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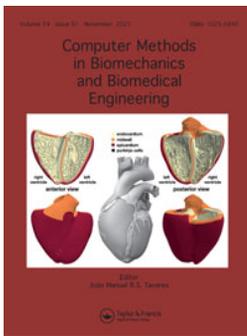
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# Intermittent mechanical actions completing inverted-pendulum-like actions for standing balance in humans

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## 1. Introduction

The control of upright standing balance is challenging for humans because it requires to maintain the whole-body Centre of Mass (CoM) high above a small Base of Support (BoS). This can be achieved using different complementary strategies, such as the ‘ankle’ and ‘hip’ strategies (Horak and Nashner 1986). These strategies were classically characterized by muscle activation patterns and/or overall body kinematics (whole-body rotation around the ankle and/or counter rotation of lower-limbs and trunk around the hips). However, these descriptions do not relate to the strategy's mechanical effects on balance.

By describing the mechanics of balance recovery strategies in absence of an additional external force, Hof (2007) classified standing balance control actions in two main categories: 1) those implying to shift the center of pressure (CoP) within the BoS, which are particularly well predicted by an inverted pendulum (IP) model, and include the ‘ankle’ or the ‘ankle and hip loading/unloading mechanisms’ (Winter 1995); 2) those implying additional variations of the horizontal ground reaction forces (GRF), typically caused by angular accelerations of segments, such as the ‘hip strategy’ or tightrope walkers rotating their arms.

Although interesting, these mechanical principles have rarely been applied to characterize standing balance control in situations differing from unperturbed quiet standing. For instance, standing on one foot challenges balance considerably as it reduces the size of the BoS. This configuration decreases the possibility to use reactions of the 1<sup>st</sup> category (‘IP-compliant’), and forces humans to rely more on the 2<sup>nd</sup> category (‘non IP-compliant’) to maintain balance.

We used simple mechanical modelling to distinguish between the two types of mechanical actions to characterize balance control in different standing configurations. We hypothesized that ‘IP-compliant’ strategies would be used primarily for quiet standing and

relatively slow swaying motion, whereas ‘non IP-compliant’ strategies will be used intermittently, to complete overall mechanical actions when the ‘IP-compliant’ mechanisms are not sufficient to maintain standing balance.

## 2. Methods

### 2.1. Participants and procedure

Eight healthy young adults (3 females, 28 ( $\pm$ 9) years old, 174.5 ( $\pm$ 10.8) cm, 69.7 ( $\pm$ 13.1) kg) performed five different trials where they were asked to maintain an upright standing posture for 60s: (1) standing with feet at hip width, arms at the side, and eyes open; (2) same as 1 with eyes closed; (3) swaying voluntarily in the sagittal plane around the ankles axis (frequency  $\simeq$  0.3 Hz); (4) same as 3 but with an anti-phase rotation around the hip and (5) standing on one foot, arms at the side, with eyes closed. Conditions 3 and 4 were chosen to mimic the kinematics of an ‘ankle’ and a ‘hip’ strategy, respectively. Condition 5 was chosen to reduce the BoS size in the mediolateral direction and limit the possible CoP shifts in this direction. In all trials, participants stood barefoot on a Bertec forceplate recording GRF and moments at 1000 Hz.

### 2.2. Data analysis

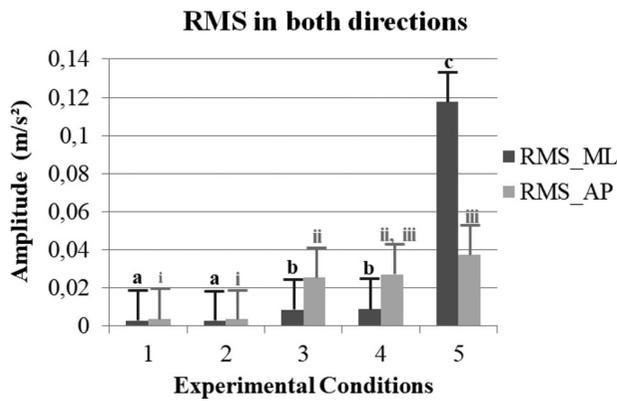
Forceplate data were low-pass filtered (Butterworth, 1<sup>st</sup> order, 20 Hz cut-off frequency) and only 30s of data from each trial were used in the analysis (Hof 2007). Accelerations of the whole-body CoM in the transversal plane were estimated from the GRF using two different methods:

1. From the horizontal forces (Newton's second law).
2. Assuming that the participant's whole-body behaves like an IP: trajectory of the CoM was first estimated by low-pass filtering the CoP trajectory (Hof 2005; Lafond et al. 2004) and CoM accelerations were then computed from the dynamics of an IP model (Winter 1995).

$$a_{IP} = \omega^2 (COM - COP)_0 \quad (1)$$

where  $\omega_0 = \sqrt{g/h}$  where  $g$  is the gravitational constant and  $h$  is chosen as 110% of the estimated height of the COM with respect to the ankles (Hof 2007).

