

# PEOPLE WALKING ON TREADMILLS CONTROL SPEED, NOT POSITION

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## INTRODUCTION

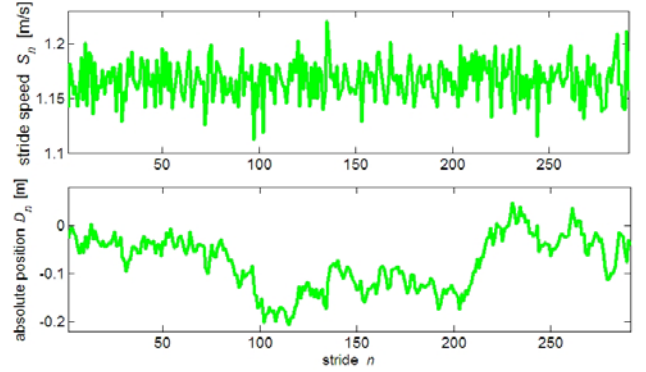
While both the vestibular and proprioceptive systems are known to be involved in the regulation of walking, visual optic flow has a dominant influence [1,2]. Altering visual optic flow induces changes in average preferred walking speeds [2]. However, it is not known how optic flow is used to control movements from each step to the next.

When subjects walk on a motorized treadmill in a static visual environment, they could try to maintain *exactly* the same scene (i.e., “absolute position control”) at each consecutive step. Conversely, they could try to minimize optic *flow* at each step, such that they do not try to control small *changes* in the visual scene, but rather strive to make it stop *moving* (i.e., “speed control”). On average, these two strategies yield the same outcome: i.e., walking with the same average speed as the treadmill will keep the subject in the same average position. However, we demonstrate here that these two control strategies predict very different patterns of stride-to-stride *fluctuations* and show that humans adopt speed control, not position control.

## METHODS

Seventeen healthy volunteers (age 18-28) walked on a level treadmill (Woodway USA) at their preferred speed. 3D movements of their feet were recorded continuously for 2 trials of 5 min each and used to compute stride times and lengths,  $T_n$  and  $L_n$ , for each stride,  $n$ .

Detrended fluctuation analysis (DFA) [3] was used to calculate stride-to-stride scaling exponents,  $\alpha$  for stride speed  $S_n$  and treadmill absolute position  $D_n$  time series (Fig. 1). Uncorrelated white noise has  $\alpha = 0.5$ , and  $\alpha = 1.5$  indicates Brownian motion. Values of  $\alpha > 0.5$  indicate statistical persistence (deviations likely go uncorrected over consecutive strides, indicating weak control), whereas  $\alpha < 0.5$  indicates antipersistence (deviations likely are corrected rapidly, indicating strong control).



**Figure 1:** Typical time series for stride speed  $S_n$  (top) and stride absolute position  $D_n$  (bottom). The  $D_n$  data exhibits substantial statistical persistence, whereas the  $S_n$  data does not.

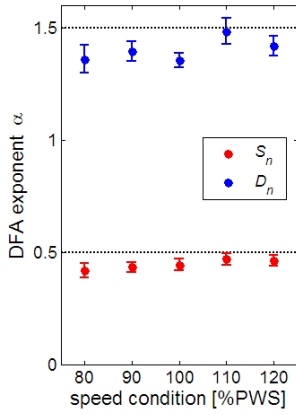
Walking on a treadmill with belt speed  $v$  simply requires that one stay on the treadmill. The absolute position after stride  $n$  is given by

$$D_n = \sum_{k=1}^n L_k - vT_k, \quad (1)$$

where  $[T_n, L_n]$  represent stride time and length, respectively. Any sequence  $[T_n, L_n]$  for which  $|D_N| < K/2$ , where  $N$  is the total number of strides in a given trial and  $K$  is the length of the treadmill, will accomplish the task. Specific strategies are formulated using *goal functions* [4],  $F$ , which, when set to zero, provide a hypothesis on the strategy actually used for task execution. The absolute position satisfies  $D_{n+1} = D_n + L_n - vT_n$ , so we consider goal functions of the form

$$F = L_{n+1} - vT_{n+1} + cD_n, \quad (2)$$

in which  $c$  is either 0 or 1,  $[L_{n+1}, T_{n+1}]$  are viewed as controlled variables, and  $cD_n$  specifies the performance “target”. The case  $c = 1$  corresponds to *absolute position control*: subjects attempt to choose  $[L_{n+1}, T_{n+1}]$  so that  $F = D_{n+1} = 0$ . The  $c = 0$  case corresponds to *speed control*: the current absolute position is ignored, and the controller attempts to set  $L_{n+1} - vT_{n+1} = 0$ , so that the stride speed  $S_{n+1} = L_{n+1}/T_{n+1} = v$ .



