“shorter 16 bouts are unsteady and dominated by the time and effort of accelerating, and longer ones are 17 steadier and faster and dominated by steady-state time and effort” (Carlisle and Kuo, 2023, p. 1)

factors of walking tasks: speed, economy, step length and width, acceleration and deceleration, habitual walking speed, urgency, COT, distance

short bouts of walking are common and have lower than steady optimum speeds

“test whether the combined costs of energy and time 79 can predict dynamic variation in walking speed. We propose a basic quantitative objective function 80 called the Energy-Time hypothesis, which includes a cost for total energy expenditure or mechan81 ical work for a walking bout, plus a penalty increasing with the bout’s time duration.” (Carlisle and Kuo, 2023, p. 3)

“For relatively short walking bouts, 84 this hypothesis predicts speeds that vary within a bout, and speed profiles that vary across bout 85 distances.” (Carlisle and Kuo, 2023, p. 3)

“For longer distances, it predicts a steady walking speed, not as an explicit outcome but 86 rather as an emergent behavior.” (Carlisle and Kuo, 2023, p. 3)

RESULTS - THE MODEL

“Energy-Time hypothesis is that humans perform walking bouts that minimize an objective including the total energy and time expended for the bout” (Carlisle and Kuo, 2023, p. 3)

* optimal control: minimization by determining the objective function under the assumption that we are moving optimally - fit parameters to structured function

“minimize (Energy expenditure) + 𝐶𝑇 (Time duration) 97 subject to: starting and ending at rest 98 with 𝑁 steps of pendulum-like walking dynamics at human-like step length” (Carlisle and Kuo, 2023, p. 3)

metabolic energy with time duration weighted by metabolic energy coefficient - doubles as the coefficient for cost of time

Energy time model produces rounded speed profile as compared to the point of the steady acceleration model or the flatter table top shape of a model favoring moving at the min cost of transport speed -- note that this a 10  b step bout of walking

work inputs have very different shapes between the models - importantly, total work is lowest in the Energy-Time model (with steady accel 31% higher and minCOT 11%

“Energy-Time hypothesis predicts a family of speed profiles.” (Carlisle and Kuo, 2023, p. 5)

for a range of walking distances, using different time valuations and step lengths

longer bouts reach higher, steadier speeds

“the value of time 𝑐𝑇 , step length, and walking bout distance” (Carlisle and Kuo, 2023, p. 6)

* “step lengths 𝑠 fixed at nominal (0.68 m), at slightly shorter and longer lengths (0.59 m 145 and 0.78 m), and increasing with speed according to the human preferred step length relationship” (Carlisle and Kuo, 2023, p. 6)
* 1-20 steps
* “time valuations 𝑐𝑇 ranging ten-fold, 0.006 to 0.06 (dimensionless)” (Carlisle and Kuo, 2023, p. 6)

speed of walking increases with distance B as does walk duration C

“speed profiles retain a gently rounded shape, accelerating from rest and leveling off at a peak speed before decelerating back to rest. Unlike min-COT profiles are always peaked. longer distance = greater the peak speed (unlike min-COT), and more sustained peak (contrast to rounded speed profiles for shorter distances) accel and decel slopes increase slightly with longer bouts, only for distances <10 m is there a steady gait near peak speed. peak speed also initially increases sharply with walking distance (Fig. 3B), but approaches an asymptote for greater distances, as the cost of acceleration becomes inconsequential.” (Carlisle and Kuo, 2023, p. 6)

to carry to experimental

* “speed profiles should fall within a single consistent family, which includes more rounded shapes for short walks, and flatter for longer walks” (Carlisle and Kuo, 2023, p. 6)
* “self-similarity, and be scalable in peak speed and time” (Carlisle and Kuo, 2023, p. 6)
* “peak speed should increase with distance” (Carlisle and Kuo, 2023, p. 6)
* “walking durations should increase with distance, in a slightly curvilinear relationship” (Carlisle and Kuo, 2023, p. 6)

RESULTS - EXPERIMENTAL

figure 4

A: speed profiles over time - colors represent different walking distances - note that there are a range of peak speeds resulting in a range of trial durations - however, the profile shapes are similar between subjects, the peak speeds increase with distance and for shorter distance the peak speed is lower than the minimum cost of transport speed

B: each individual’s trajectories scaled by the duration and maximum speed of their longest bout and rescaled to match the average duration and peak speed across subjects.

* once scaled: similarity between individuals as well as a family of distance-determined profiles are evident
* “Peak speeds increased with distance, 211 sharply for short distances and then saturating for longer distances” (Carlisle and Kuo, 2023, p. 8) --- exponential model
* normalization reduced variability of peak speeds - this suggests that while subjects walked their own pace, they tended to be consistent across distance
* “even though each individual walked at their own pace, that tendency was consistent across 219 all distances” (Carlisle and Kuo, 2023, p. 8)
* “Walking durations increased with distance in a slightly curvilinear fashion” (Carlisle and Kuo, 2023, p. 8)
* change in “peakiness”

As a fraction of duration, rise and fall times take up a greater proportion for short bouts (very small proportion spent at steady speed)” (Carlisle and Kuo, 2023, p. 8)

peak speed  and total walk duration increase with a curvilinear relationship (increasing faster with respect to distance at first) and are captured with a saturating exponential curve

Figure 5 peak speeds and walking durations from each participant’s normalized data

note that these peak speed and total durations were similar when walking over grass

“relationship between human valuation of time and steady walking speed” (Carlisle and Kuo, 2023, p. 9)

using an empirical human metabolic power curve from Elftman 1966, predicted how steady walk speed should increase with metabolic value of time - in this model steady walking speed and cost of transport compete

* time valuation of 0 results in minCOT speed estimate