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Modulation of foot placement during landings from different jump lengths

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1. Introduction

Foot placement is essential for maintaining balance during human movements (Bruijn & van Dieën, 2018). Precise foot placement modulates the whole-body centre of mass (WBCoM) acceleration in proportion to the distance between the WBCoM and the centre of pressure. This strategy is key to decelerating the WBCoM when transitioning from movement to posture (Bechet, Tisserand, Fradet, & Colloud, 2025).

Models such as the extrapolated centre of mass (XCoM) can be used to predict the foot position relative to the WBCoM required to reach a postural state (Hof, 2008). However, they have been tested mainly during steady-movements such as gait (Bruijn & van Dieën, 2018) and not under more constrained circumstances. Thus, it remains unknown to what extent these models are valid.

Jump landing represents a good experimental paradigm to test the importance of foot placement for balance. First, during landing, foot placement is crucial because no other mechanism can reduce the WBCoM velocity during the air time. Thus, inadequate foot placement may provoke more muscular adjustments during ground contact. Second, jump landing represents a situation where participants must decelerate to transit from movement to posture, without taking any extra step, representing the assumptions of foot placement models. Third, the antero-posterior (AP) velocity of the WBCoM can be adjusted with jump length. We can thus

expect a linear increase in foot placement relative to the WBCoM with increase in jump length, to enhance AP WBCoM deceleration upon contact, according to the xCoM model. However, this assumption that has not been tested yet represented the aim of the study. Here, we characterised the relationship between foot placement and AP WBCoM velocity during landings from different jump lengths, in comparison with the conventional model used in gait.

2. Methods

2.1 Participants and Procedure

All data were extracted from an open source dataset (Westermann, Lin, & Kulić, 2020). Twenty healthy participants (8 females, 25.8 ± 3.58 years old, 1.71 ± 0.10 m, 66.3 ± 13.2 kg) were equipped with 30 reflective markers. First, they performed maximal long jump with arm motion: they jumped as far possible from a quiet upright posture, landed with the two feet simultaneously and parallel without taking extra steps, and returned to the same initial upright posture. Then, they jumped with the same instructions 12 times on each target placed at 50, 70 and 85% of their maximal jump length. Three dimensional markers trajectories were recorded at 200 Hz.

2.2 Data and Statistical analysis

Marker trajectories were already lowpass filtered by the authors at 6 Hz and used to create a 12 segments

whole-body model (excluding hands and head). Segments centre of mass were computed according to anthropometric tables and used to compute the WBCoM as the weighted sum of segment positions. The WBCoM velocity was computed as the first derivative of the WBCoM. The take-off and landing events were determined when the vertical WBCoM velocity was maximal and minimal, respectively.

The AP distance between the WBCoM and the averaged midpoint between the first and fifth metatarsal markers was computed because it approximates the centre of pressure position during the beginning of contact. This distance was normalized by the lower-limb length of each participant, to be unitless. We tested the correlation of Pearson between this distance and the AP WBCoM velocity during air-time, and reported the linear equation of the relationship. XCoM was computed to compare with the recorded foot placement, and was also made unitless (lower-limb length of 1).

3. Results and discussion

We found a significant positive correlation between the AP WBCoM velocity during air-time and the position of the mid metatarsal markers at contact ($r = 0.64$, $p < 0.001$, Figure 1).

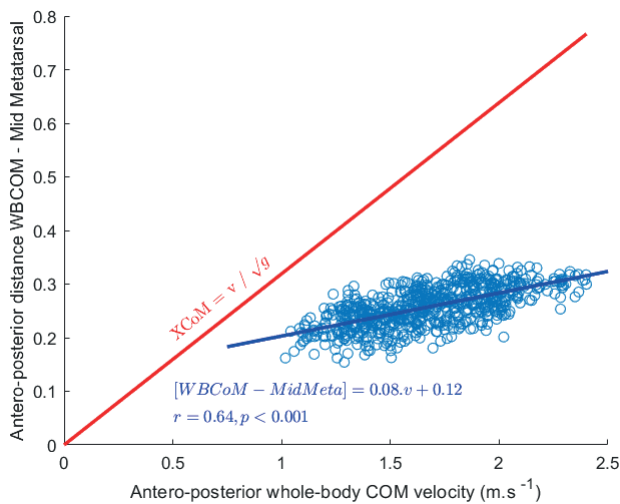


Figure 1. Relationship between foot placement, characterised by the distance between the WBCoM and the mid metatarsal, and the AP WBCoM velocity, in blue. The red line represents the XCoM for the corresponding AP WBCoM velocity.

Credit: Romain Bechet

As expected, the foot was placed further from the WBCoM as the AP WBCoM velocity increased, suggesting that WBCoM velocity is already considered during the air-time period to modulate the anticipatory kinematic adjustments (Bechet, Tisserand, Fradet, & Colloud, 2024). This increased distance enables to increase the WBCoM deceleration required to transit from movement to posture, and maintain balance. Further studied should asses how joints are coordinated to appropriately place the foot.

The difference between the recorded foot placement and the XCoM model increased as the AP WBCoM velocity increased. It is not known whether the increase in difference comes from the addition of a downward velocity not considered in the XCoM model, and/or the fact that humans cannot place their feet further away while satisfying a proper foot orientation at contact. Our results still suggest that contribution of muscle force to decelerate the WBCoM increases as the AP WBCoM velocity increases, complementary to foot placement.

4. Conclusions

We characterised a linear relationship between foot placement and WBCoM velocity during landing from different jump lengths, enabling to decelerate and transit to a postural state. The linear relationship was different than the one from the XCoM model. Further research is needed to clarify this relationship during a larger range of velocity.

Conflict of Interest Statement

All authors disclose any financial and personal relationships with other people or organisations that could inappropriately influence this work.

Contributor Roles

RB: Conceptualization, Formal Analysis, Writing-original draft, Writing-review & editing; RT: Validation, Writing-review & editing; LF: Validation, Writing-review & editing; FC: Validation, Writing-review & editing.

Data availability

The dataset can be downloaded at <https://www.nature.com/articles/s41598-020-67901-x#Sec20>

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