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A Simple Model of Stability Limits Applied to Sidestepping in Young, Elderly and Elderly Fallers

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Abstract — **Impaired lateral balance involving the frontal plane is particularly relevant to the problem of falls with aging. Protective stepping is critical to avoiding falling, and medio-lateral (M-L) stepping involves two quite complicated action choices – lateral side step and crossover stepping. The aims of this study were to identify differences in movement patterns between young healthy subjects and elderly fallers and non-fallers (determined prospectively over a year), and to identify performance differences for the two types of stepping response. Our tool for these evaluations was a computational model of the center of mass as a pendulum, which identifies the limits of stability beyond which additional steps are required. In response to multi-directional stepper-motor induced waist-pull perturbations of standing balance, the older groups took multiple steps more often than the young (55% compared to 9% of the trials), and the largest differences were seen in the pulls to the side. On these side pulls, crossover stepping and limb collisions increased with age and prospectively determined fall risk. Consequently the model analysis focused only on the most problematic lateral pulls, and only on pulls to the right. In both stepping off and landing, the young most closely approached the stability limits predicted by the model, followed by the older non-fallers and then fallers. In crossover stepping, all groups landed closer to their limits when multiple steps occurred, though older fallers were closest to instability. These findings revealed distinctive age differences related to fall risk and shed light on such modeling approaches for understanding the reasons why older fallers may select stepping responses and the effectiveness of such responses in recovering balance.**

I. Introduction

Falls and their consequences are among the major problems in the medical care of older individuals [1-3] and are the leading cause of deaths due to injury [4]. Here we demonstrate how a simple mathematical model of biomechanics and neural control is a promising way of differentiating behavior between young, older, and older fallers.

There is accumulating evidence that aging effects on balance may be accentuated in the lateral direction [5, 6]. In response to lateral waist-pull perturbations of stance, balance recovery through protective stepping involves two main strategies – a direct sidestep strategy with the limb that is passively loaded by the perturbation-induced sway to the side, or a crossover step with the limb that is passively unloaded by the perturbation [5, 6]. We therefore distinguish these two patterns of movements as *loaded* side step (LSS) or *unloaded* crossover step (UCS). Older adults, particularly those who fall, often respond to lateral challenges to standing balance using UCS patterns with high-risk collisions between the limbs and multiple additional recovery steps [5]. Our hypothesis is that people choose to make these different movements based on feasible stability and the limits of the neuromechanical system, which can be predicted by modeling these behaviors.

Our modeling approach mathematically represents the relationship amongst mechanical, environmental, and physiological constraints that define balance stability. These constraints can arise internally (e.g., strength limits), externally from the environment (e.g., support surface friction), or from objectives (e.g., stepping) [7, 8]. For example, if shear forces exceed the threshold coefficient of friction constraint, slipping begins. All constraints are mathematically mapped to the same space: positions and velocities (states) plus controller actions (torques). For example, all inequalities related to ground reactions (avoid a slip left, avoid a slip right, etc.) are related to the dynamics of a pendulum via the equations of motion. The result is a multiple inequality expression governing the dynamic variable combinations that do not precipitate a fall. This corresponds to a mathematical intersection of inequality-defined sets, defining the *feasible dynamics* for the system. Both stability and variability can be better understood if the limits to stability are known. Such a modeling approach was used previously in studying steps in the sagittal plane [9-13]. What has not yet been done is a similar analysis in the frontal plane, even though elderly fallers are particularly vulnerable to falls to the side [14].

In this paper we present our initial modeling efforts focused on mechanical pulls to the side. Relative to the stability boundaries, we show distinctive differences among the groups (healthy young, elderly fallers and elderly non-fallers), and provide an initial modeling framework upon which to build a more comprehensive analysis in the future.

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II. PROCEDURES

A. Apparatus

A customized multi-directional waist-pull perturbation system (Fig. 1) was used to induce steps. The system allows for independent control of pulling displacement, velocity, and acceleration. Six directions of balance perturbations are possible, and by changing the initial orientation of the subject, virtually all directions are feasible. This multidirectional capability prevents subjects from advanced pre-planning of their responses. The pulley-cable system and a switching transmission with a beaded metal chain can select and engage one of the six cables (1/16-in. diameter steel wire). 16 pulleys mounted on seven symmetrically-positioned height-adjustable vertical posts can accommodate different body heights. A LVDT position transducer records pulling motion and an in-line load cell records pulling force.

