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Short communication

Centre of pressure or centre of mass feedback in mediolateral balance assessment

L. Eduardo Cofré Lizama [a], Mirjam Pijnappels [a], N. Peter Reeves [b], Sabine M. Verschueren [c], Jaap H. van Dieën [a,*]

[a] MOVE Research Institute Amsterdam, Faculty of Human Movement Sciences, VU University Amsterdam, The Netherlands
[b] College of Osteopathic Medicine, Michigan State University, USA
[c] Department of Rehabilitation Sciences, Faculty of Kinesiology and Rehabilitation Sciences, Katholieke Universiteit Leuven, Leuven, Belgium

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ABSTRACT

The mediolateral balance assessment method (MELBA) consists of tracking a sinusoidal or multisine target with the center of pressure as feedback (CoP_{fb}). The aim of the CoP trajectory is to elicit weight-shifting, i.e. movement of the center of mass (CoM). However, it is not known whether CoP_{fb} elicits consistent mediolateral displacements of the CoM, whether CoM feedback (CoM_{fb}) is required to achieve this and whether CoP_{fb} or CoM_{fb} elicit different kinematic strategies.

The aims of this study were to determine (1) the extent to which CoP imposes CoM displacements (CoM_d) during CoP_{fb}, (2) whether larger CoM_d are elicited by CoM_{fb} and (3) whether different kinematic strategies arise when using CoP_{fb} or CoM_{fb}. Nineteen young adults performed MELBA with CoP_{fb} and CoM_{fb} from which coherence, gain and phase-shift between CoP–CoM and leg–trunk kinematics were calculated. CoM_d and CoP_d and leg and trunk excursions were also calculated.

Results show that for CoP_{fb} tasks, CoP–CoM coherence was high, while the gain dropped with increasing frequency. The drop in gain was highly consistent between subjects. Reasonable trunk–leg coherence ($\approx$.6) was found over all frequencies and tasks. The leg–trunk angle gain increased with frequency in all tasks and was significantly higher in the CoM_{fb} compared to the CoP_{fb}. Significant interaction indicated that this difference increased with frequency.

CoP_{fb} in MELBA elicits consistent CoM_d. However, different kinematics are employed in CoM_{fb} with more trunk movement and an ankle-to-hip shift as frequency increases. Hence CoM_{fb} may be preferable over CoP_{fb} despite the larger measurement effort involved.

1. Introduction

Impairments of balance in the mediolateral (ML) direction, reflected in inabilities to correctly shift weight and in impaired stepping responses are of special interest since these are associated to an increased number of falls (Mille et al., 2013; Robinovitch et al., 2013). Recently a mediolateral balance assessment method based on tracking of predictable and unpredictable target signals with the center of pressure (CoP), coined MELBA, has been proposed (Cofré Lizama et al., 2013). MELBA characterizes balance control through the phase-shift (PS) and gain (G) between the CoP and a target signal that moves mediolaterally under a predictable (sinusoidal) or unpredictable (multisine) pattern. From these measures the frequency at which PS and G drop below a predefined threshold and the averages within the bandwidth defined by these frequencies are calculated. The method was shown to be reliable and did not show ceiling effects, not even among young adults (Cofré Lizama et al., 2013).

During locomotion, transitions and standing, stability of the CoM has to be maintained through voluntary and reflexive motor commands to avoid falling (Woollacott, 2000). The use of center of pressure feedback (CoP_{fb}) in balance testing therefore relies on the assumption that consistent ML-CoM displacements (CoM_d) are elicited by ML-CoP displacements (CoP_d), as the CoM is the controlled variable in balance control (Winter, 1995). Since the distance between CoP and CoM is roughly proportional to the CoM acceleration, for limited angular excursions in upright stance a consistent relationship is expected albeit with CoM_d decreasing at constant CoP_d as frequency increases (Morasso et al., 1999; Winter et al., 1998). Although CoP_{fb} during MELBA tasks can thus impose consistent CoM_d, control over CoP may not arise as intuitively as control over the CoM, hence center of mass feedback (CoM_{fb}) may be more suitable when demanding CoM_d. Furthermore, it is

* Correspondence to: MOVE Research Institute Amsterdam, Faculty of Human Movement Sciences, VU University Amsterdam, van der Boechorststraat 9, 1081BT, The Netherlands. Tel.: +31 20 5988501.
E-mail address: j.van.dieen@vu.nl (J.H. van Dieën).

