Adaptive gait: Lower-limb Joint-angle Variance as a Function of Obstacle Height

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INTRODUCTION

- Tripping while walking is a main contributor to falls.
- Trail foot (Fig.1) contacts are more frequent (67-100% of all contacts).
- The swing-foot toe is the endpoint of the lower-limb-segment chain (foot, shank and thigh of both the stance and swing limbs, and pelvis) with multiple angular degrees of freedom [1].
- Variability structure of the input variables provide insights into control properties; examination of merely the average endpoint does not [2].

PURPOSE

To (a) quantify the toe-height variability when crossing obstacles of different heights, and (b) investigate the source of the toe-height variability by examining the lower-limb joint-angle variance.

METHODS

- 10 young adults (age: 23.8±3.4 years, 3 females).
- 15 m walkway, obstacle (unobstructed, 3, 10, and 26 cm), 10 trials.
- Toe height and bilateral ankle, knee, hip joint flexion-extension angles isolated at two gait events in each trial
  - Unobstructed trials: time of minimum toe height of each foot.
  - Obstacle trials: time when lead toe is over the obstacle (lead-toe frame) and trail toe is over the obstacle (trail-toe frame, **Fig.1**).

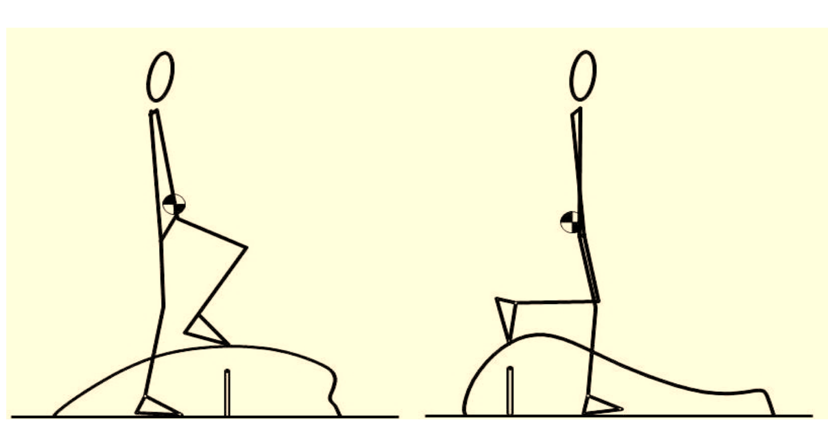

Fig. 1 *Lead-toe crossing frame (left) and trail-toe crossing frame (right)*

- Outcome measures (computed across trials)

(1) Toe-height variability: standard deviation of toe height.
(2) Total joint-angle variance: sum of the variances of all six joint angles.
(3) Joint-angle variances in stance and swing limb: the sum of the variance in the joint angles of each limb.
(4) Individual joint angle variance: variance of joint angle.

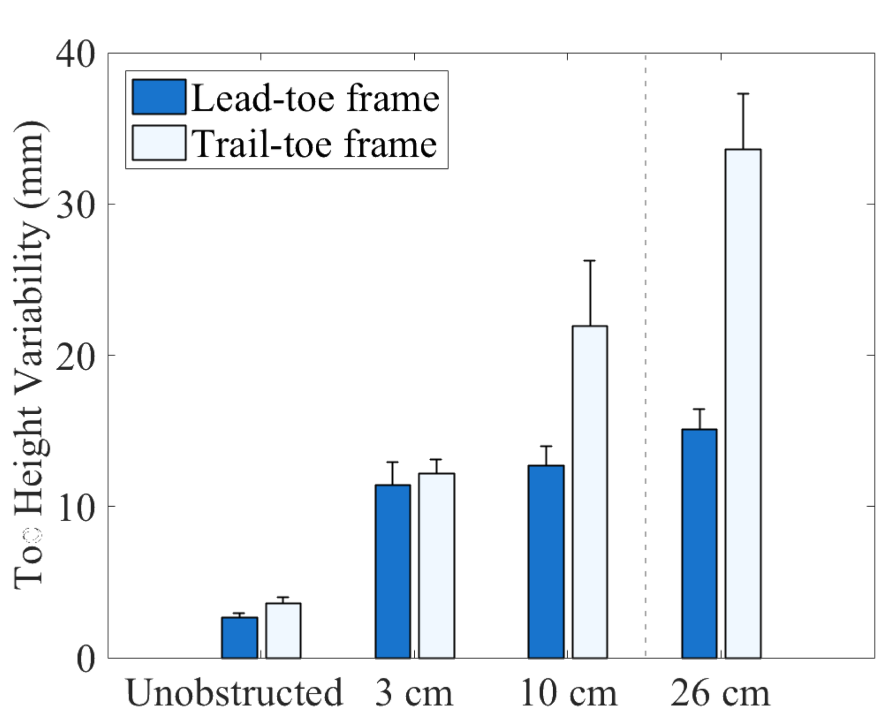

Fig. 2 *Effect of obstacle height and crossing frame for toe height variability. Data for 26-cm obstacle shown but not included in statistical analysis due to obstacle contacts. Error bar indicates the standard error.*

RESULTS

Obstacle contact

Six subjects contacted the obstacle once, all with the 26 cm obstacle. Contacting the obstacle modifies foot trajectories in subsequent trials [3], so the 26-cm obstacle condition was excluded from statistical analyses resulting in three height conditions (unobstructed, 3 cm, 10 cm).

