A Feedback Model Predicts Changes in Postural Responses as Stance Width Increases

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Background

Is standing with a wide stance more stable? If we were static objects this would be the case, however our postural stability depends upon a nonlinear musculoskeletal system and delayed neural control. Interaction between the nervous system and musculoskeletal configuration has been observed experimentally. In healthy subjects, muscle activity in response to postural perturbations decreases as stance width is increased (Henry 2001) but in Parkinson's patients, this modulation is absent (Dimitrova 2004). 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, to investigate the effects of altered stance width on delayed feedback gains, we studied a four-bar linkage model stabilized by delayed feedback.

Hypothesis: Changes to mechanical dynamics of the body from increased stance width constrain the set of stable delayed feedback gains.

Prediction: In order to maintain balance, delayed feedback gains must be decreased as stance width increases.

Methods

- **Four-bar model of medial-lateral stance with delayed feedback (Fig. 1)**
  - Geometry and inertia of links based on 1.8 m tall, 70 kg adult male.
  - Single degree-of-freedom system driven at the ankle joint, q_A (Eq. 1).
  - Torque applied as delayed angular position and velocity of hip, q_B.
  - Feedback delay of 150 ms (100 ms neural and 50 ms mechanical).

$$\mathbf{M}\left(q_A(t)\right)\ddot{q}_A(t) = \mathbf{G}\left(q_A(t)\right) + \mathbf{T}\left(q_B(t-\tau), \dot{q}_B(t-\tau)\right) \quad \text{EQ 1}$$

- **Mechanical properties determined at different stance widths**
  - Linearized about the symmetric upright configuration (Eq. 2)
  - Geometric changes to effective inertia, M_e, and gravitational "stiffness", K_e, were examined with respect to stance width.

$$M_e\ddot{q}_A(t) = K_e q_A(t) - \left(\frac{S}{W}\right)^2 \left[k_p q_A(t-\tau) + k_v \dot{q}_A(t-\tau)\right] \quad \text{EQ 2}$$

- **Analyzed stability of delayed feedback gains for different stance widths**
  - The delay-differential equation (Eq. 1) was analyzed analytically and numerically using the DDE-BIFTOOL routines written for Matlab.
  - Stability boundaries for the proportional, k_p, and derivative, k_v, delayed feedback were found
- **Found 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.
- **Compared human kinematics and EMG 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, five trials each.

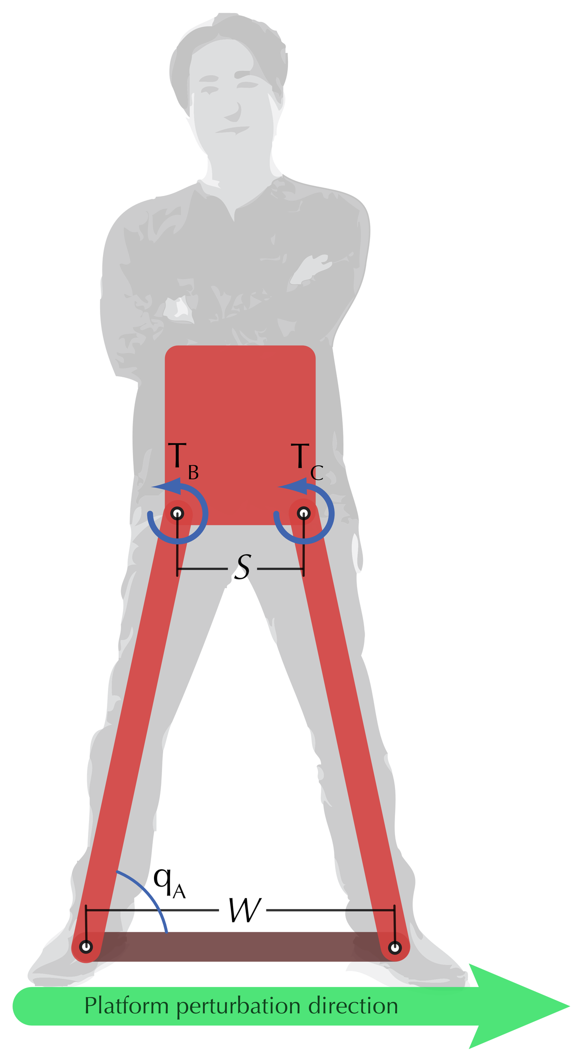

Fig. 1 - Four-bar linkage model of human stance.

Conclusions

As stance width increases the effective inertia decreases, so less torque is required to drive the four-bar linkage. This change in mechanical properties and delayed state-feedback results in ranges of stable feedback gains that do not fully overlap for different stance widths. This suggests that using a single neural control strategy at both narrow and wide stance could lead to instability.

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.

Furthermore, the model was capable of matching observed center-of-mass kinematics and trends in healthy subjects. As predicted, the delayed feedback gains for the four-bar model decreased as stance width increased. The reduction in stable gain space in wide stance may explain the preference for narrow stance widths in Parkinson's patients, who do not modulate muscle activity when stance width is changed (Kim 2009).

