Can segmental model reductions quantify whole-body balance accurately during dynamic activities?

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Abstract

When investigating whole-body balance in dynamic tasks, adequately tracking the whole-body centre of mass (CoM) or derivatives such as the extrapolated centre of mass (XCoM) can be crucial but add considerable measurement efforts. The aim of this study was to investigate whether reduced kinematic models can still provide adequate CoM and XCoM representations during dynamic sporting tasks. Seventeen healthy recreationally active subjects (14 males and 3 females; age, 24.9 ± 3.2 years; height, 177.3 ± 6.9 cm; body mass 72.6 ± 7.0 kg) participated in this study. Participants completed three dynamic movements, jumping, kicking, and overarm throwing. Marker-based kinematic data were collected with 10 optoelectronic cameras at 250 Hz (Oqus Qualisys, Gothenburg, Sweden). The differences between (X)CoM from a full-body model (gold standard) and (X)CoM representations based on six selected model reductions were evaluated using a Bland-Altman approach. A threshold difference was set at ±2 cm to help the reader interpret which model can still provide an acceptable (X)CoM representation. Antero-posterior and medio-lateral displacement profiles of the CoM representation based on lower limbs, trunk and upper limbs showed strong agreement, slightly reduced for lower limbs and trunk only. Representations based on lower limbs only showed less strong agreement, particularly for XCoM in kicking. Overall, our results provide justification of the use of certain model reductions for specific needs, saving measurement effort whilst limiting the error of tracking (X)CoM trajectories in the context of whole-body balance investigation.

Key words: biomechanical modelling, postural balance, center of mass, extrapolated center of mass, dynamic sport activities.

Highlights

- Adequately tracking the whole-body centre of mass (CoM) or derivatives such as the extrapolated centre of mass (XCoM) can be critical when investigating whole-body balance in dynamic tasks, but can add considerable measurement effort.
- A number of reduced kinematic models were evaluated to see whether they can provide adequate CoM and XCoM representations during a variety of dynamic sporting tasks.
- Considerably reduced kinematic models were unjustified for CoM and XCoM representation, however a reduction based on lower limbs, trunk and upper limbs showed strong agreement in antero-posterior and medio-lateral displacement profiles.
- (X)CoM representations from certain model reductions can save effort with acceptable error in the context of whole-body balance investigation.

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Introduction

The whole body centre of mass (CoM) is a key variable when investigating balance in dynamic sporting tasks. Estimating the CoM can however be time consuming when having to measure the motion of all body segments. Many markers need to be placed on the body (at least three per modelled segment) and tracked to calculate the CoM.. Particularly in dynamic activities this can be challenging as sometimes markers are lost with complex or rapid movement, or they are difficult to keep in view of more than two cameras at any moment in time. Therefore, if the researcher is interested in the detailed kinematics and/or kinetics of a specific part of the body or joint only, but wishes to retain a good representation of the CoM for the purpose of investigating aspects of balance, then one could save considerable time and effort if adequate CoM representation were still possible while reducing the amount of modelled segments.

Several approaches have been used to represent the CoM during dynamic tasks such as walking [1], running [2], side cutting [3] and jumping [4], but the trade-off between detail of the representation and accuracy has been a continued concern. For example, One study investigated three different representations (38 markers, a simplified 13-marker model, and a single marker model at sacral) to estimate the three dimensional CoM during quiet standing, gait and balance recovery [1]. Whilst the simplified 13-marker model or single marker model could serve a purpose in those movements, they no longer allow a detailed investigation of one part of the body. In one of our previous studies we compared CoM representations between four different marker sets that gradually reduced the amount of modelled upper limb segments, retaining the lower limb segments, and found that a CoM representation based on lower limbs and trunk segments have a strong enough agreement with CoM values from a full body model in terms of relevant velocity values for side cutting manoeuvres [3]. This model has allowed numerous studies to investigate lower limb kinematics and/or kinetics of side cutting whilst controlling whole body running speed. The question remains though, whether a similar model reduction is justified for other dynamic sporting tasks such as drop vertical jumping or kicking, and whether similar model reductions would be possible when one wishes to retain detailed kinematics and/or kinetics of the upper limb, for example when performing a tennis serve.