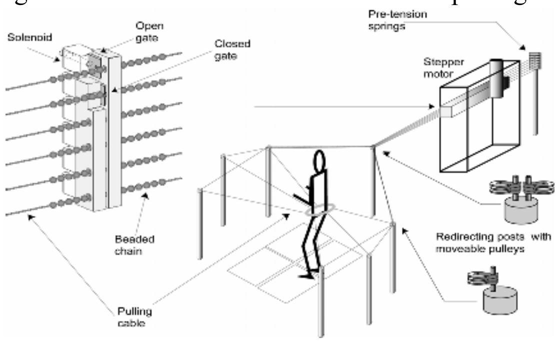

Fig 1. Schematic Representation of the Multi-Directional Waist-Pull Perturbation System..

B. Protocol

26 community-living subjects (9 young, 9 older non-fallers, and 8 older and prospectively identified as fallers [mean age = 73.3 years ± 6.3 years, range 62 to 86 years]) received waist-pull perturbations in 12 different directions, using a single magnitude determined to always evoke stepping (displacement: 22.5 cm; velocity 31.5 cm·s^{-1} and acceleration: 900 cm·s^{-2}). Perturbations were randomly applied to standing subjects who were instructed to react naturally and prevent themselves from falling. For model simplicity and since there were no detectable differences between pulls to the left or the right side, we only investigated pulls to the right. Each subject contributed 5 stepping movements to the analysis.

The fall history of each subject was followed prospectively for a period of one year after completion of laboratory testing. (Fallers were defined as having 1 or more falls in 12-month prospective follow-up).

C. Model

We began with a simple inverted pendulum model of balance. Our earlier work [11] described how dynamic modeling could identify the limits to standing dynamics when terminating whole body movement. An inverted pendulum-and-foot model combined with nonlinear optimization techniques identified feasible state boundaries beyond which standing balance could no longer be maintained.

The constraints were modeled similar to these previous approaches [11, 12] but altered slightly for frontal plane motion. Because the foot was not rigidly attached to the floor, the model's ability to transmit forces from the floor was limited by three base-of-support (BOS) constraints:

- Gravity constraint: The net vertical ground reaction force, Fgy, must be positive: $F_{gy} \geq 0$
- Friction constraint: The horizontal ground reaction force, Fgx, must not exceed the slip threshold dictated by the coefficient of friction, μ: $|F_{gx}| < \mu F_{gy}$
- Center of pressure (COP) constraint: The COP must be maintained within the BOS: $0 < COP < w_f$

where w_f is the width of the feet. Ankle strength limitations were neglected in this analysis.

The model considered both the limits to stability in the stepping off phase (destined to be violated in this task), and the limits of stability on the landing of the step (Fig. 2).

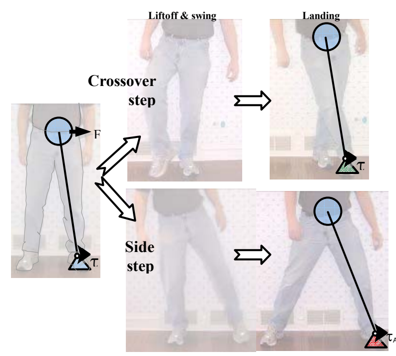

Fig 2. Schematic of the dynamic stability model and its applications used to analyze the relative balance stability limits before the subjects stepped and upon landing.

D. Data Analysis:

The beginning and end of the step was defined from the vertical velocity of the step side ankle marker in order to identify the beginning and ending of the limb movement phase of the first step. Segmental angular displacements and velocities in the frontal plane were computed for the single stance leg with respect to the ground, the swing leg with respect to the hip line, the trunk with respect to the hip line, and the head with respect to the shoulder line. Center of Mass (COM) trajectories were determined using segment kinematics data and standard anthropometric models [15]. We calculated summary statistics (means and 95% confidence intervals) on the locations in the state space corresponding to these critical points.

III. RESULTS

Across all directions of perturbations, the percentage of trials with multiple additional steps (>1) was larger for all older subjects (55% of trials) compared with the young (9% of trials) who typically secured stability with single steps.

