Control Models of Lateral Stepping in Human Walking

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1 Introduction

Falls are very common and extremely perilous events in the lives of the elderly (age ≥ 65) [1]. Lateral (sideways) falls are especially dangerous [2]. This is likely because humans are inherently more unstable in the lateral direction [3,4]. Most walking environments impose some soft lateral constraints (e.g., treadmills, sidewalks, walking paths, hallways, store aisles, etc. all have finite width). However, it remains unclear how humans *regulate* their stepping movements in such contexts. We previously demonstrated how humans exploit redundancies available in their stepping movements to achieve stride-to-stride control of sagittal plane walking [5,6]. Here, we extend this theoretical framework to *frontal* plane stepping control.

2 Methods

The only absolute *requirement* for lateral stepping control in walking is to not exceed the lateral boundaries of the path you are walking on. Thus, because of neuro-biomechanical redundancy [6], there are an infinite number of *potential* strategies one could adopt to achieve this. Here, we tested 3 candidate phenomenological models that were as simple as possible, yet still captured the key relevant features of step-to-step dynamics. We first identified the critical stepping variables directly associated with each proposed control law (Fig. 1): maintain absolute lateral *position* (z_B in Fig. 1), maintain forward *heading* (i.e., keep walking in the +x direction, regardless of current position: Δz_B in Fig. 1), or maintain constant *step width* (w in Fig. 1), regardless of current position or heading.

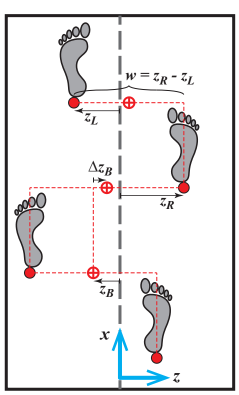

Figure 1: Candidate variables for lateral step control: z_B is lateral deviation from some absolute position (e.g., center). Δz_B is lateral deviation from previous z_B. w is step width. Candidate control policies: maintain absolute position (z_B control), maintain current "heading" (Δz_B control), or maintain step width (w control) [3].

Stochastic control computational models of stepping were developed based on pre-defined goal functions [6], in a manner similar to [5]. Three candidate controllers (Fig. 1) tried to maintain either constant absolute lateral position (z_B), constant heading (forward motion) (Δz_B), or constant step width (w). For each candidate strategy, the process for regulating step-to-step walking dynamics on the treadmill was modeled as a discrete map, written in the general scalar form of a step-to-step update equation [5]:

$$q_{n+1} = q_n + g(1+\eta_M)u_q(q_n) + \eta_A,$$

where x_n is a suitable controller state variable (i.e., $q \in \{z_B, \Delta z_B, w\}$) for current step n, q_{n+1} is the state for the subsequent step, and $u(q_n)$ is an input from an inter-step controller derived from one of the three goal functions (F):

$$F(q) = q_n - q^*,$$

where q^* is the desired value of q: i.e., here, $z_B^* = \Delta z_B^* = 0$ and $w^* = \bar{w} \equiv$ the mean step width obtained in our experiments. For each candidate control strategy and model, the corresponding controller (u_q) was derived. Walking data were simulated for twenty trials of 1000 steps each.

Experimental data were collected from 13 able bodied individuals (age 22-40). Participants walked in a "CAREN" virtual reality environment [4] on a wide (1.8m) treadmill. Each participant completed five 3-minute walking trials at a comfortable speed [4]. Kinematic data were recorded (Vicon) of their whole body and stepping movements.

Stepping parameters analyzed included time series of left and right foot placements (z_L and z_R), absolute lateral position (z_B), change in lateral position (Δz_B), and step width (w). Means, standard deviations, and Detrended Fluctuation Analysis (DFA) α exponents [5] were calculated for each time series and used to compare the correlation properties predicted by each controller to experimental results.

3 Results and Discussion

Humans exhibited relatively consistent step widths while walking, as expected [3], but also exhibited considerable lateral "drift" on the treadmill (Fig. 2). Stepping movements for the 3 controller models (Fig. 2) reflected the redundancies exploited by each: The z_B controller maintained very tight control over absolute position (i.e., the midpoint between the feet), but exhibited substantial fluctuations in step width including numerous cross-over steps. The Δz_B controller likewise maintained very tight control over heading, but with substantial fluctuations in both absolute position and step width. And the w controller maintained very consistent step widths, but larger fluctuations in absolute position than humans (Fig. 2).

