

Center of Mass Velocity Redirection Predicts COM Work in Walking

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INTRODUCTION

Humans perform simultaneous positive and negative work on the body's center of mass (COM) to redirect its velocity between single support phases, in *step-to-step transitions* (Donelan, 2002b). This work predicts a major component of the metabolic energy expended during walking (Donelan, 2002a). A simple mathematical model of dynamic walking predicts the amount of work from the COM velocity change, which in turn is predicted from step length and walking speed (Kuo, 2002). The model assumes that the step-to-step transition occurs impulsively, so it may not apply well to actual human walking, in which the transition is distributed over time, roughly coincident with double support. We tested model predictions of changes in the COM velocity's magnitude and direction, as well as the hypothesized link between velocity change and work performed on the COM, over a wide range of step lengths and speeds. We find that COM velocity change and the associated work performed on the COM by the legs are predicted well by a remarkably simple model.

METHODS

The simple dynamic walking model comprised a point mass for the COM (Fig. 1), supported by two light and rigid legs with point mass feet (Kuo, 2002). During each single support phase, the COM moves in an arc prescribed by the stance leg. Between these phases, the legs must perform work on the COM to redirect its velocity,

and the change in velocity increases with both step length s and speed v . The COM velocity is predicted to undergo an angular change δ governed by the angle between the legs and therefore roughly proportional to step length, $\delta \propto s$. The amount of work performed on the COM, W , is predicted to be proportional to the square of velocity and the square of angular change, $W \propto (v^-)^2 \delta^2$.

Human walking can differ substantially from the model. Because the legs are not rigid, COM velocity need not be perpendicular to the leg as in the model, and the angular change δ need not be proportional to step length. The model's prediction for work assumes impulsive push-off and collision in sequence. In humans, these events take place and even overlap in time. The model's predictions will not hold if these assumptions are too inaccurate, and especially if humans alter how they perform the step-to-step transition at different speeds and step lengths.

We analyzed data previously collected (Donelan, 2002a) on subjects walking overground under four different types of gait variations, with a total of 24 different conditions. Ten healthy young adults walked at six different average speeds \bar{v} , 0.75 to 2.0 $\text{m} \cdot \text{s}^{-1}$. The four variations applied these speeds to (A) normal walking at self-selected step length s and step frequency f ; (B) walking with increasing s but at a single fixed f (the same as preferred at 1.25 $\text{m} \cdot \text{s}^{-1}$); (C) walking with increasing f but at a fixed s (the one preferred at 1.25 $\text{m} \cdot \text{s}^{-1}$),

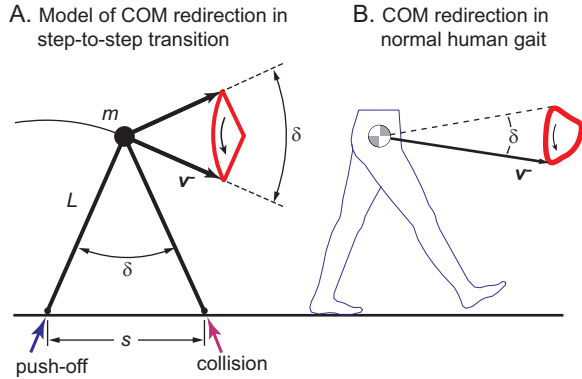


Figure 1: A) Simple model of the step-to-step transition. An impulsive push-off followed by an impulsive collision sequentially redirect the COM velocity through the angle δ . The COM velocity is perpendicular to the legs. B) These assumptions need not apply to humans, where push-off and collision occur over a longer duration and COM velocity is not always perpendicular to the legs. The work of step-to-step transitions can therefore be different between model and humans. The changes in the COM velocity are shown as a path, also known as a hodograph, running counter-clockwise. Vector \mathbf{v}^- marks the velocity just before the step-to-step transition.

and finally (D) walking at a constant $1.25 \text{ m} \cdot \text{s}^{-1}$, with nine different step lengths and frequencies.

We measured ground reaction forces to calculate COM velocity and the rate of COM work performed by each leg. The step-to-step transition was defined as the period between the largest differences in angle of COM velocity. We performed linear regression to test the trends predicted by the model.

RESULTS AND DISCUSSION

Angular redirection of the COM velocity was predicted by step length s (Fig. 2), $\delta \approx 0.30s + 0.09$, $r^2 = 0.66$. Negative step-to-step transition work was also predicted by $W^- \approx 0.80(v^-)^2 \delta^2 + 0.01$, $r^2 = 0.84$. Step length and speed therefore predict work similar to the simple model, over a very wide range of gait conditions.

These results indicate that, even though humans do not exactly follow the

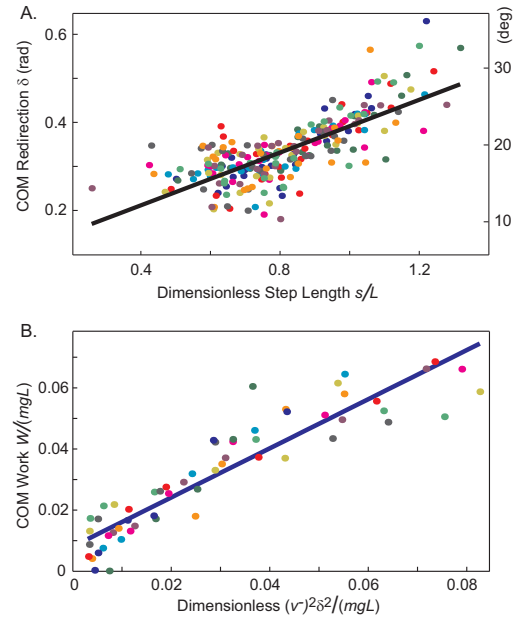


Figure 2: A) COM redirection angle δ vs. step length s . COM redirection increases with step length as predicted by the model, $r^2 = 0.66$. B) COM work performed by the leading leg W vs. the model prediction $(v^-)^2 \delta^2$. Step-to-step transition work is predicted well by COM velocity and angular change ($r^2 = 0.84$), or by walking speed and step length.

assumptions of the simple model, their COM velocity undergoes redirection similar to the model and with similar dependence on step length and speed. Humans are also fairly consistent in how they perform the step-to-step transition, so that a single model applies reasonably well to a much wider variety of speed, step length, and step frequency conditions than is observed in daily life. Step-to-step transition work, and from previous findings (Donelan et al., 2002a), the associated metabolic energy expenditure, are both predicted by speed and step length.

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