vertical moment to move the legs requires a reaction on the body. This reaction can be transmitted to the ground through the stance leg, perhaps with muscular effort needed to sustain that moment within the leg. In addition, some of the reaction can also produce twisting counter-rotation of the upper body. The induced motion of the swing leg, the counter-rotations of the body, and transmission of reaction moment to the ground may all require active muscle effort. These effects, more so than conventional measures gained from inverse dynamics, appear to explain the high energetic cost of swing limb circumduction.

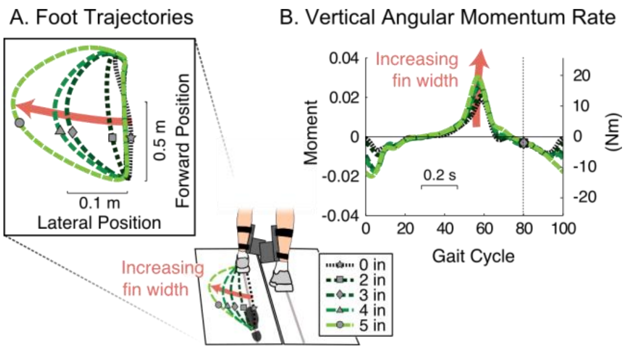

Figure 1: Mean foot trajectories (A) and vertical angular momentum rates of swing leg about COM (B) from 5 fin conditions (N=7).

References: [1] J.M. Donelan et al. *P.R.S.L.B.*, 268:1985-1992, Oct 2001. [2] K.A. Shorter et al. D.W. 2013.