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possible that CoP_{fb} and CoM_{fb} may elicit different strategies to control the CoM, which may be of utility in identifying the source of balance impairment at the effector levels. Therefore, a modified version of MELBA used CoM_{fb}. This was shown to be reliable and sensitive to age effects (Cofré Lizama et al., 2014). However, CoP feedback (CoP_{fb}) may be preferable in view of the instrumentation required.

The aim of this study therefore was to determine the extent to which CoP imposes CoM displacements (CoM_d) during CoP_{fb}, whether larger CoM_d are elicited by CoM_{fb} and whether different kinematic strategies arise when using CoP_{fb} or CoM_{fb}. The results of this study will help to improve MELBA and its utility to determine ML balance impairments in older adults.

2. Methods

2.1. Participants

Nineteen young adults (11 women and 8 men, age: 26 ± 3 years; height: 1.71 ± .09 m; weight: 67.2 ± 12 kg) participated in this study. Participants were excluded if they presented any musculoskeletal or neurological condition. This study was approved by the local Ethical Committee in accordance with the standards of the declaration of Helsinki and all participants signed informed consent.

2.2. Task and procedure

Participants performed a series of ML CoP_{fb} and CoM_{fb} tracking tasks (for set-up details refer to (Cofré Lizama et al., 2014, 2013)). CoP data were obtained using a Kistler-9281B forceplate (Winterthur, Switzerland) sampling at 60 samples/s. Body CoM was calculated with a 9-markers frontal plane model tracked with an Optotrak-Certus system (NDI, Waterloo, Canada). Gender specific CoM calculations were performed using anthropometric scaling and inertial parameters (de Leva, 1996). D-flow 3.10.0 (Motek Medical, Amsterdam, The Netherlands) was used to produce target signals as well as to record (60 samples/s) and display target and either CoP or CoM data on a screen. ML-tracking consisted of tracking a predictable or an unpredictable target signal, represented by a 11 cm white sphere projected on a screen, using the ML displacement of the CoP or CoM represented by a 9 cm red sphere.

The *predictable* task was 135 s long for which the target signal was constructed using 2 blocks of 20 s, 1 block of 10 s and 17 blocks of 5 s, each composed by one sine wave, which increased in frequency from .1 to 2.0 Hz in steps of 1 Hz. The *unpredictable* task was 132 s for which the target signal was constructed using 15 blocks composed by the sum of 6 consecutive sine waves separated by 1 Hz. A pseudorandom phase-shift between sine waves between −1 and 1 period was introduced in order to avoid predictability. After each block the lowest frequency, which started at 1 Hz, was increased by 1 Hz until it reached 1.5 Hz. Duration was 40 s for block 1, 20 s for block 2, 10 s for block 3, 8 s for blocks 4 and 5, 6 s for blocks 6–7 and 15, and 4 s for blocks 8–14.

Each participant performed 6 CoM followed by 6 CoP tracking trials: 3 blocks of 1 predictable and 1 unpredictable tasks for each type of feedback were provided (CoP_{fb} and CoM_{fb}). One practice trial was allowed for each condition. Target maximum side-to-side displacement for both, predictable and unpredictable targets, was normalized for each subject at 100% of the between-heels distance when using CoP_{fb} and 50% when using CoM_{fb}. These distances were chosen based on pilot experiments, which showed that subjects were unable to move CoM as far as CoP in the ML direction during MELBA tasks using CoM_{fb}. On average, the participants stood on the forceplate with 18.9 ± 1.1 cm distance between heels, which determined a maximum target displacement of 18.9 ± 1.1 cm when using CoP_{fb} and 9.4 ± .5 cm when using CoM_{fb}.

CoP–CoM relationship over the frequency ranges in the target signal was described by the gain of the linear constant coefficient transfer function between CoP_d and CoM_d from which gain (G) and coherence (Coh) were calculated (Cofré Lizama et al., 2013). G values < 1 for the CoP–CoM relationship will indicate a lower magnitude of the ML CoM_d in response to ML CoP_d. Coh was used to determine linearity between CoP and CoM. Perfect linearity yields $Coh = 1$ over all frequencies comprising the target signal. CoP_d and CoM_d were calculated over the time windows described above. These measures were used to compare the amount of CoP_d and CoM_d imposed when having CoP_{fb} and CoM_{fb} in both, predictable and unpredictable tasks.