Key points

- Wider stances are less stable for large gain on delayed feedback
- Non-stepping behavior constrains set of stable gains
- Gains must decrease as stance width increases in order to maintain balance

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 reduces passive resistance to rotation

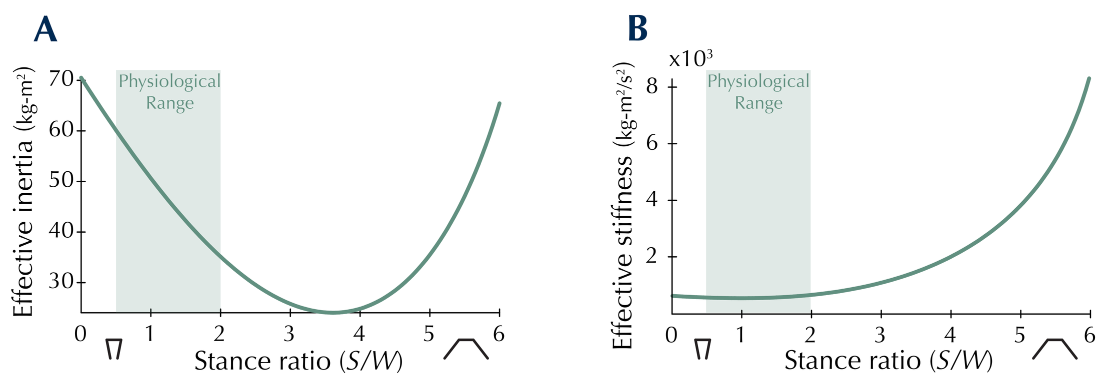

Fig. 2 - Stance width effects on A) inertia and B) gravitational "stiffness". Shaded region marks physiological stance ratios.

- Physiological ratios of stance width (S) to hip width (W) range from 0.6-2.0.
- Effective inertia decreases with increasing stance width within the physiological range.
- Gravitational "stiffness", or toppling moment, has similar magnitude in physiological range.
- Without feedback, increasing stance width reduces effort required to rotate model.

Stable gain space decreases as stance width increases

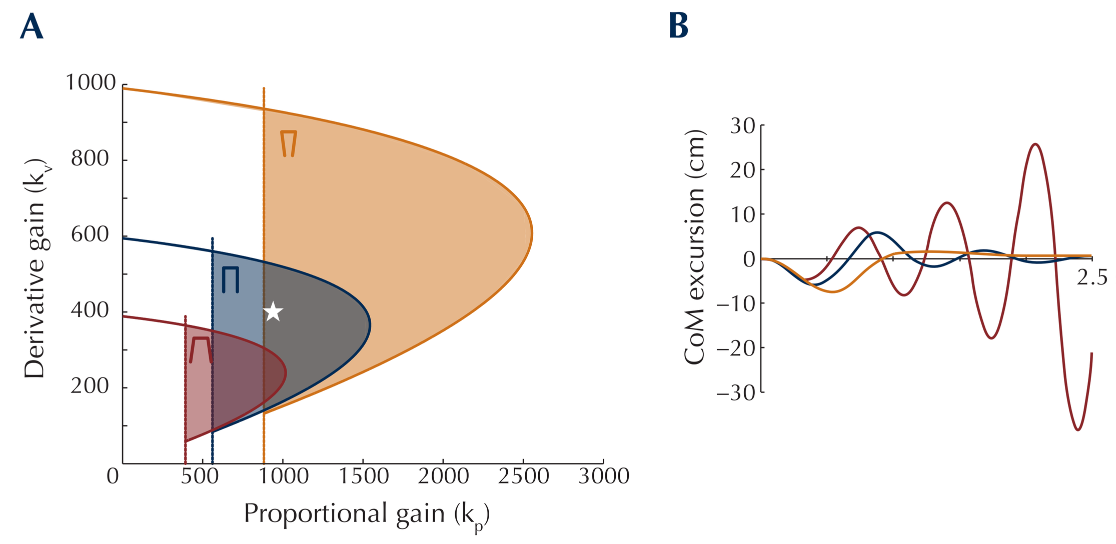

Fig. 3 - A) Shaded areas represent stable gain values for stance ratio of 0.8 (orange), 1.0 (blue) and 1.2 (red). B) Center-of-mass trajectories for each stance-ratio and same gain value, marked as white star in gain space.

- Wider stance width has smaller stable gain space.
- Narrow stance is stable for high gain.
- Maximum and minimum values of stable gain decrease as stance width increases.
- Non-overlapping regions of stable gain can lead to instability when changing stance width.