Toe-height variability

A significant *Crossing frame × Obstacle condition* interaction was observed (**Fig.2**; p=0.04). Post hoc analyses revealed the following:

- Trail toe-height variability was 72% higher than lead-toe variability, but only for the 10-cm obstacle (p<0.01).
- Lead toe-height variability was higher for the obstacle conditions than unobstructed walking.
- Trail toe-height variability was 237% higher for the 3-cm obstacle than unobstructed walking (p<0.01) and 79% higher (p<0.01) for the 10-cm than the 3-cm obstacle.

Total Joint-angle Variance

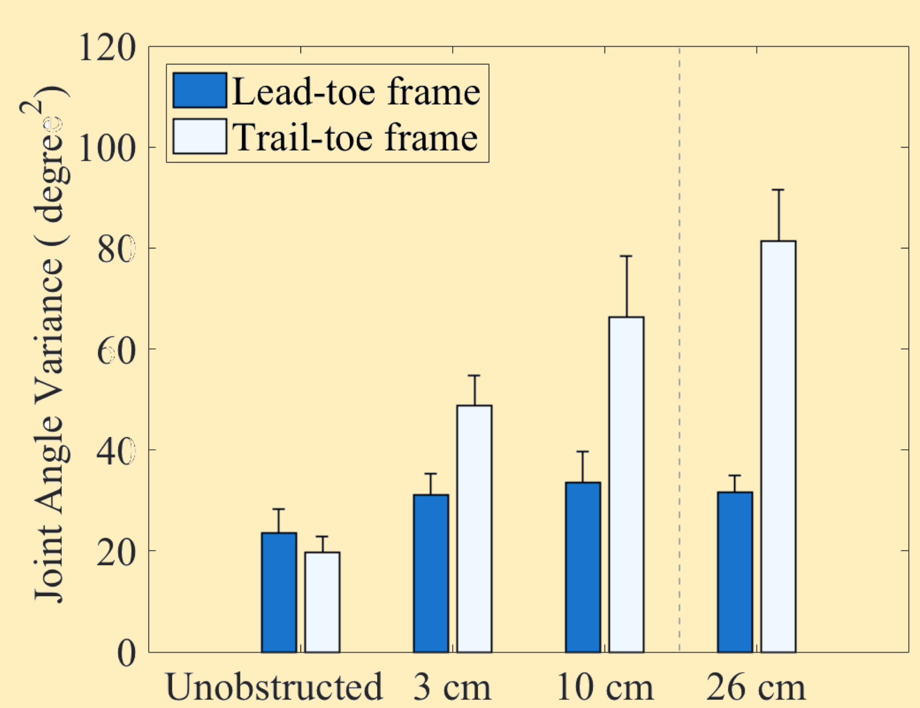

Fig. 3 *Effect of obstacle height and crossing frame for total joint-angle variance. Data for 26-cm obstacle shown but not included in statistical analysis due to obstacle contacts. Error bar indicates the standard error.*

A significant *Crossing frame × Obstacle condition* interaction was observed (**Fig. 3**; p=0.01). Post hoc analyses revealed the following:

- Larger total joint-angle variance for trail-toe frame than that for lead-toe frame (98% higher), but for 10-cm obstacle only (p<0.01).
- No significant obstacle-height effect on total joint-angle variance for the lead-toe frame.
- Total joint-angle variance increased 164% for the 3-cm obstacle (p<0.01) and 259% for the 10-cm obstacle (p<0.001) compared with unobstructed walking for the trail-toe frame.

In summary, higher toe height variability generally corresponded to higher total joint-angle variance, consistent with the idea that total joint variance prescribes toe variability.

However, while both toe-height variability and joint-angle variance for the trail-toe frame increased with obstacle height, only toe-height variability increased for the lead-toe frame. We plan to determine if the joint angles co-vary to control the variability in the toe height.