Legs (Φ_{legs}) and trunk (Φ_{trunk}) angles relationship over the frequency ranges in the target signal was described by the gain of the linear constant coefficient transfer function between Φ_{legs} and Φ_{trunk} from which gain (G) and coherence (Coh) were calculated. $G < 1$ for the legs–trunk angles relationship will indicate a lower magnitude of the Φ_{trunk} in response to Φ_{legs}. Coh was used to determine linearity between Φ_{legs} and Φ_{trunk}. Legs ($legs_{ad}$) and trunk ($trunk_{ad}$) angular

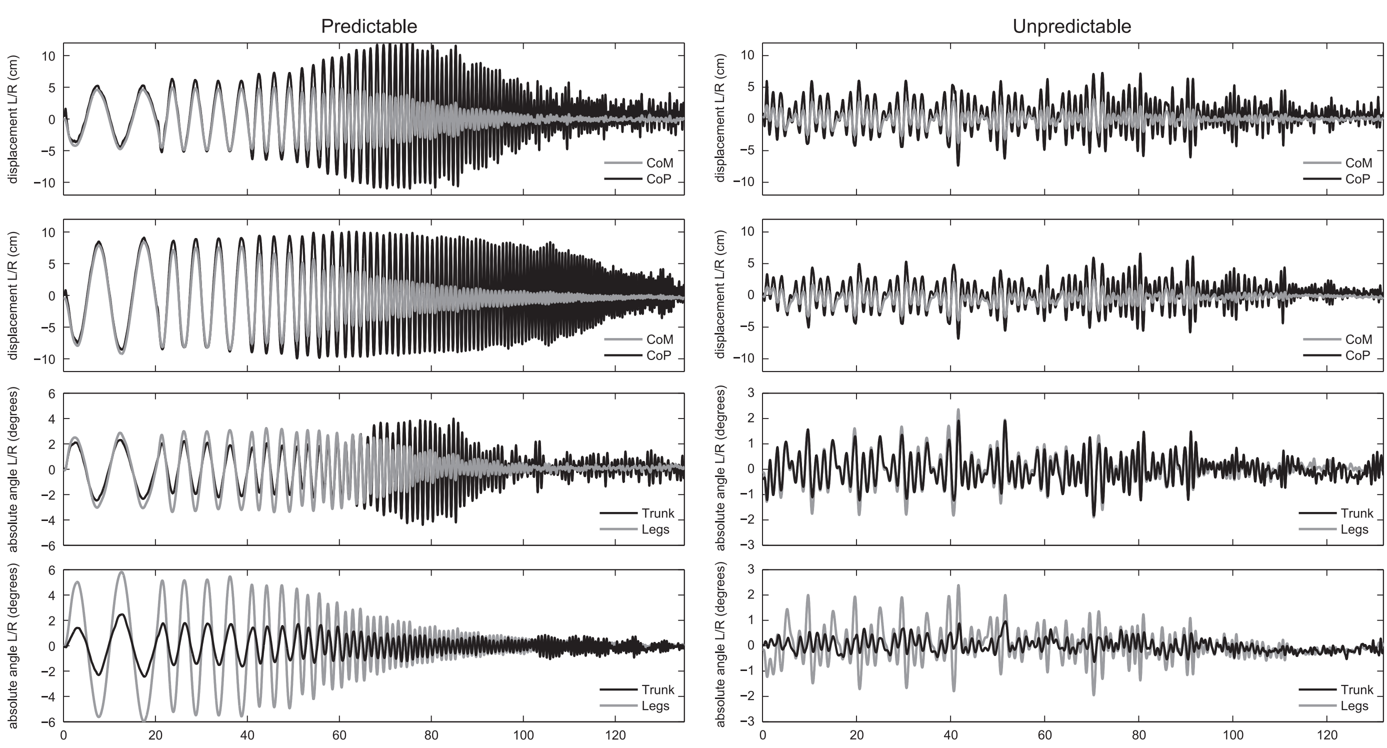

Fig. 1. Averaged plots for CoM and CoP displacements (meters) during both MELBA tasks (predictable on the left panel and unpredictable on the right panel) when using CoM_{fb} (first row) and CoP_{fb} (second row). Averaged plots for leg and trunk angles (degrees) during both MELBA tasks when using CoM_{fb} (third row) and CoP_{fb} (fourth row) are also presented.

displacements were calculated over the whole trials and within the time windows described for the MELBA tasks. These measures were used to compare the amount of $legs_{ad}$ and $trunk_{ad}$ imposed when having CoP_{fb} and CoM_{fb} in both, predictable and unpredictable tasks.