When evaluating balance during dynamic tasks, the extrapolated CoM (XCoM) has been proposed based on controlling balance through pendulum like behaviour. The XCoM adds a velocity-based correction to the CoM and has seen considerable attention in recent literature [1, 5, 6, 7, 8]. Therefore, scientists interested in associating detailed lower or upper limb kinematics/kinetics with dynamic balance strategies would benefit from knowing whether reduced CoM and XCoM representations can still be sufficiently accurate. Our aim was therefore to investigate whether CoM and XCoM representations of reduced kinematic models can be sufficiently accurate whilst retaining detailed kinematics of the lower or upper limbs in commonly observed dynamic sporting tasks such jumping, kicking, or overarm striking.

Methods

Participants

17 healthy recreationally active athletes, 14 males and 3 females, mean (±SD) age 24.94 ± 3.23 years, height 177.32 ± 6.94 cm, and body mass 72.64 ± 7.02 kg, participated in the study. Participants were questioned on their injury history and none had a recent (< 6 month) muscle injury. This study was approved by the Liverpool John Moores ethics committee (15/SPS/016).

Experimental design and protocol

72 reflective markers were placed on anatomical landmarks to record segmental motions. Participants then completed a 10 min warm up (consisting of light jogging and dynamic movements). After a standardised warm-up routine, subjects performed 5 trials of 3 different dynamic sports activities: a drop vertical jump (bilateral drop vertical jump from a box with height of 30 cm, jumping up with an arm swing and then landing on the same spot), a kicking imitation (starting with forward run then imitating a kicking motion with the right leg and then keeping moving forward using a countering arm swing) and an overarm tennis serve imitation (standing on both feet and completing a tennis serve action). No ball or racket was used.

Data collection and model reductions

Kinematic data were collected with 10 infrared cameras at 250 Hz (Oqus Qualisys, Gothenburg, Sweden) and using a full-body six-degree-of-freedom kinematic model (FB). This kinematic model allows calibrating and tracking of segmental motion of 13 segments, that is, head, upper arms and forearms (including hands), thorax, pelvis, thighs, shanks and feet, with segmental data based on Dempster's regression equations [9] and using geometrical volumes to represent each segment [10]. The FB model was used as the gold standard measurement against which to compare CoM representations for models with different segmental reductions (see figure 1). Segmental reductions existed of neglecting the mass of certain segments in the calculation of the (X)CoM. A first reduction was the removal of the head segment, leaving the lower limbs, trunk, and upper limbs (LL+T+UL). This segment is expected not to move much relative to the much heavier trunk, and with a segment mass of only 7.8 percentage of total body mass this would be expected not to play an important role [9]. For throwing or striking actions though, it may be possible to also ignore motion of the non-throwing or non-striking arm, keeping detailed kinematics of lower limbs, trunk as well as the dominant upper limb (LL+T+DUL). A further reduction was the omission of upper limbs altogether, keeping lower limbs and trunk (LL+T), which is, including thorax, pelvis, thighs, shanks, and feet. This reduction has already been shown to sufficiently accurately represent the CoM velocity characteristics for side-cutting manoeuvres [3]. When a focus on segmental motion of the lower limbs only exists, then one may also consider a further reduction to lower limbs only (LL), considering pelvis, thighs, shanks and feet only. Alternatively, in serving or throwing actions the interest may be solely on detailed upper limb segmental motion, and one may wish to ignore lower limb motion altogether. Hence, we also considered a trunk and upper limbs reduction (T+UL), as well as a trunk and dominant upper limb only reduction (T+DUL).

