# Is wide stance stabilizing? Predictions of postural stability and stepping threshold from a frontal-plane delayed feedback model


Jeffrey T Bingham• - Julia T Choi° - Lena H Ting°•

°Department of Biomedical Engineering - Georgia Institute of Technology / Emory University
•School of Mechanical Engineering - Georgia Institute of Technology


381.2

## Background

Is standing with a wide stance more stable? If we were rigid and static this would be the case, however our postural stability depends upon a nonlinear musculoskeletal system and delayed neural control. Interactions between the nervous system and musculoskeletal configuration observed in healthy subjects show that muscle activity in response to postural perturbations decreases as stance width is increased (Henry 2001). However, in Parkinson's patients this modulation is absent (Dimitrova 2004). Our hypothesis is that the nervous system must adapt rapidly to biomechanical changes to the musculoskeletal system in order to stand stably in different configurations. We previously described muscle activity in response to postural perturbations with a simple inverted pendulum model stabilized by delayed feedback (Welch and Ting 2008). Here, we present a model to investigate the effects of altered stance width and delayed feedback on medial-lateral postural stability and the transition to stepping.

Predictions: Changes to biomechanics from increasing stance width requires neural control to decrease the feedback gain magnitude for postural stability.

Transition to stepping is predicted for different perturbation magnitudes from an analytical measure of stability.

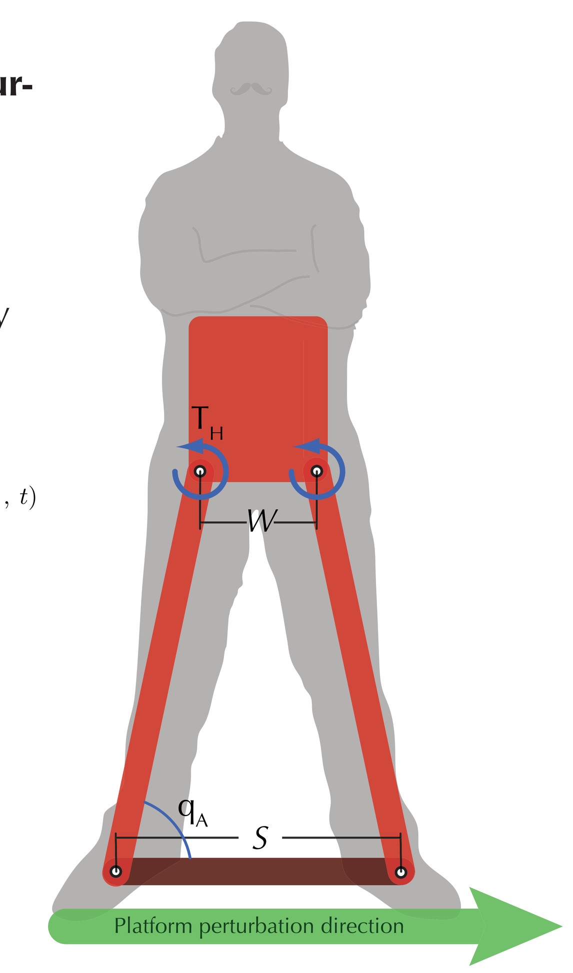
## Methods

- **Dynamics of medial-lateral stance were modeled by a four-bar linkage with delayed feedback**
  - Geometry and inertia of links scaled to subject height and mass.
  - Single degree-of-freedom system, $q_A$.
  - Torque applied as delayed angular position and velocity of hip, $T_H$.
  - Feedback delay of 150 ms (100 ms neural and 50 ms mechanical).

$$\mathbf{I}\left(q_A(t)\right)\ddot{q}_A(t)+\mathbf{V}\left(q_A(t),\dot{q}_A(t)\right)+\mathbf{G}\left(q_A(t)\right)=\mathbf{T}\left(q_A(t-\tau),\dot{q}_A(t-\tau)\right)+\mathbf{P}\left(q_A(t),t\right)$$

- **Stability of the biomechanics was determined from the linearized model at different stance widths**
  - Linearized about the symmetric upright configuration.
  - Geometric changes to effective inertia, $I_e$, and effective stiffness, $G_e$, were examined with respect to stance width.

$$\mathbf{I}_e\ddot{q}_A(t)-\mathbf{G}_e q_A(t)=-\left(\frac{S}{W}\right)^2\left[k_p q_A(t-\tau)+k_v\dot{q}_A(t-\tau)\right]$$