2.3. Statistical analysis

A multivariate ANOVA was performed to determine differences in *G* and *Coh* between CoP–CoM and legs–trunk angles for the predictable and unpredictable MELBA tasks at each frequency (.1–2.0 Hz at steps of .1) between CoP_{fb} and CoM_{fb} (feedback) as well as the interaction between frequency and feedback. A multivariate ANOVA was also performed to determine differences in CoP_d, CoM_d, $legs_{ad}$ and $trunk_{ad}$ between targets and feedbacks (CoP_{fb} and CoM_{fb}). Statistical analyses were performed using IBM-SPSS (Statistics 21) with the significance level set at $p < .05$.

3. Results

Averaged plots of CoP_d, CoM_d, $legs_{ad}$ and $trunk_{ad}$ during the CoP_{fb} and CoM_{fb} for both, predictable and unpredictable targets are presented in Fig. 1. Figs. 2 and 3 present the CoP–CoM and legs–trunk *G* and *Coh*, respectively. Table 1 presents the results for the statistical tests performed to determine the effect of feedback (CoP_{fb} and CoM_{fb}) and frequency (.1–2.0 Hz) on *G* and *Coh* respectively. Table 2 presents means and statistical results aimed

Table 1
Results for the multivariate ANOVAs tests performed to determine the effect of feedback (CoP_{fb} and CoM_{fb}) and frequency (.1–2.0 Hz at steps of .1) as well as interaction effect on CoP–CoM and legs–trunk *G* and *Coh* for both, predictable and unpredictable target. Significant differences are presented in bold.

		Predictable		**Unpredictable**	
		G	*Coh*	*G*	*Coh*
CoP–CoM	Feedback	< **.01**	< **.01**	< **.01**	< **.01**
	Frequency	< **.01**	< **.01**	< **.01**	< **.01**
	Feedback*frequency	< **.01**	< **.01**	< **.01**	< **.01**
Legs–trunk	Feedback	< **.01**	.18	< **.01**	< **.01**
	Frequency	< **.01**	< **.01**	< **.01**	< **.01**
	Feedback*frequency	< **.01**	.98	< **.01**	**.05**

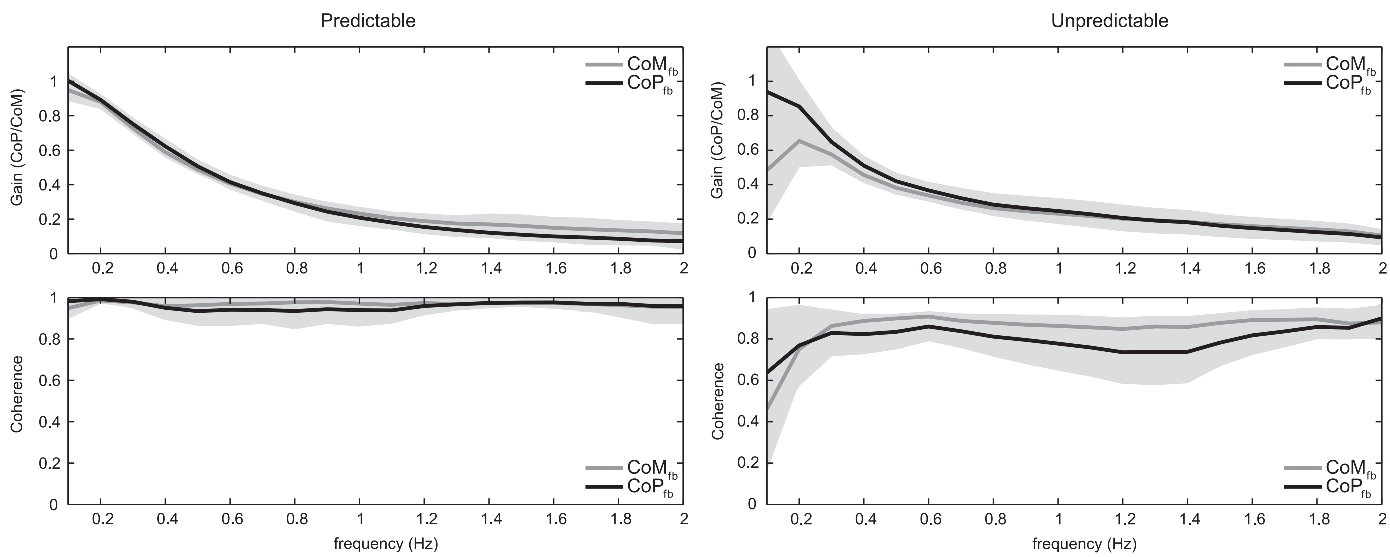

Fig. 2. Averaged plots for CoP–CoM *G* and *Coh* for the predictable (left panel) and unpredictable (right panel) tracking tasks when using CoP_{fb} (black line) and CoM_{fb} (dark gray line). Shaded light gray area represents ±SD.