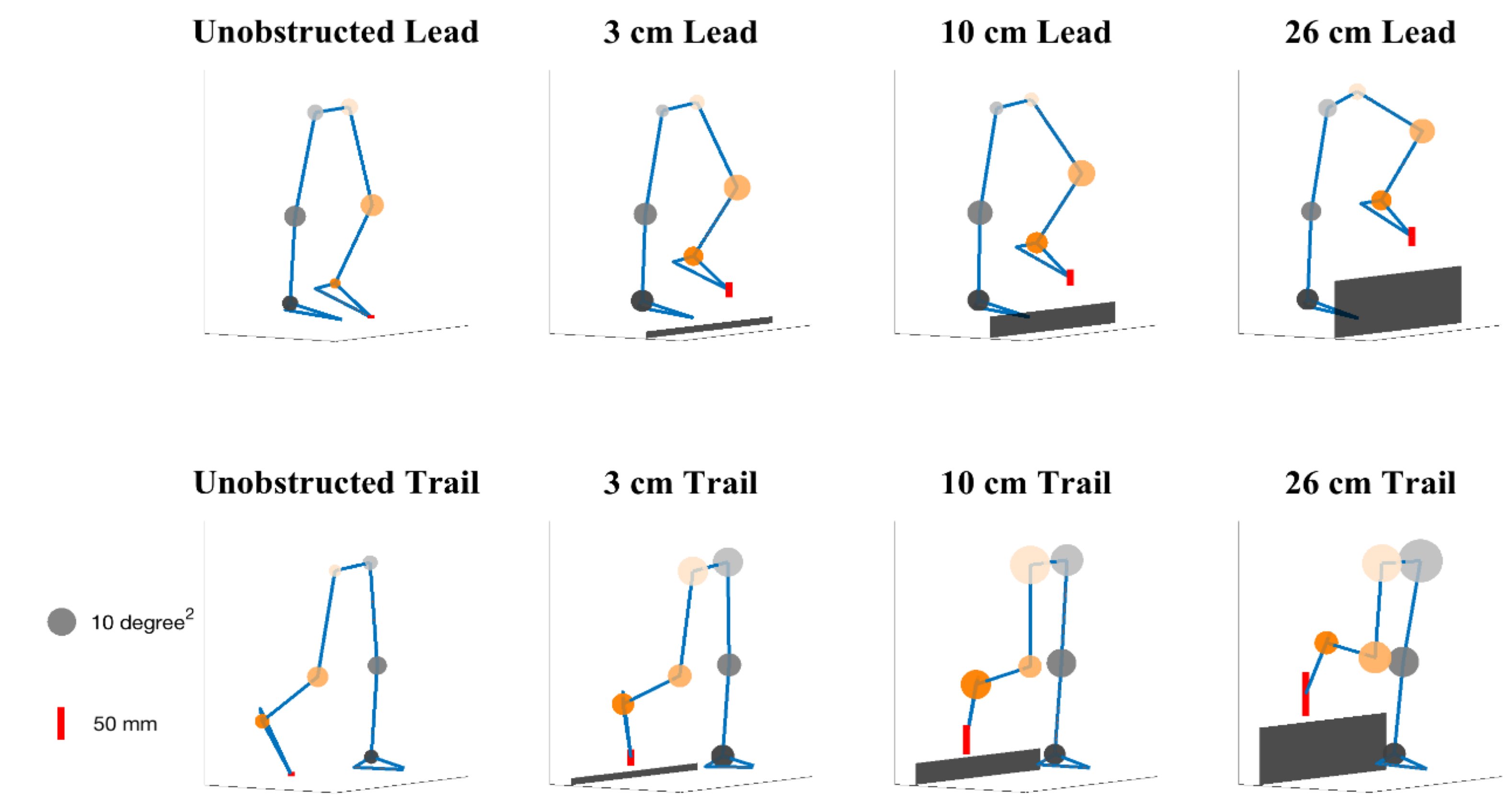

Fig. 4 *Toe height variability and individual joint-angle variance. Length of the red bar proportional to toe height variability. Area of circle proportional to joint-angle variance. Black rectangles are obstacles.*

Stance vs. Swing Joint-angle Variance

No significant difference between joint-angle variance from stance and swing limb, indicating that both limbs impact toe height variability.

Individual Joint-angle Variance

A significant *Obstacle height × Crossing frame × Joint* interaction was observed. Post hoc analyses revealed the following:

- Stance hip (p<0.001), swing hip (p<0.001) and swing ankle (p=0.05) angle variances were higher for trail-toe frame than lead-toe frame.
- Joint-angle variance was not affected by obstacle height for the lead-toe frame.
- Several joint-angle variances increased as obstacle height increases for trail-toe frame.

CONCLUSION

- Larger toe variability and total joint variance for the trail limb, especially for taller obstacles, are consistent with more failures for the trail limb and for higher obstacles [3].
- The joint angle variances are distributed over the joints of both the swing and stance limb, indicating that the contribution of the stance limb to obstacle contacts must be considered.
- Similar amount of joint-angle variance from swing and stance limbs suggests existence of compensatory covariance in the lower limb joint angles to control toe height.
- Further investigation into coordination between multiple joints of both limbs is necessary.

REFERENCES

[1] Winter, *Phys Ther,* 1992.
[2] Latash et al., Exerc. Sport Sci, 2002
[3] Heijnen et al., *Exp Brain Res*, 2012.

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