**Figure 2:** Experimental DFA exponents for stride speed (blue) and absolute stride position (red) showing that  $S_n$  is antipersistent, suggesting speed control, whereas  $D_n$  is persistent, suggesting no control. Error bars are 95% confidence intervals.

Stochastic control models [5] of the form

$$\mathbf{x}_{n+1} = \mathbf{x}_n + (I + N)\mathbf{u}(\mathbf{x}_n) + \boldsymbol{\eta}, \quad (3)$$

were constructed, where  $\mathbf{x}_n = [T_n, L_n]^T$ ,  $\mathbf{u}(\mathbf{x}_n) = [u_1, u_2]^T$  was a vector of control inputs,  $N$  was multiplicative (motor output) noise, and  $\boldsymbol{\eta}$  was additive (sensory and/or perceptual) noise. The controllers were found by minimizing the expected value of the cost function

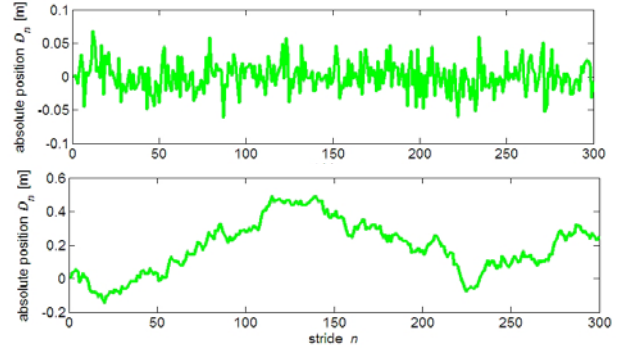
$$C = \alpha F^2 + \beta p^2 + \gamma u_1^2 + \delta u_2^2, \quad (4)$$

where the first term penalized error as specified by  $F$ , the second term penalized the distance,  $p$ , of the current state from the preferred operating point (POP),  $[L^*, T^*]$ , and the last two terms penalized the control inputs,  $\mathbf{u} = [u_1, u_2]^T$ .

## RESULTS AND DISCUSSION

The absolute position time series  $D_n$  obtained in the experiments visibly exhibited strong persistence (Fig. 1, bottom), whereas the stride speed  $S_n$  appeared to have very low persistence (Fig. 1, top). This observation was confirmed quantitatively by the DFA results, which showed that across all conditions the scaling exponent for absolute position  $\alpha(D_n) \approx 1.40$ , corresponding to strong persistence approaching Brownian motion, whereas for the stride speed  $\alpha(S_n) \approx 0.44$ , indicating antipersistence. This suggests that it is speed, not position that is controlled.

This interpretation was supported by the simulations from the optimal control models (Eq. 3). Speed control ( $c = 0$  in Eq. 2) gives  $D_n$  time series that



**Figure 3:** Typical simulated absolute position ( $D_n$ ) time series from optimal control models (Eqs. 3 and 4): (top) position control ( $c = 1$  in Eq. 2) with  $\alpha \approx 0.44$ ; (bottom) speed control ( $c = 0$  in Eq. 2) with  $\alpha \approx 1.48$ . Compare both to Fig. 1 (bottom).

mirror those observed in the experiments (Fig. 3). However, position control ( $c = 1$  in Eq. 2) gives behaviors that are entirely different. Thus, the hypothesis that humans control speed while walking on a treadmill is supported. The hypothesis that humans control absolute position is rejected.

## CONCLUSIONS

Both speed and position control could be used to successfully walk on a treadmill. Indeed, based on average behavior alone it is impossible to distinguish between them. However, our analysis of stride-to-stride fluctuations has unequivocally demonstrated that humans use speed, and not position, to regulate walking. These results show that hypotheses on specific movement strategies formulated using goal functions, together with relatively simple stochastic optimal control models, allow one to successfully distinguish different movement regulation strategies.

## REFERENCES

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