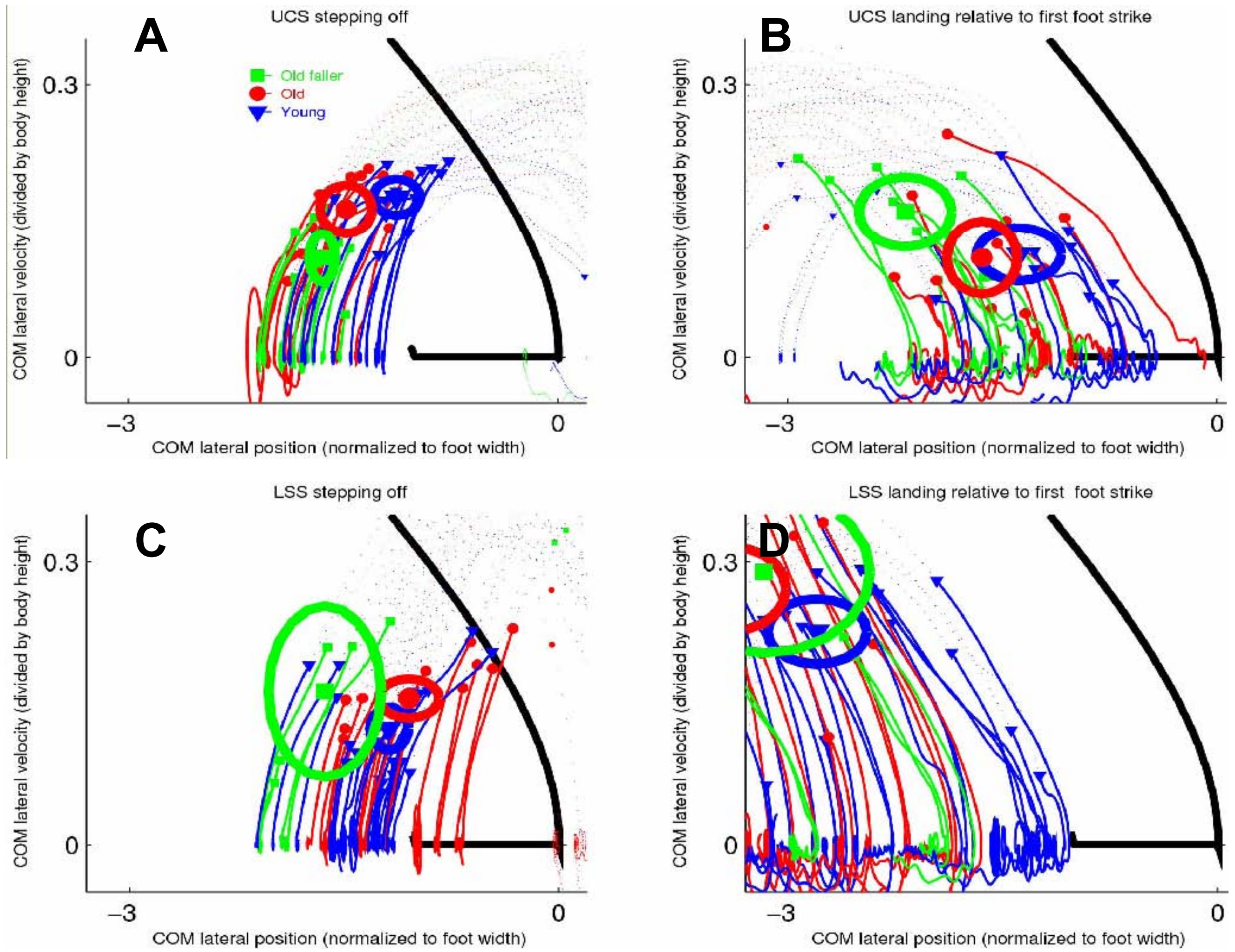

Fig 3. Movement trajectories for trials with single steps of all the subjects in each group. Center of mass trajectories are plotted in the phase plane (velocity vs. position). Each color represents a group of subjects. Data is further separated into unloaded crossover steps (UCS) (upper plots A and B) and loaded side steps (LSS) (lower plots C and D). Steps are required, as dictated by the model, if a trajectory crosses to the right of the bold lack line. Dotted lines trace the trajectories between stepping off and landing. In (A) and (B), the states of individual trajectories at foot-off were pooled for each subgroup to show mean (bold dot) and 95% confidence interval (ellipse). Similarly, in (C) and (D), these same statistics are shown for states at foot landing. Velocity values are normalized to body height and position values to the width of the foot.