(Figure1)

Data reduction and analysis

The position of the whole body CoM, and reductions thereof, was estimated according to basic principles of adding segmental mass locations. The CoM of the total system is located at (x0, y0, z0) and each of these coordinates can be calculated for an n-segment body [11]. Equations were implemented through the use of Visual3D (C-motion, Germantown, MD, USA). In this study, we estimated the (X)CoM position, yet because we considered this over the duration of each task this reflects displacement and we hence refer to the 'displacement profile' or 'displacement trajectory'. The (X)CoM trajectories were extracted from touch down until landing in the drop vertical jump, from touch down and take off of the support leg for the kicking, and from the moment when the hitting arm started moving up until the moment when the wrist of the hitting arm finished the follow-through in the tennis serve imitation. The antero-posterior and medio-lateral displacement trajectories were evaluated considering their role in balance evaluation. Evaluations of vertical displacement of CoM have been presented in Appendix A.

The 95% limits of agreement (LoA) and bias used for comparison two methods. The 95% limits of agreement estimated by mean difference ±1.96 standard deviation of the difference that provide an interval within which 95% of differences between measurements [12]. It carried out to compare trajectories of the six (X)CoM representations against the gold standard FB model. Bias between methods is shown as the mean difference between the methods (subtracting data of model reductions from the full body model data), and in theory could be corrected for as long as the bias were consistent. Consistency of this bias is indicated by the limits of agreement, as measured by the amount of variation of the difference between methods. A lack of agreement is therefore a consequence of the fact that the (X)CoM representation is a mismatch from the (X)CoM (bias), or due to the fact that the (X)CoM representation does not consistently follow the actual (X)CoM (LoA). To help the reader interpret the agreement between methods, an arbitrary threshold range was set at ±2 cm, yet one should adopt a suitable threshold for every application or study.

Results

Temporal profiles of CoM and XCoM for the three tasks can be found in Appendix B. Temporal profiles of bias and LoA for CoM and XCoM representations showed considerable similarity for all three tasks as depicted side-by-side in Figure 2, 3 and 4.

(Figure 2)

Jumping

In the M/L direction, all model reductions stayed within the threshold range of ±2 cm. Three models (LL+T+UL, LL+T+DUL, and LL+T) had less bias than other model reductions (T+UL, T+DUL, and LL) and limits of agreement were around 0.5 cm. In the A/P direction, LL+T+UL was closest to the FB model. Only during the first 30% of the contact phase, the limits of agreement slightly exceeded 2 cm. All other model reductions had considerable bias and showed excessive limits of agreement (see figure 2A). For the effect of model reductions on XCoM trajectories, LL+T+UL was found to be the best model reduction in the M/L direction. In the A/P direction, during the first 20% of time, LL+T+UL exceeded 2 cm but most of the time the LL+T+UL model did not exceed 2 cm. Furthermore, when exploring the LoA it also supported that LL+T+UL has moderate to good agreement with the actual XCoM trajectory (see figure 2B).

(Figure3)

Kicking

In M/L direction, three models (LL+T+UL, LL+T, and LL+T+DUL) had less bias than other model reductions and limits of agreement although in A/P direction only LL+T+UL and LL+T could be accepted. All other model reductions had considerable bias and showed large limits of agreement (see figure 3A). For the XCoM representations, LL+T+UL was again closest to the gold standard and had small variation for both M/L and A/P directions even though limits of agreement of differences between LL+T+UL and the gold standard slightly exceeded for about 20% of time in A/P direction. Other model reductions exceeded the threshold range considerably; particularly T+DUL, T+UL, and LL model reductions (see figure 3B).

(Figure 4)

Tennis serve

In M/L direction, both LL+T+UL and LL+T+DUL representations of CoM had limited bias and limits of agreement. The LL+T+UL model was better than the LL+T+DUL model. During the last 20% of the movement LL+T+DUL exceeded the 2 cm threshold and the limits of agreement also showed that LL+T+DUL exceeded 2 cm between 60%-70% of the movement time (see figure 4A). In A/P direction LL+T+UL was the best model reduction even if the bias at beginning and end of the movement slightly exceeded the threshold. All other model reductions had considerable bias and large limits of agreement. For XCoM representations, both bias and limits of agreement for the M/L direction showed that only the LL+T+UL model reduction is acceptable. For the A/P direction, also only the LL+T+UL could be within reason but in the bias plot it exceeded the threshold for approximately 20% of the time while in the limits of agreement plot for almost 50% (see figure 4B).