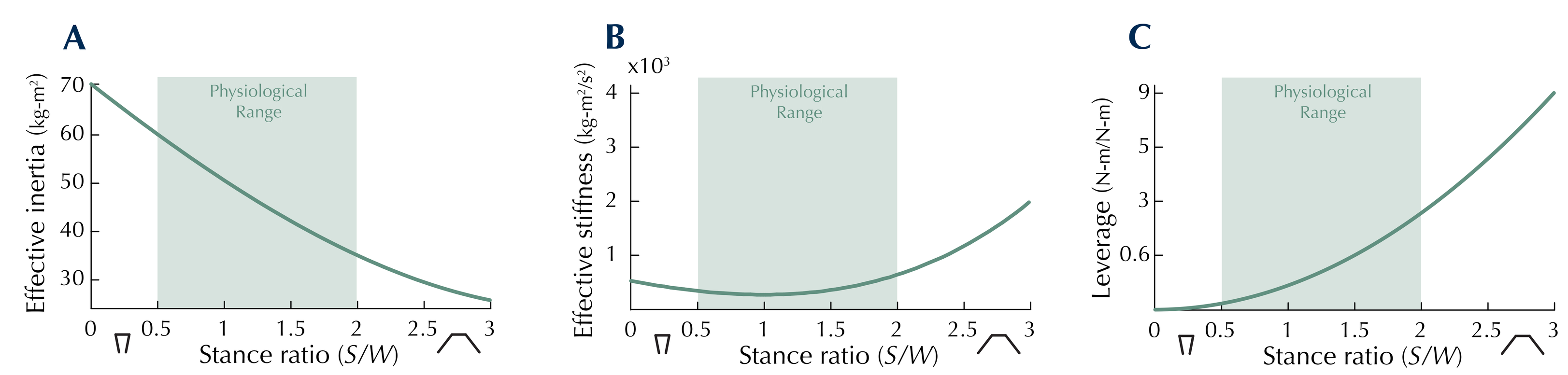

- **Stability of the delayed feedback model was determined across different stance widths**
  - The delay-differential equation was analyzed analytically and numerically using the DDE-BIFTOOL routines written for Matlab.
  - Stability boundaries for the position, $k_p$, and velocity, $k_v$, delayed feedback gains were found.
- **Simulations of the model were used to find the delayed feedback gains producing "feet-on-ground" behavior**
  - Numerical simulation of ramp-and-hold perturbations as stance width and feedback gains were varied.
  - Perturbations were applied as inertial accelerations consisting of two Gaussian pulses 500 ms apart with opposite sense.
- **Subject specific gains were determined from comparison of experimentally measured and simulated kinematics from platform perturbations**
  - Platform perturbations to subjects were ramp-and-hold translations in the medial-lateral direction with peak acceleration of 0.3 g.
  - Five healthy subjects, three stance widths, ten trials each.

### References


Dimitrova, Horak and Nutt. 2004. J Neurophysiology. 91(1) 489-501.
Kim, Horak, Carlson-Kuhta and Park. 2009. J Neurophysiology. 102(5) 2910-2920.
Henry, Fung and Horak. 2001. J Neurophysiology. 85(2) 559-570.
Welch and Ting. 2009. J Neurophysiology. 101(6) 3294-3309.