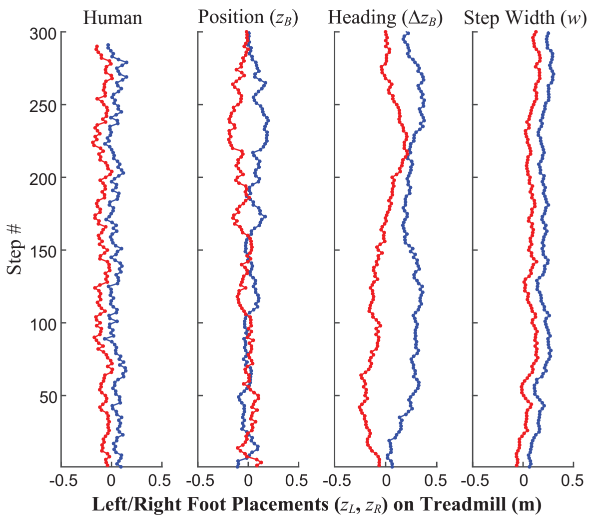

Figure 2: Stepping patterns for left (z_L: red) and right (z_R: blue) feet exhibited by humans and by each controller.

Observations of Fig. 2 were quantitatively confirmed (Fig. 3). Experimental DFA α's for the various relevant time series were best captured by the step width control model.

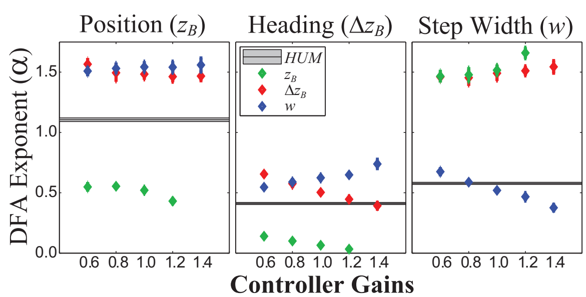

Figure 3: DFA α exponents for step-to-step fluctuations in lateral position (α(z_B), left), heading (α(Δz_B), middle), and step width (α(w), right) for each of the three control models as control gains were varied. Horizontal lines indicate experimental ranges (mean±SD) for Humans.

Likewise, direct measures of how deviations in each variable ("Relative q") were then corrected on subsequent strides (Δq) (Fig. 4) showed that humans strongly corrected deviations in w, and possibly also Δz_B, but only very weakly corrected deviations in absolute position (z_B).

Wang & Srinivasan [7] used experimental data of current foot and pelvis states to predict subsequent foot placements. However, adding current absolute position explained *no* additional variance in lateral foot placement (their Fig. S9). They likewise concluded healthy humans do not try to maintain absolute position on the treadmill. Also, their participants walked on treadmills much narrower (0.92 or 0.51 m) than that used here (1.80 m), where one might expect a greater need for lateral position control.

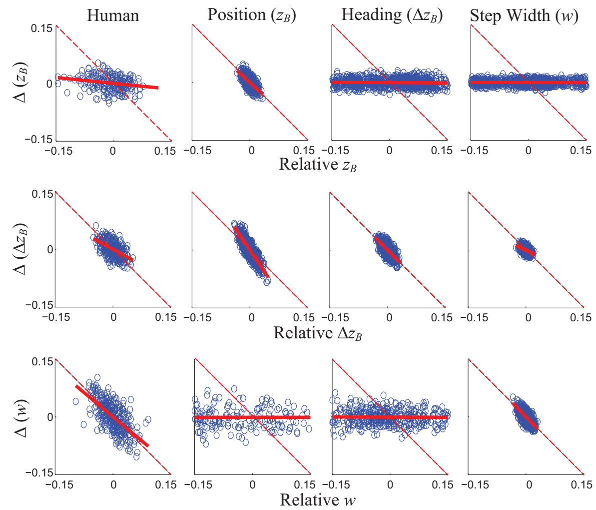

Figure 4: Degree of direct control with respect to each variable. *Perfect* correction of deviations in "Relative q" ($q \in \{z_B, \Delta z_B, w\}$), by a subsequent Δq are indicated by relationships with slope = –1. Thus, the ideal position controller perfectly corrects deviations in z_B, the ideal heading controller perfectly corrects deviations in Δz_B, and the ideal step width controller perfectly corrects deviations in w. Human subjects (left column) exhibited behaviors most closely aligned with step width (w) control.

4 Conclusions

Computational controller predictions support the idea that humans walk with hierarchical / multi-objective control that prioritizes step width, but also takes into account some degree of lateral position and/or heading control.

Prioritization of step width control is likely directly related to maintaining lateral balance/stability [3,4] and is thus highly relevant for those prone to falling [1,2].

More elaborate and/or nuanced multi-objective and/or multi-step controllers may better capture the ability of humans to achieve multiple simultaneous goals [6].

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