Discussion

The aims of this study were to find the most appropriate reduced kinematic models that still provide adequate (X)CoM representations during dynamic sport activities. Our results demonstrated that modelling the head is unnecessary to obtain a good CoM representation during dynamic manoeuvres, but further model reductions tend to generate inadequate CoM representations for some of the sporting movements we measured.

In jumping activities one may have an interest in lower limb segmental motion only, but retaining CoM information. Our results showed that the LL+T+UL model reduction accurately represents CoM motion, but any further reductions that exclude upper limbs and/or trunk are inadequate to track the CoM.. Importantly, the jump task that we observed involved an arm swing. If the arm swing were not present, such as by crossing the arms in front of the chest, or by holding the arms akimbo, which is common in laboratory based experiments, then LL+T model may have been sufficiently accurate but this remains unconfirmed. In fact, this has been assumed in previous work investigating lower limb kinematics and kinetics during standing vertical jumps [13, 14].

Concerning kicking, in the M/L direction the results showed that three models including LL+T+UL, LL+T, and LL+T+DUL could be accepted as indicated by a low bias and limits of agreement. In the A/P direction, only LL+T+UL and LL+T could be accepted. The acceptable CoM representation through LL+T could be explained by opposite (out-of-phase) motion between both arm segments, which leads to negligible effects on the CoM. Hence, if one uses LL+T with dominant arm only (LL+T+DUL) then this leads to inadequate CoM representation as the CoM representation is expected to be off by the motion of the non-dominant arm. The other model reductions also showed considerable error. Our findings are similar to a previous study [3] where an LL+T model reduction was deemed suitable for side cutting. This offers opportunities for researchers who wish to investigate detailed lower limb mechanics in kicking, as it may well be possible to save a considerable amount of time for placing markers and tracking marker locations on upper extremities for getting an acceptable CoM representation.

During overarm motion activities with the tennis serve as an example, both in the M/L direction and in the A/P direction we found that only the LL+T+UL was suitable. The LL+T+DUL may also be acceptable but slightly exceeded the threshold. Any other model reductions showed considerable error. Hence, the results of this study suggest that for evaluating balance mechanisms based on CoM motion, one most likely needs both upper limbs included in the kinematic model. The tennis serve task has both arms mostly extended and swinging upwards and forwards (partly in-phase) during ball tossing and striking, and this leads to a considerable effect on CoM motion. We expect this to be similar for the majority of dynamic tasks involving overarm motions and suggest that using LL+T+UL model is needed for quantifying CoM motion, and any further reductions based on tracking only upper limb kinematics even when including the trunk would be inadequate.

The comparison between the M/L and A/P CoM motion revealed that in jumping there were only small differences between model reductions and the gold standard, but that only for the M/L direction. This is a consequence of the fact that there was only a minimal movement in M/L direction during the predominantly symmetrical and sagittal plane task. This means that despite small differences based on a 2 cm threshold, these differences would still be meaningful if one were to investigate M/L whole-body balance effects. Both the kicking and tennis serve tasks involved more M/L movement than the drop vertical jump, and hence differences between model reductions and the gold standard were increased and likely of more importance in those tasks compared to the jump.

The main reason for this study was to investigate CoM motion in the context of postural balance strategies in dynamic sporting tasks. As XCoM adds a velocity-based component to the CoM, its motion in activities that involve rapidly changing movement would be expected to be considerably different from CoM motion. We found though that XCoM results were largely similar to the results of the CoM for all dynamic activities with the only major differences observed in kicking. While LL+T was good for CoM representation in kicking, the accuracy of the LL+T model reduction was deemed unsuitable for XCoM. The kicking activity is a rapid dynamic movement, especially in the A/P direction, which involves forward running and one leg stays on the floor while the kicking leg is rapidly swinging forward, and also the arms have a considerable velocity component.

A limitation of this study is the choice of the threshold range, which was done arbitrarily and only intended to help the reader interpret which model is likely appropriate for their studies. If a higher accuracy is required for example for observing small effect sizes, then the reader should make their own judgement for what they believe to be an acceptable (X)CoM representation. Also, other model reductions such as T+UL with pelvis and thighs could be explored further as these might still be acceptable in term of accuracy and consistency of (X)CoM representation.