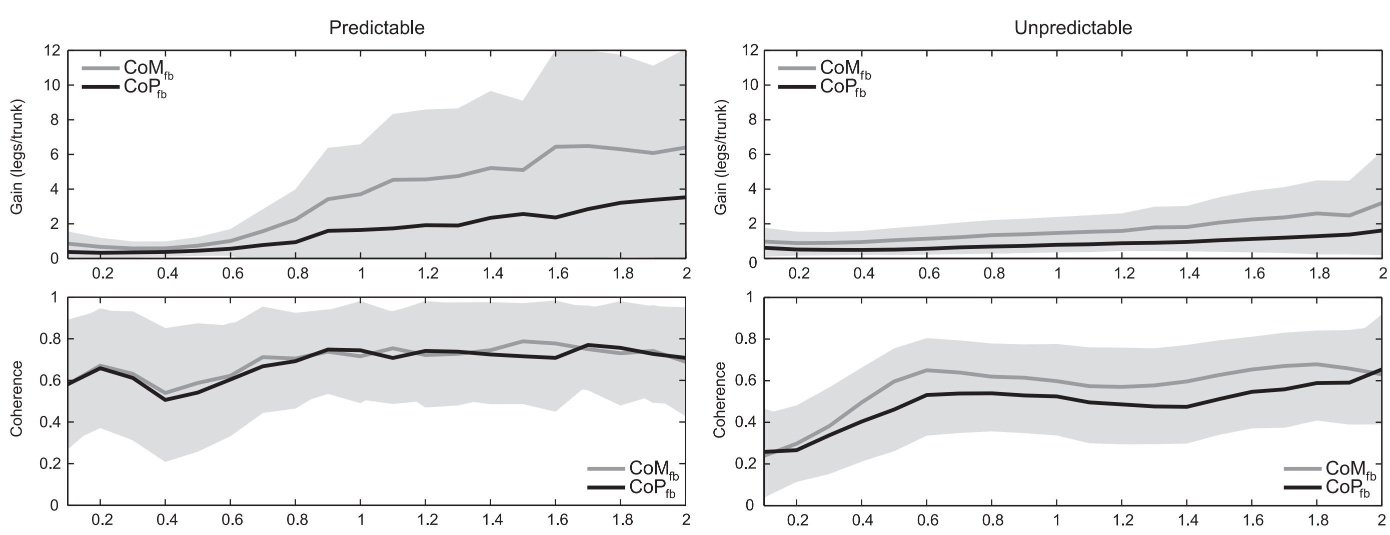

Fig. 3. Averaged plots for leg–trunk *G* and *Coh* for the predictable (left panel) and unpredictable (right panel) tracking tasks when using CoP_{fb} (black line) and CoM_{fb} (dark gray line). Shaded light gray area represents ±SD.

Table 2
Descriptive statistics (mean ± SD) and results for the statistical tests performed to determine differences in CoP_d, CoM_d, $legs_{ad}$ and $trunk_{ad}$ between targets (predictable and unpredictable) and feedback (CoP_{fb} and CoM_{fb}) as well as interaction effect (tar = target, fb = feedback). Significant differences are highlighted in bold.

	Predictable				Unpredictable						
	CoM_{fb} Mean	SD	CoP_{fb} Mean	SD	CoM_{fb} Mean	SD	CoP_{fb} Mean	SD	tar	fb	tar*fb
CoM_d	10.8	1.5	9.3	1.1	7.2	1.0	4.9	1.0	< **.001**	< **.001**	**.020**
CoP_d	45.8	7.3	40.4	4.3	38.0	7.9	29.9	4.7	< **.001**	< **.001**	.101
$Legs_{ad}$	554.0	159.5	597.0	113.7	337.3	65.5	291.3	75.4	< **.001**	.916	**.003**
$Trunk_{ad}$	1592.3	944.4	769.2	759.2	579.5	282.7	290.9	167.3	< **.001**	< **.001**	**.001**

to determine differences in CoP_d, CoM_d, $legs_{ad}$ and $trunk_{ad}$ between CoP_{fb} and CoM_{fb} respectively.

