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## Stability criteria compared using markerless and marker-based data

A. Chaumeil, B. K. Lahkar, A. Muller, R. Dumas and T. Robert

Univ Lyon, Univ Eiffel, Univ Claude Bernard Lyon 1, LBMC UMR\_T 9406, Lyon, France

### 1. Introduction

Markerless motion capture is a rapidly evolving field, due to its promising improvements in video-based pose estimation (Stenum et al. 2021). Theia3D (Theia Markerless Inc., Canada) is a commercially available software which relies on deep learning to perform 3D human pose estimation. Validation studies have shown that the lower limbs kinematics obtained with Theia3D was comparable to those obtained via marker-based analysis (Kanko et al. 2021). However, to the best of our knowledge, no study related to stability assessment using Theia3D has been published. We propose to focus on classical metrics for dynamic stability (Hof et al. 2005), including the extrapolated center of mass (XCoM, projection of the center of mass (CoM) on the ground augmented by a proportion of its velocity), the base of support (BoS) and the margin of stability (MoS, shortest distance from the XCoM to the boundaries of the BoS). According to Hof et al. (2005), the XCoM should remain in the BoS to maintain balance.

The goal of this study is to evaluate if a markerless pose estimation software such as Theia3D can be used to compute the position of the XCoM with respect to the BoS and thus derive the corresponding MoS. This is done by comparing the metrics obtained with Theia3D with those obtained using retroreflective markers, considered as the reference measurement system.

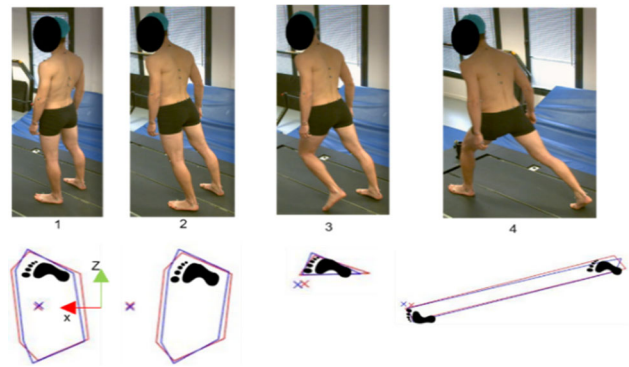
### 2. Methods

#### 2.1. Participants

For this study 9 male participants were recruited, with age:  $25.8 \pm 2.2$  years old, height:  $1.79 \pm 0.09$  m and mass:  $74.6 \pm 11.4$  kg. Participants had no history of musculoskeletal or balance problems. They signed an informed consent form and the study was approved by our institutional review board.

#### 2.2. Experimental setup

Data was collected simultaneously using an optoelectronic marker-based system (10 Qualisys Miquis M3



**Figure 1.** The phases of the movement and associated positions of the mbBoS (red), mlBoS (blue), mbXCoM (red cross) and mlXCoM (blue cross).

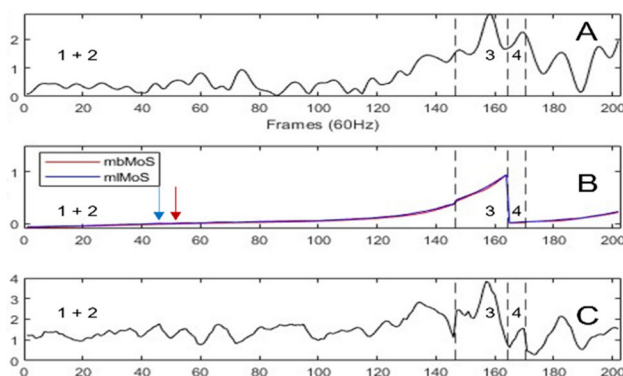
cameras) at 300Hz and a markerless 2D video-based system (10 Qualisys Miquis Video cameras) at 60Hz. Participants performed the experimental procedure on an instrumented treadmill (Treadmetrix, USA), recording data at 3000 Hz. Camera systems and treadmill were synchronized in time and space. Participants were equipped with a set of 46 retro-reflective markers placed on relevant bony landmarks. Participants were asked to stand still with eyes open and then lean forward slowly until they lost their balance. Participants were free to do as many recovery steps as needed to get their balance back. Three repetitions per participant were performed.

#### 2.3. Data processing and analysis

Markerless data was processed using Theia3D (v2021.2), which provided pose matrices for each of the body segments composing the whole-body model. These pose matrices were then imported to Visual3D (C-motion, USA, v2021.11.3), where the included 17-segment body model was modified to have inertial parameters based on Dumas and Wojtusich (2018).

Marker-based data was first labeled, gap filled and then imported to Visual3D. There, a custom model was built to have the closest body segments and joint constraints to those of the Theia3D model, given the available information provided with Theia3D. Inertial parameters were also based on Dumas and Wojtusich (2018).