In summary, our recommendation would be that studying (X)CoM motion based on a LL+T+UL model reduction would be considered suitable for dynamic sporting tasks. As a consequence of this model reduction, only a small amount of time could be saved. This study for example involved 17 participants, with three conditions and 5 trials each. Reducing the FB model to the LL+T+UL model could have theoretically saved approximately 4 hours of work associated with placing and tracking the head markers. Whilst for the CoM representation, the LL+T model was good for kicking, its accuracy was less accurate for representing XCoM motion. Further model reductions, for example ignoring upper limbs or trunk, or ignoring lower limbs, generally showed poor agreement and are likely unsuitable if one wishes to evaluate whole body balance control in dynamic tasks based on CoM or XCoM motion.

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Conflict of interest

The authors declare no conflicts of interest.

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Figures

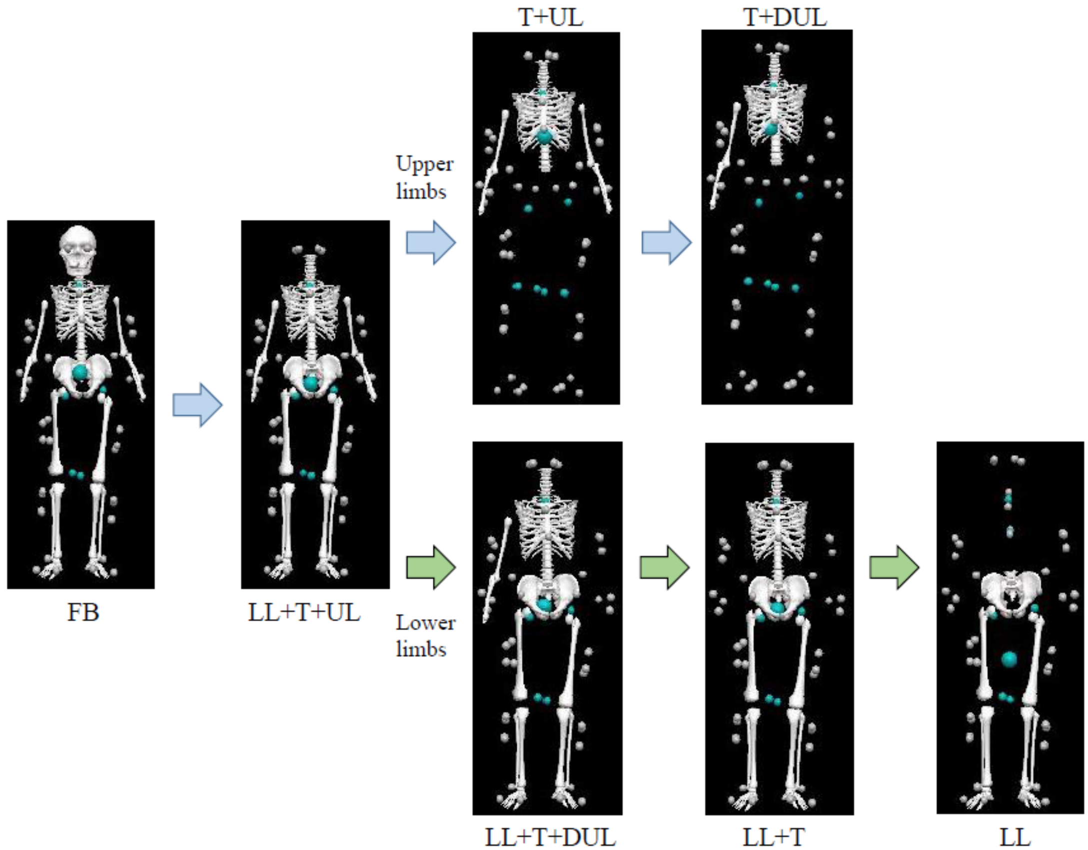

Figure 1. The details of biomechanical models, FB, LL+T+UL, T+UL T+DUL, LL+T+DUL LL+T, and LL model. Model reductions either were done to allow detailed kinematics/kinetics on upper limbs (top part) or lower limbs (lower part).

