Estimation of Sagittal-plane Whole-body Angular Momentum During Perturbed and Unperturbed Gait Using Simplified Body Models

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1 Introduction

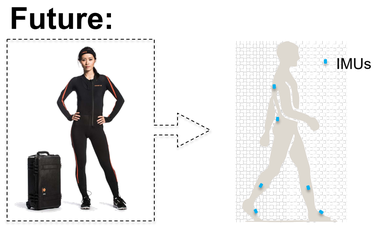
Background:

The capability to monitor gait stability during everyday life could provide key information to guide clinical intervention for patients with lower limb disabilities. Whole body angular momentum (WBAM) is a convenient stability indicator for wearable motion capture systems [1]. However, WBAM is costly to estimate, because it requires monitoring all major body segments using expensive sensor elements [2].

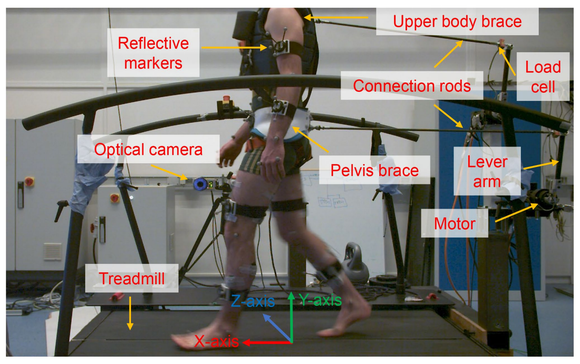
Objectives:

- Investigating the performance of different simplified models in estimating the sagittal-plane WBAM during perturbed and unperturbed gait
- Evaluating segmental contributions to the WBAM under the condition of pure sagittal-plane WBAM perturbations.

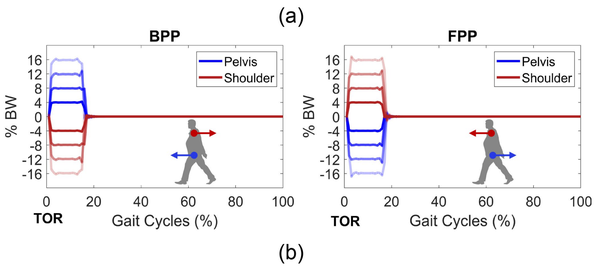
Future:



2 Methods



(a)



(b)

Figure 1. (a) Experimental setup. (b) The forces generated by two motors under different perturbation conditions were represented by % of body weight (% BW). Positive forces were denoted if forces were pointing in the positive direction of the X-axis, otherwise vice versa.

- **Protocol**

Walking speed: 1.25 m/s and 0.44 m/s. Conditions:

- 3 minutes of unperturbed walking
- Forward pitch perturbation (FPP)
- Backward pitch perturbation (BPP

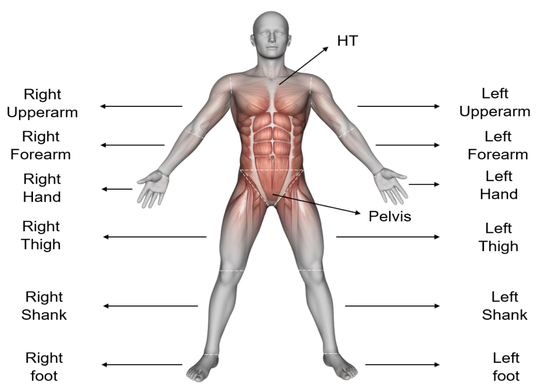


Figure 2. Human body model with 14 segments, which was rearranged from the Opensim model with 22 bones. * The background 3D male medical figure was downloaded from freepik, and it contains a free license for commercial and personal projects.