For both models, position of the whole-body CoM was exported from Visual3D to be processed in Matlab (MathWorks, USA, v2021b), where it was filtered with a 4<sup>th</sup> order, low-pass Butterworth filter with 7Hz cutoff frequency, and derived to obtain the velocity. The XCoM was computed based on Hof et al. (2005). The marker-based BoS (mbBoS) was computed using the position of the feet markers



**Figure 2.** (A): Distance (cm) between mbXCoM and mlXCoM. (B): mbMoS (red) and mlMoS (blue) (m). (C): Difference (cm) between mbMoS and mlMoS. The phases correspond to those displayed in Figure 1. Data for one typical participant and trial.

(calcaneus, 1<sup>st</sup> and 5<sup>th</sup> metatarsal head markers). To compute markerless BoS, the reference frame of each foot was computed based on the origin of the foot and toe pose matrices, which allowed to compute the position of the calcaneus, 1<sup>st</sup> and 5<sup>th</sup> metatarsal heads based on their average positions in the segments (Dumas et al. 2007). Both BoS were geometrically computed as convex surfaces including the three points of each foot in contact with the ground. For each foot, contact was identified using the vertical ground reaction force.

The root mean square difference (RMSD) between marker-based XCoM (mbXCoM) and markerless XCoM (mlXCoM) was assessed in antero-posterior (AP), medio-lateral (ML) and superior-inferior (SI) directions, as well as the mean of the distance between mbXCoM and mlXCoM.

The agreement between mbBoS and mlBoS was assessed by computing two quantities: 1°) the mbBoS (*resp.* mlBoS) was discretized and the percentage of points in mbBoS (*resp.* mlBoS) which were also in mlBoS (*resp.* mbBoS) was computed; 2°) the mean difference of area between the mbBoS and mlBoS was computed.

The MoS was computed for both marker-based (mbMoS) and markerless (mlMoS) systems following Hof et al. (2005). It was negative when the XCoM was in the BoS, and positive otherwise.

Mean values are given across all participants.

### 3. Results and discussion

Figure 1 displays the different phases of the movement. The leaning phase is split in two (phases 1 and 2) to show the difference of sign of the MoS. Phase 3 corresponds to the swing phase, and phase 4 to the following double support phase.

#### 3.1. Comparison of mbXCoM and mlXCoM

The RMSD values in AP, ML and SI directions are, respectively, 1.2 cm, 0.5 cm and 0.7 cm. The mean distance between mbXCoM and mlXCoM is  $1.3 \pm 0.7$  cm, with a mean peak value of  $4.0 \pm 0.6$  cm. This distance is bigger during phases 3 and 4, for which the movement is more dynamic.

#### 3.2. Comparison of mbBoS and mlBoS

The percentage of points of the mlBoS which are also in the mbBoS is  $94 \pm 8\%$  and the percentage of points of the mbBoS which are also in the mlBoS is  $90 \pm 6\%$ . Overall, the BoS overlap quite well (Figure 1), the mlBoS being more included in the mbBoS than the opposite. The mean difference in area between the mlBoS and mbBoS is  $33.7 \pm 23.7$  cm<sup>2</sup>. This difference is especially bigger during standing and leaning phases and is due to differences in anterior and posterior boundaries (Figure 1).

#### 3.3. Comparison of mbMoS and mlMoS

The mbMoS and mlMoS are displayed in Figure 2B and their difference in Figure 2C. The blue (*resp.* red) arrow indicates the moment at which the mlXCoM (*resp.* mbXCoM) is out of the mlBoS (*resp.* mbBoS). The mean difference between these moments defined by the two measurement systems is  $0.13 \pm 0.15$  s.

The mean difference between mbMoS and mlMoS is  $1.4 \pm 0.7$  cm and  $2.1 \pm 1.0$  cm during phases (1 + 2) and (3 + 4), respectively. For the later, the mbXCoM/mlXCoM difference seems to explain mainly the mbMoS/mlMoS difference, as the mlBoS and mbBoS are very similar in area and position. This difference of resulting XCoM could be explained by a decreased accuracy of the video-based pose estimation, coming from both the dynamic aspect of the motion and the distance from the standing standard posture. For phases (1 + 2), although the mbXCoM/mlXCoM difference is non-negligible, it seems that the difference of position of the BoS boundaries also has a clear influence on the mbMoS/mlMoS difference.

### 4. Conclusions

Overall, the markerless system provides results that are consistent with the reference marker-based system. However, the measure of stability using the MoS should be handled with care for dynamic movements. A study of the position and velocity of the CoM will be conducted to determine which parameter produces the biggest error on the XCoM.

## Disclosure statement

No potential conflict of interest was reported by the authors.

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 [thomas.robert@univ-eiffel.fr](mailto:thomas.robert@univ-eiffel.fr)