Intermittent linearity of foot force direction vs center of pressure in quiet standing

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Introduction

Standing Balance via F control

- Maintaining upright postural control is an important component of human daily life and essential for preventing falls
- The control strategy is insufficiently understood to enable the development of appropriate rehabilitation for balance deficits
- Recently, we showed that the frequency-specific multi-joint coordination used to stand exhibits coordination yielding ground-on-foot force (*F*) with an intersection point (IP)[1] (Fig. 1)
- The IP height (*zIP*) varies with frequency; above the CM for f<1.75 Hz and below the CM for f>1.75 Hz (Fig. 3)

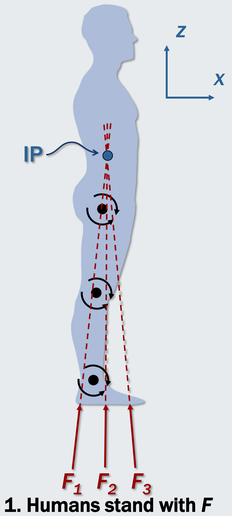

Figure 1. Humans stand with *F* vector changes ($F_{1\text{-}3}$) that exhibit an intersection point (IP), with height that varies with frequency[1] (Fig. 3).

Background

- Postural control involves sensing body posture and enacting muscular responses in a time-appropriate manner.
- In the sagittal plane the body consists of multiple linked segments that will not remain upright without muscular forces that produce torques at each joint (primarily ankle, knee, and hip).
- The multi-segmental nature of this mechanical linkage has infinite fall modes. Posture can deviate from upright in various distinct manners. Two distinct examples are pivoting only at the ankle ('falling like a board') and opposite angular motion of adjacent segments ('collapsing in a heap').
- Those fall modes have distinct kinematic motions and distinct inertial properties. Thus, each mode requires a distinct muscle coordination and temporal response.
- The force of the ground on the feet *(F)* is the net effect of the numerous muscles recruited.
- *F* change patterns quantify the complexity of standing control and may be useful for rapid and efficient diagnosis of balance disorders as well as tracking recovery.

Questions

- We test two hypotheses during quiet standing in non-disabled humans:
  1) Intermittent episodes[3] of foot-force change exhibit IP behavior
  2) *zIP* varies with duration of *xCP* change

Methods

- 87 young adults (18-59 years, 56 female, median 28 years)[2]
- Stood quietly: each for 3 60s trials
- 6-axis force plate (100Hz)
- Calculate anterior-posterior center-of-pressure (*xCP*) & force ratio (F_x/F_z) (Fig. 2)

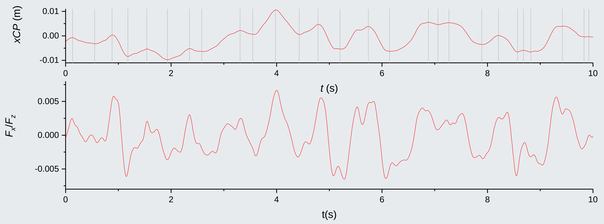

Figure 2. Time windows segmented at d(*xCP*)/dt=0.

- **Band-pass Method**[1]: band-pass filtered *xCP* and F_x/F_z in 0.2Hz non-overlapping intervals from 0–6Hz (2nd order zero-lag Butterworth), PCA of *xCP* vs F_x/F_z (Fig. 3) calculated *zIP* for each frequency band
- **Intermittent Method**: *xCP* velocity zero-crossings segmented time windows of intermittent control (Fig. 2), PCA of *xCP* vs F_x/F_z (Fig. 3) calculated *zIP* for each window, window duration (*dt*) converted to 'frequency' = 1/(2*dt*)
- Used *zIP* for windows with Variance-Accounted-For > 90%. Student's t-test (with Bonferroni correction) to infer *zIP* differences between two methods.