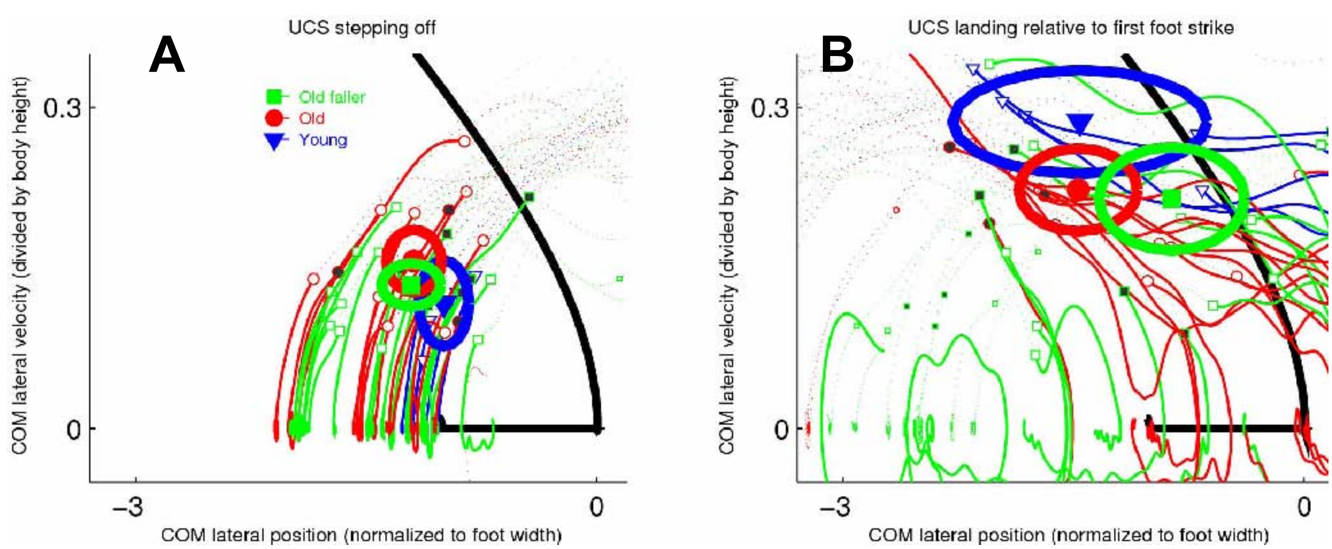

Fig 4. Movement trajectories for multiple sidestep movements for unloaded crossover steps (UCS). Conventions are the same as in Fig 3. (A) stepping off , (B) landing of the first step.

For all lateral pulls, older non-fallers favored the riskier crossover stepping strategy (69% of trials), and older fallers even more so (74% of the trials). There was also an interaction between these two behaviors: 80% of trials with multiple steps in older subjects occurred when crossover stepping was used.

For the modeling application (Figs 3 & 4), we focused on the lateral pulls to the right side. Overall, older fallers adopted a wider initial stance prior to the perturbations, and, in both stepping off and landing, the young most closely approached the stability limits, followed by the older non-fallers and then fallers. (Fig. 3 A and C; Fig 4 A).

When comparing loaded side step (LSS) and unloaded crossover steps (UCS), all groups landed closer to their stability limits for single crossover UCS step trials (Fig. 3B and D) particularly when multiple steps occurred (Fig. 4B). During single step crossover steps, older fallers placed their landing foot so that they were farther from instability than the young and non-fallers (Fig. 3B, green ellipse). However, the faller group approached their stability limits more closely when UCS responses involving multiple steps occurred, (Fig. 4B). Moreover, older fallers tended to initiate steps at slower speeds (Figure 3A), reach higher peak speeds in mid-swing, and then plant their foot at higher speeds in landing (Figure 3B). Note that multiple step data for LSS in young and in older non-fallers was not obtained and hence omitted from Figure 4.

IV. Discussion

This analysis revealed some distinctive differences in behavior between the groups in relation to age and fall status. First, younger subjects (and to a lesser extent, older non-fallers) tended to secure their balance by more closely exploiting their boundaries of stability. All groups landed closer to the boundary limits in UCS compared with LSS especially when additional multiple steps were taken compared with when a single step was used to recover balance (compare 3B and 4B). The older fallers showed the "least stable" crossover landing configuration with multiple steps. These observations suggested that, in addition to the increased risk of interlimb collisions and more complex step trajectories that accompany CSS compared with LSS [5, 6] , the more prevalent CSS recovery pattern displayed by older individuals could be predisposing them to a more precarious state of stability boundary conditions that exacerbate fall risk.

While all questions cannot be answered by this simple analysis, the data indicate the feasibility of applying the approach to multidirectional global balance problems beyond the sagittal plane. This paves the way for more comprehensive modeling. For example, we propose that aging limitations in regional medio-lateral postural mechanisms (e.g. hip/trunk control) compromise global lateral balance stability by disrupting the control of protective stepping [6]. Consequently, many older people may be particularly vulnerable to lateral instability and injurious falls.

What is currently not clear from these analyses is why subjects displayed such balance recovery patterns, nor is it known what aging changes in underlying mechanisms might lead to these differences. More detailed models combined with experiments are needed in order to identify the mechanisms by which different stepping solutions for balance recovery are possible or restricted by physiological or mechanical constraints. What is clear from the present study, however, is that there are stability differences amongst these groups that warrant further analyses.

Acknowledgments

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