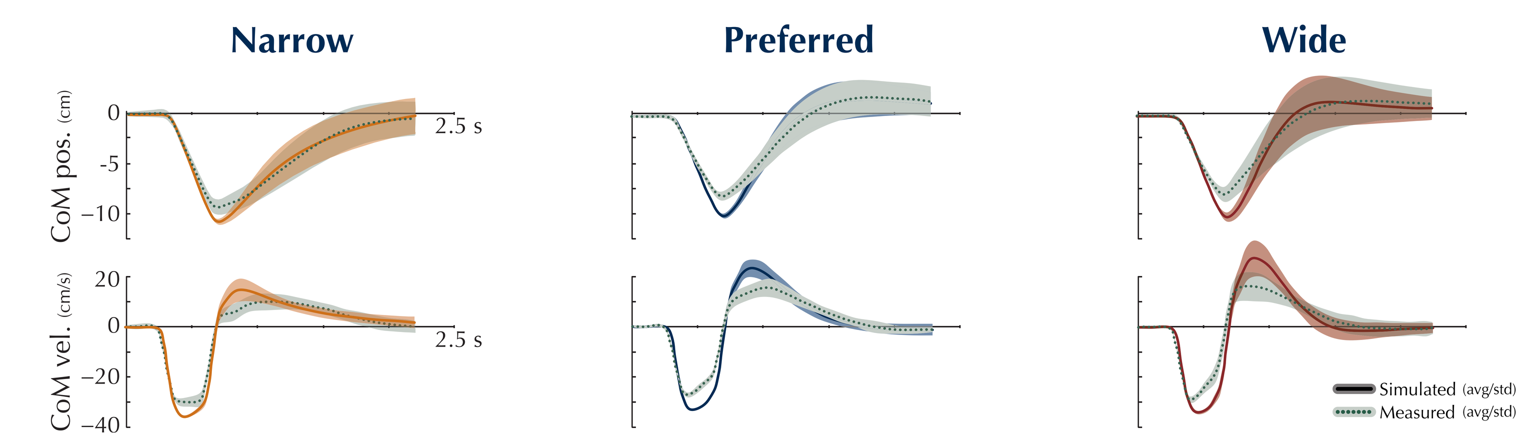

## Results

### Increasing stance width reduced biomechanical stability



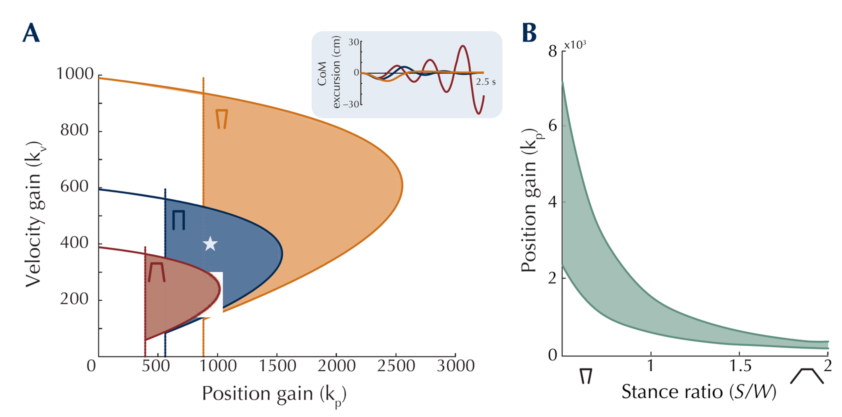

- Increased stance width resulted in decreased effective inertia, $I_e$.
- Effective stiffness, $G_e$ (gravitational instability) was roughly constant.
- Increased stance width increased leverage of hip torque on center-of-mass moment.

### Model matched subject specific center-of-mass trajectories




- Human subjects maintained similar center-of-mass kinematics across stance widths.
- The fit of simulated trajectories improved as stance width decreased.
- The four-bar model consistently over-predicted maximum center-of-mass excursion.

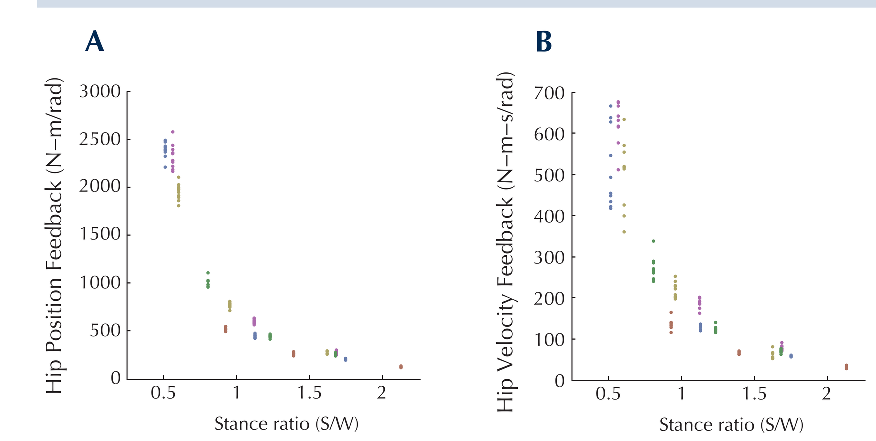
### Stable feedback gains decreased as stance width increased




A) Shaded areas of stable gains for stance ratios of 0.8 (orange), 1.0 (blue) and 1.2 (red). Inset shows center-of-mass trajectories for stance ratios and gains marked by the star in gain space. B) Stable position gain across stance widths.

- Increased stance width resulted in decreased stable gain space.
- Stable gain space was non-overlapping across stance widths.
- A single feedback gain pair was not stable across stance widths.
- Maximum and minimum values of stable gain space decreased as stance increased.

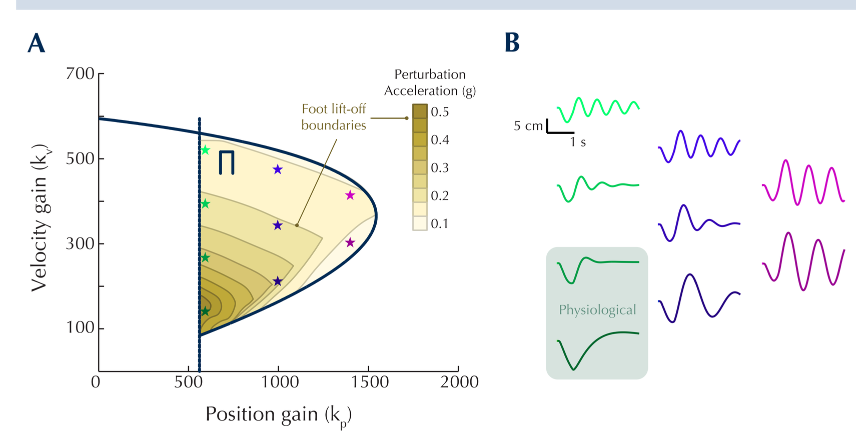
### Subject feedback gains decreased as stance width increased