- **Data processing**

The WBAM with respect to the whole-body's CoM was calculated by following equation, where j represented each body segment,

$$\boldsymbol{H}_{full} = \sum_{i=1}^{14} \boldsymbol{H}_{seg,j} = \sum_{i=1}^{14} \left[\left(\boldsymbol{x}_{CoM}^{j} - \boldsymbol{x}_{CoM} \right) \times m_j \left(\boldsymbol{x}_{CoM}^{j} - \boldsymbol{x}_{CoM} \right) + \boldsymbol{I}_j \boldsymbol{\omega}_j \right]$$

- **Evaluation**

1) Segmental angular momentum contribution

➢**Pearson's correlation coefficients**: $\rho_{seg,j}^{overall}$, $\rho_{seg,j}^{RAM}$, and $\rho_{seg,j}^{TAM}$

➢**Median of the relative angular momentum percentages** between segmental angular momentum and the WBAM: $perc_{seg,j}^{overall}(\%)$, $perc_{seg,j}^{RAM}(\%)$, and $perc_{seg,j}^{TAM}(\%)$

2) Simplified body models evaluation

➢**Pearson's correlation coefficients**: $\rho_{\mathrm{model},j}$

➢**Median of the relative angular momentum percentages** between simplified models' angular momentum and the WBAM: $perc_{model,j}(\%)$

➢**Incremental perturbation sensitivity**, comparing the relative change of the range of each model to that of the full body model: $incre_{model,j}(\%)$

- **Analysis of results**

1) All evaluation metrics of the segments and simplified models were evaluated across all repetitions and subjects, and presented as mean ± SD.

2) Statistical analysis using linear mixed models for incremental perturbation sensitivity.

Reference:

[1] H. Herr and M. Popovic, "Angular momentum in human walking," *J Exp Biol*, vol. 211, no. Pt 4, pp. 467–81, 2008.

[2] M. Liu et al., "A simplified model for whole-body angular momentum calculation," *Med Eng Phys*, vol. 111, p. 103944, 2023.

[3] M. I. M. Refai et al., "Portable gait lab: Tracking relative distances of feet and com using three imus," *IEEE Trans Neural Syst Rehabil Eng*, vol. 28, no. 10, pp. 2255–2264, 2020.

[4] D. Martelli, V. Monaco, and S. Micera, "Detecting falls by analyzing angular momentum," *IEEE Int Conf Rehabil Robot*, vol. 2011, p. 5975404, 2011.

3 Results

- **Segmental angular momentum contributions**

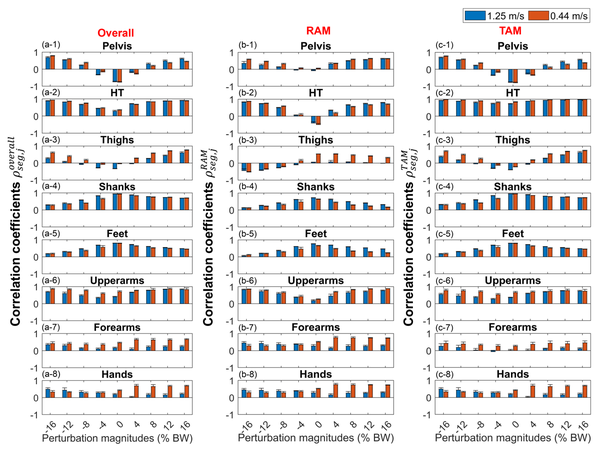


Figure 3. Mean and SD of the segmental correlation coefficients $\rho_{seg,j}^{overall}$,$\rho_{seg,j}^{RAM}$,and $\rho_{seg,j}^{TAM}$.

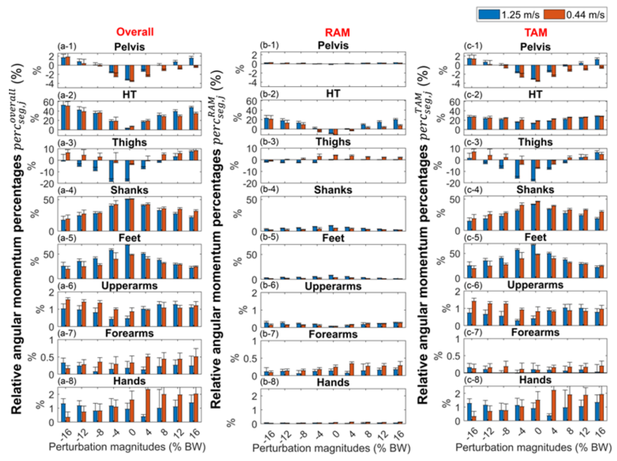


Figure 4. Mean and SD of the segmental relative angular momentum percentages $perc_{seg,j}^{overall}$, $perc_{seg,j}^{RAM}$,and $perc_{seg,j}^{TAM}$.