CoM acceleration computed from the two methods were compared using the root mean square (RMS). RMS medians were first compared using a Kruskal Wallis test, with ‘condition’ as factor. Wilcoxon tests were performed as *post-hoc* to compare individual condition with each other. The level of significance was set at 0.05.



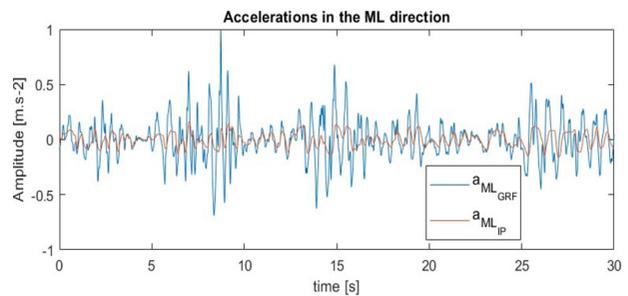
**Figure 1.** RMS results through conditions. Conditions not connected by the same letter (ML) or the same roman number (AP) are statistically different.

### 3. Results

The factor ‘condition’ had a significant effect on the RMS on both Anterior-Posterior (AP) and Medio-Lateral (ML) directions (both  $p < 0.001$ , Figure 1). The RMS was minimal in condition 1 and 2 and no statistical differences were observed between them in both directions. RMS in conditions 3 and 4 were similar in both directions, and larger than in condition 1 and 2, but remained relatively small (about 5 to 6% of the acceleration amplitude). RMS in condition 5 was always significantly superior to all other conditions (except with the condition 4 in the AP direction), and particularly high in the ML direction (about  $10\times$  higher than all other ML conditions). A typical example of CoM accelerations estimated with both methods in condition 5 is displayed below (Figure 2), where we can see the intermittent actions not predicted by the IP model.

### 4. Discussion

The RMS results reflect the relevance of the IP hypothesis: a small RMS indicates the whole-body dynamics are nicely captured by a single IP model and therefore that balance control is mostly driven by ‘IP-compliant’ strategies (*i.e.* CoP shifts within the BoS). Conditions 1 and 2 (quiet standing) displayed very small RMS, which is in line with previous research showing that the whole-body dynamics can be correctly captured with an IP model during quiet standing (Lafond et al. 2004; Hof 2007). The small RMS increase in condition 3 and 4, compared to conditions 1 and 2, and the absence of statistical difference between them suggest humans still behave like an IP when they are instructed to reproduce the kinematics of both the ‘ankle’ and ‘hip’ strategies proposed by Horak and Nashner (1986). This highlights the limits



**Figure 2.** Example of CoM acceleration computed with Newton’s law (blue) and simple IP (red) methods for one participant in condition 5 (one-foot standing).

of describing only the kinematics of a balance recovery strategy, particularly for the ‘hip strategy’, which is generally assumed to be a ‘non-IP compliant’ strategy relying on acceleration of rotating segments. Condition 5 was the most difficult condition for balance control, because the BoS surface was reduced to a minimum (one foot), limiting the use of ‘IP-compliant’ strategies. In this condition, ‘non-IP compliant’ balance strategies (accelerations of rotating segments) were observed intermittently (Figure 2), and particularly in the direction where the BoS has been reduced the most (in the ML direction here).

### 5. Conclusions

Our study suggests approaching standing balance control through analysis of its dynamics can better illustrate which type of strategy is being used compared to a kinematic description. Humans undertake ‘IP-compliant’ mechanical actions during both quiet standing and voluntary oscillations, whereas their ‘non IP-compliant’ mechanical actions are highlighted by important mechanical constraint imposed to their whole-body. Further research is necessary to quantify the proportion of ‘non IP-compliant’ actions for standing balance control.

### Disclosure statement

No potential conflict of interest was reported by the authors.

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**KEYWORDS** Standing balance; inverted pendulum; strategy; center of mass

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