Discussion

- Standing requires humans to coordinate ankle, knee, & hip muscles to arrest infinite fall modes
- Those fall modes are associated with varying amounts of whole body acceleration (Fig. 4), both translational acceleration of the center-of-mass (CM) and rotational acceleration of the whole body
- The emergence of an IP is likely the product of linear covariation of joint torques, analogous to muscle synergies or motor primitives[4]
- An *IP* is present and *zIP* varies with 'speed' for **both** brief time periods (Intermittent) **and** on average over long times (Band-pass)
- Correlation with 'speed' may be a tuning to the mechanical impedance of the fall modes
- *zIP* useful for diagnosis of balance disorders

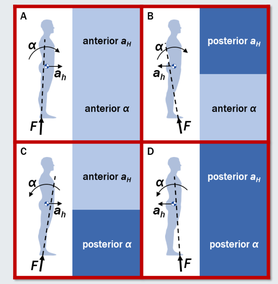

Figure 4. Coordination of joint torques determines the *F* that produces the various amounts of angular & translational accelerations of the whole body required to stop all fall modes.

Results

- Human muscle coordination during quiet standing produces ***a* highly stereotypical pattern** of variation in *F* (Fig. 3)
- That pattern can be characterized as a linear change in F_x/F_z with respect to *xCP* (Fig. 3 left panels)
- 80% of windows had VAF>90%
- Linearity viewed as IP
- *zIP* varies with *dt* (Fig. 3, upper panels) and frequency (Fig. 3 lower left,)
- *zIP* similar for both methods but higher for Intermittent > 1.75 Hz (Fig. 3, right column)

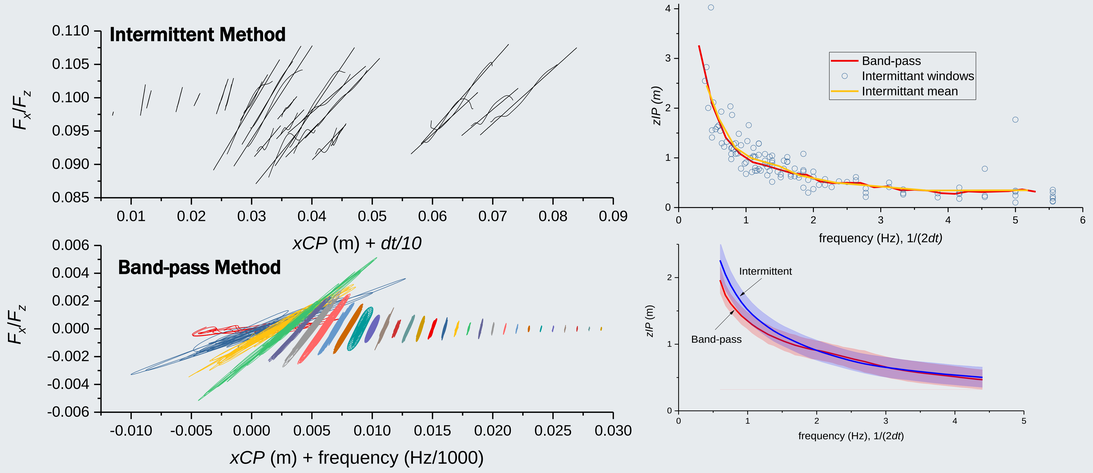

Figure 3. Linearity of F_x/F_z with respect to *xCP* (10s of trial in upper left panel with PCA lines, full trial lower left panel) consistent with IP (Fig. 1). Slope =1/*zIP*. Both methods give similar *zIP* variation with duration (Intermittent) or frequency (Band-pass) (1 full trial, upper right). zIP is similar for both methods but Intermittent is slightly higher at frequencies below 1.75 Hz (all trials mean ± standard deviation, lower right).

References

1. Boehm, Wendy L., Kieran M. Nichols, and Kreg G. Gruben. "Frequency-dependent contributions of sagittal-plane foot force to upright human standing." *Journal of biomechanics* 83 (2019): 305-309.
2. Santos, Damiana A., and Marcos Duarte. "A public data set of human balance evaluations." *PeerJ* 4 (2016): e2648.
3. Suzuki, Yasuyuki, et al. "Intermittent control with ankle, hip, and mixed strategies during quiet standing: a theoretical proposal based on a double inverted pendulum model." *Journal of Theoretical Biology* 310 (2012): 55-79.
4. Singh, Rajat Emanuel, et al. "A systematic review on muscle synergies: From building blocks of motor behavior to a neurorehabilitation tool." *Applied bionics and biomechanics*2018 (2018).

Acknowledgements

Conflict of Interest: K Gruben has an ownership interest in KIINCE LLC which develops rehabilitation technology. K Gruben & K Nichols have filed a US patent application related to this methodology.

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