- The HT segment and lower limbs contributed to the majority of the sagittal-plane WBAM under all conditions.
- TAMs made up the majority of segmental angular momenta for most of the segments whether under unperturbed or perturbed conditions, except for the HT segment.

- **Simplified body models evaluation**

	HT segment		Thighs		Shanks		Feet	
	RAM	TAM	RAM	TAM	RAM	TAM	RAM	TAM
HT model	✓	✓	✗	✗	✗	✗	✗	✗
Fiveseg model - 1	✗	✓	✗	✓	✗	✓	✗	✗
Fiveseg model – 2	✓	✓	✗	✓	✗	✓	✗	✗
Fiveseg model - 3	✓	✓	✓	✓	✓	✓	✗	✗
Sevenseg model - 1	✓	✓	✗	✓	✗	✓	✗	✓
Sevenseg model - 2	✓	✓	✓	✓	✓	✓	✓	✓

Tips:

Only segments having large correlation coefficients and relative angular momentum percentages were chosen in simplified models. There are several potential simplified models that could be selected.

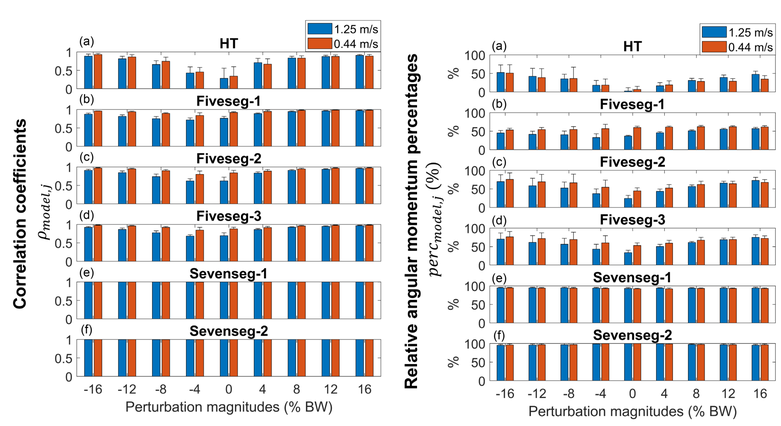


Figure 5. Mean and SD of the correlation coefficients $\rho_{model,j}$ for simplified models.

Figure 6. Mean and SD of the relative angular momentum percentages $perc_{\mathrm{model},j}(\%)$

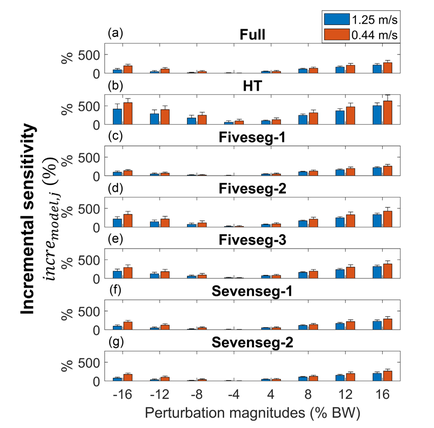


Figure 7. Mean and SD of the incremental perturbation sensitivity $incre_{\mathrm{model},j}(\%)$.

4 Discussion

- **Segmental contributions**

The separation of RAM and TAM provides us with an insightful understanding of the importance of different components of segmental angular momenta.

1) Firstly, our current results showed that RAMs of lower limbs are small such that they can be ignored in simplified models. This may simplify the kinematics measurement of lower limbs.
2) Secondly, this separation also helps us to better understand how segmental angular momenta are coordinated.

- **Simplified model selection**

The choice of the simplified model to be used depends on the following two factors.

1) The trade-off between model performance and the number of IMUs should be considered [3].
2) The applicability of the selected simplified model in different applications should also be considered, estimating WBAM or detecting perturbation [4].

5 Conclusion

The evaluation of the performance of simplified body models indicates that we were able to accurately estimate the sagittal-plane WBAM from a reduced number of segments, especially for the seven-seg models. Although other simplified models with fewer segments had limited performance in the sagittal-plane WBAM estimation, they could be potentially used in other applications, such as detecting perturbations.

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