Plots of A) position and B) velocity feedback gains that produced matching experimentally observed CoM trajectories are plotted with respect to stance ratio. Each point represents a single trial. Each color represents a subject.

- Both position and velocity feedback gains decreased for all subjects as stance width increased.
- Variability of feedback gains decreased as stance width increased.
- Feedback gains were similar across subjects for a given stance ratio.

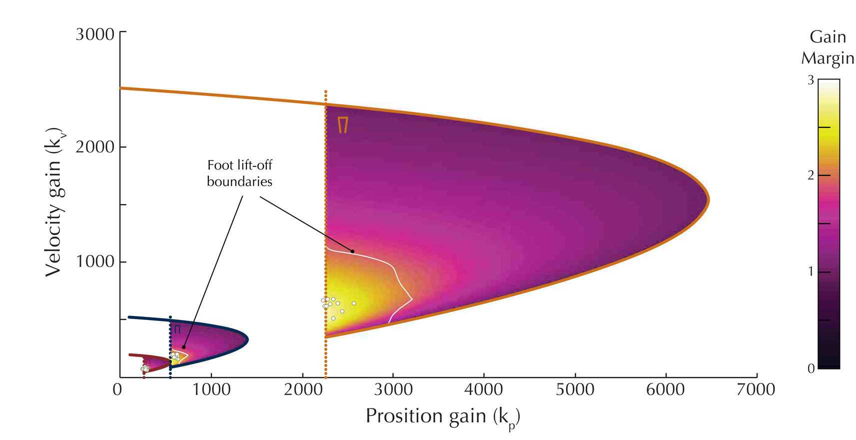
### Ground contact criterion reduced set of stable feedback gains




For a stance ratio of 1.0 A) Blue line is stability boundary, shaded areas are non-stepping gains B) Center-of-mass trajectories from 0.5 g perturbation. Color corresponds to starred gain pair. Physiological trajectories are in shaded box.

- Left-hand boundary corresponded to gravitational toppling moment.
- Right-hand boundary corresponded to over-correction.
- Gains producing physiological center-of-mass trajectories were a small subset of stable gains.
- Simulation predicted reduced sets of stable gains based on perturbation magnitude and foot lift-off.

### Relative stability predicted stepping in subjects




Stability boundaries of narrow (orange), preferred (blue), wide (red), gain margins (color field) and predicted stepping boundary (white line ≈ 0.3g) are plotted for a single subject. White dots represent fitted feedback gains for each trial.

- Subjects' feedback gains from experiments were within stable boundaries (gain margin ≥ 1.85).
- Analytical relative stability (gain margin) matched simulated feet-on-ground threshold.
- Subjects' relative stability was similar across all stance widths.
- Position and velocity feedback gains scaled proportionally across stance widths ($k_p \approx 4k_v$).

## Conclusions

Increasing stance width reduces the effective inertia, so less torque is required to move the model. Changes in mechanical properties and delayed feedback result in gains that do not fully overlap for different stance widths. This suggests that using a single set of gains across stance widths could lead to instability. The reduced gain space in wide stance may explain Parkinson's patients preference for narrow stance, since they do not modulate muscle activity when stance width is changed (Kim 2009).

The four-bar linkage allows for detecting foot lift-off. Specifying a non-stepping criterion reduces the set of stable gains based on perturbation magnitude. This criterion is neglected in inverted pendulum models of both frontal- and sagittal-plane balance control. Utilizing this criterion may explain transitions to stepping behavior in both planes.

The model was capable of matching observed center-of-mass kinematics in healthy subjects. The delayed feedback gains for the model decreased as stance width increased. As predicted, gain margin was closely related to the foot lift-off boundary. Fitted gains were found to have similar gain margins across stance widths and be more stable than those associated with foot lift-off. Gain margin may therefore be a useful analytical predictor of step transitions and postural stability without the need for simulation.

**Key points**

- Wide stance is destabilizing without adjustment to delayed neural feedback.
- Non-stepping behavior constrains set of stable gains.
- Gains must decrease as stance width increases in order to maintain balance.
- Gain margin predicts non-stepping behavior for different perturbation magnitudes.