Overall, using both feedbacks CoP–CoM coherence values show high linearity (> .7), however, *Coh* was significantly higher when using CoM_{fb}. Significant effects of frequency and feedback* frequency interaction on *Coh* were found. These differences were greater in the unpredictable target. CoP–CoM *G* dropped with increasing frequency and was highly consistent between subjects. However, for the unpredictable target when using CoM_{fb} there was a significantly lower CoP–CoM *G* in the .1–.8 Hz range. Significant effects of feedback* frequency interaction were also found for *G*. For the latter, a steeper drop was observed when using CoM_{fb} in the predictable target.

In relation to legs–trunk *Coh*, no effect of feedback was found for the predictable target, however, for the unpredictable this was significantly lower when using CoP_{fb}. A significant effect of frequency was found for *G* and *Coh* when tracking both targets. Whereas an interaction effect was found for *G* and *Coh* in the unpredictable task, this interaction was only present for *G* in the predictable task.

Significantly greater CoP_d, CoM_d, and $trunk_{ad}$ were found when using CoM_{fb} and when tracking the predictable target. Significantly greater $legs_{ad}$ target in CoM_{fb} was only found when tracking the predictable. A significant target*feedback effect was found for CoM_d, $legs_{ad}$ and $trunk_{ad}$ but not for CoP_d.

4. Discussion

This study primarily aimed to determine the extent to which CoP_{fb} imposes consistent CoM displacements (CoM_d). CoP–CoM coherence values show a high linearity in the response of CoM–CoP displacements. This response, however, is scaled with frequency content of the target signals, with higher frequencies imposing larger CoM acceleration (Morasso et al., 1999), as is reflected in the consistent drop in CoP–CoM gain.

The second aim of this study was to determine whether larger CoM_d are elicited by CoM_{fb} when compared to CoP_{fb}. CoP_{fb} elicited smaller CoM_d and CoP_d than CoM_{fb} even when the side-to-side maximum CoP_d demanded in the CoP_{fb} tasks was double than in the CoM_{fb}. This shows that to challenge the balance control system by increasing the demands of CoM_d, direct CoM_{fb} is preferable. Furthermore, a greater *G* and *Coh* when using CoM_{fb} may indicate that subjects were more responsive to the demands of the tracking tasks than when using CoP_{fb}. It is noteworthy that in CoM_{fb} *G* was lower than in CoP_{fb} at the lowest frequencies, especially in the unpredictable tracking task. CoM_{fb} involved relatively larger CoP_d to displace the CoM than CoP_{fb}. This coincided with similar $legs_{ad}$ and $trunk_{ad}$ during CoM_{fb} in contrast to CoP_{fb} where $legs_{ad}$, was much larger than $trunk_{ad}$.

The third aim of this study was to determine whether different kinematic strategies arise when utilizing CoP_{fb} and CoM_{fb}. Significantly larger $legs_{ad}$ and $trunk_{ad}$ and the frequency dependent ratio between the two when using CoM_{fb} show that a wider variety of motor strategies are called into play than when using CoP_{fb}. This may also indicate a greater challenge for the balance control system, since kinematic strategies shift from ankle to hip–trunk muscles as demands of the tracking tasks increase. Since an age-related proximal–distal shift in locus of function has previously been shown in gait (DeVita and Hortobagyi, 2000), an earlier strategy shift (increased hip muscle activity) in MELBA using CoM_{fb} may indicate deterioration of distal neuromuscular function in the older adults, such as reduced muscle strength at the ankle joint.

The use of CoP_{fb} in the context of geriatric assessment or clinical settings may be preferable over CoM_{fb} given the lower costs and lesser requirements with respect to time and equipment (Pasma et al., 2014). However, to make sure that the test is sufficiently challenging for older adults, who may exhibit only minor impairments of balance, the greater demands in terms of CoM_d, and $trunk_{ad}$ that are imposed using CoM_{fb} may better reflect maximal capabilities of the balance control system than CoP_{fb} tracking tasks (Cofré Lizama et al., 2014). Although CoM_{fb} may be cumbersome to be implemented at present, current developments of markerless motion capture systems are likely to allow simpler implementation in the near future (Yang et al., 2014).

5. Conclusions

CoP_{fb} in MELBA elicits consistent CoM_d. However, different kinematics are employed in CoM_{fb} with more trunk movement and an ankle-to-hip shift as frequency increases. Hence CoM_{fb} may be preferable over CoP_{fb} despite the larger measurement effort currently involved.

Conflict of interest statement

There are no known conflicts of interest.

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