Gains associated with physiological behavior are a subset of stable gains

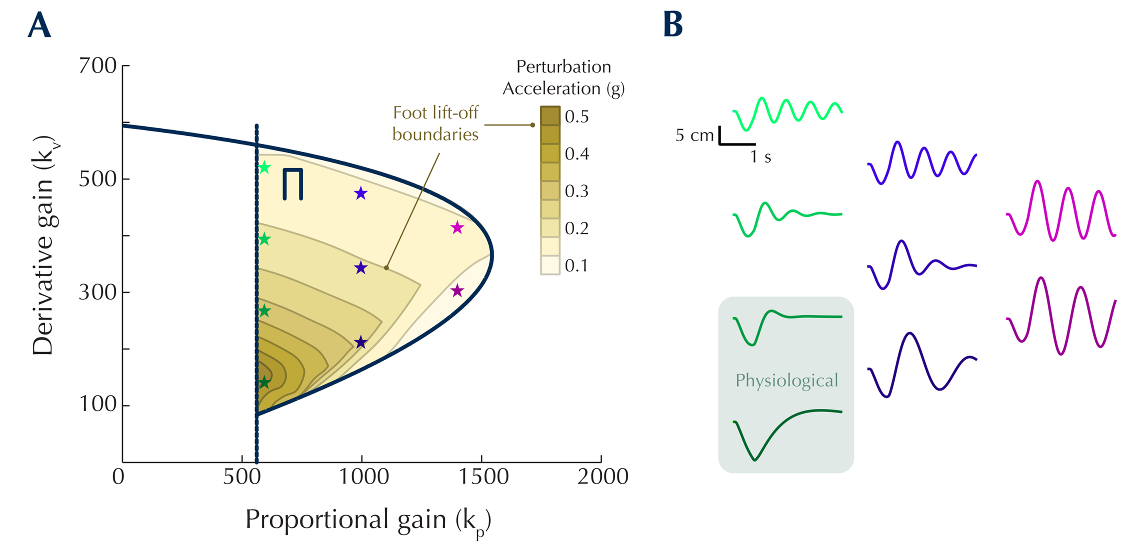

Fig. 4 - For a stance ratio of 1.0 A) Blue line is stability boundary, shaded areas are non-stepping gains B) Center-of-mass trajectories from 0.5 g perturbation. Color corresponds to starred gain pair. Physiological trajectories are in shaded box.

- Left-hand boundary instability corresponds to gravitational toppling moment.
- Right-hand boundary instability corresponds to over-correction.
- Gains producing physiological center-of-mass trajectories are a small subset of stable gains.
- Forward simulations predict foot lift-off for some stable gain values.
- Increased perturbation acceleration magnitude reduces the set of stable gains associated with non-stepping behavior.

Gains decrease with increasing stance width to maintain CoM kinematics

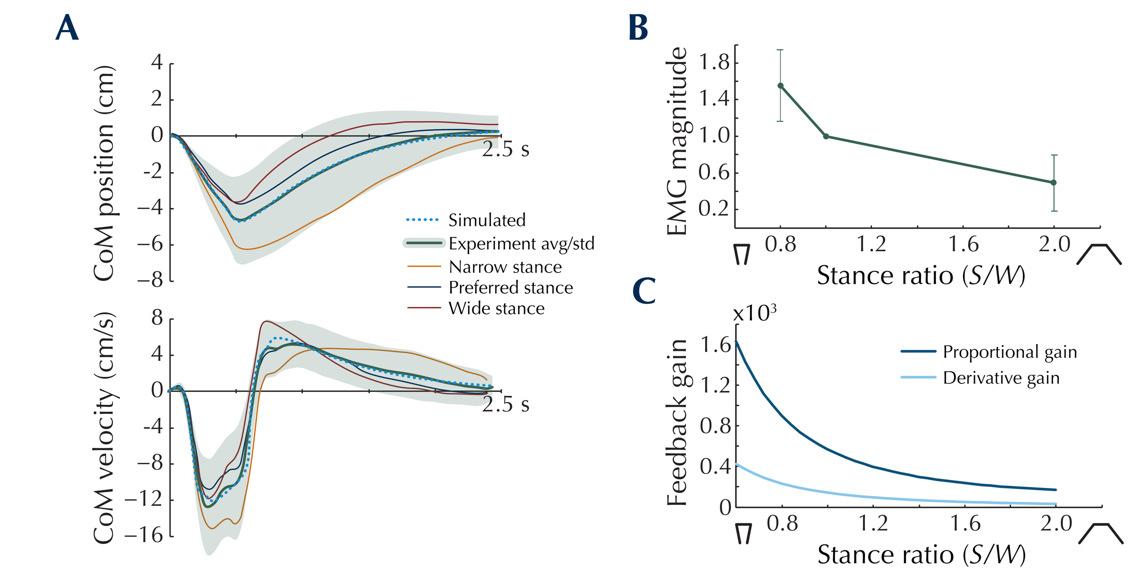

Fig. 5 - A) Experimentally measured and simulated center-of-mass trajectories. Corresponding to the average trajectory are the B) EMG average activity 100-175 ms after perturbation in *tensor fasciae latae* muscle and C) feedback gains across stance widths from simulation.

- Human subjects maintain the similar center-of-mass kinematics across different stance widths.
- Experimental data from human subjects show EMG magnitude decreases with increasing stance width.
- To maintain same center-of-mass trajectory simulated feedback gains must decrease as stance width increases.