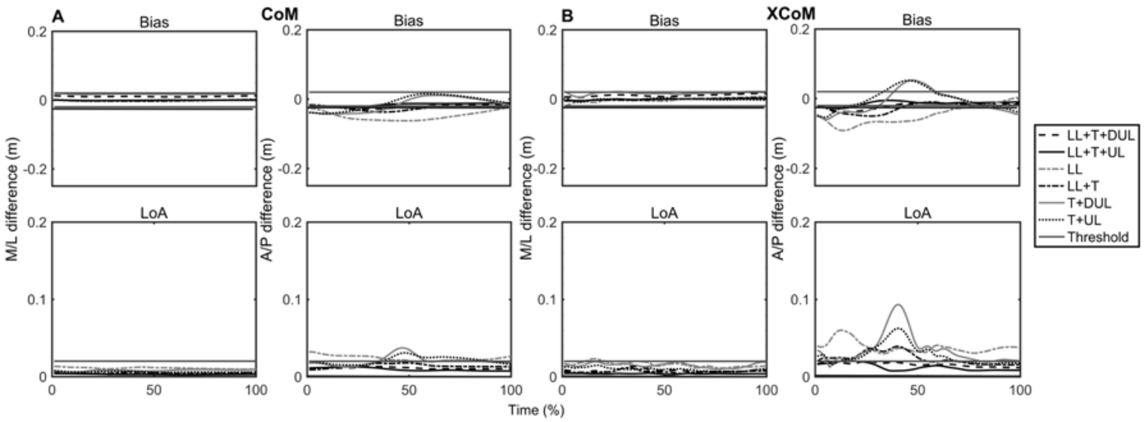

Figure 2. (A) shows the difference of CoM trajectories, whereas (B) shows the differences of XCoM trajectories in M/L (left panels) and A/P (right panels) directions between FB kinematic model and selective model reductions during a drop vertical jump.

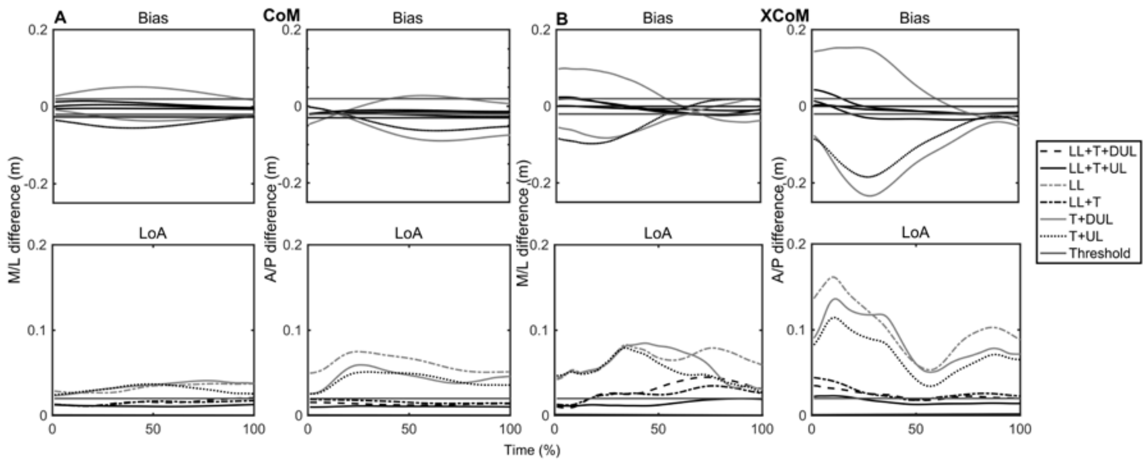

Figure 3. (A) shows the difference of CoM trajectories, whereas (B) shows the differences of XCoM trajectories in M/L (left panels) and A/P (right panels) directions between FB kinematic model and selective model reductions during kicking.

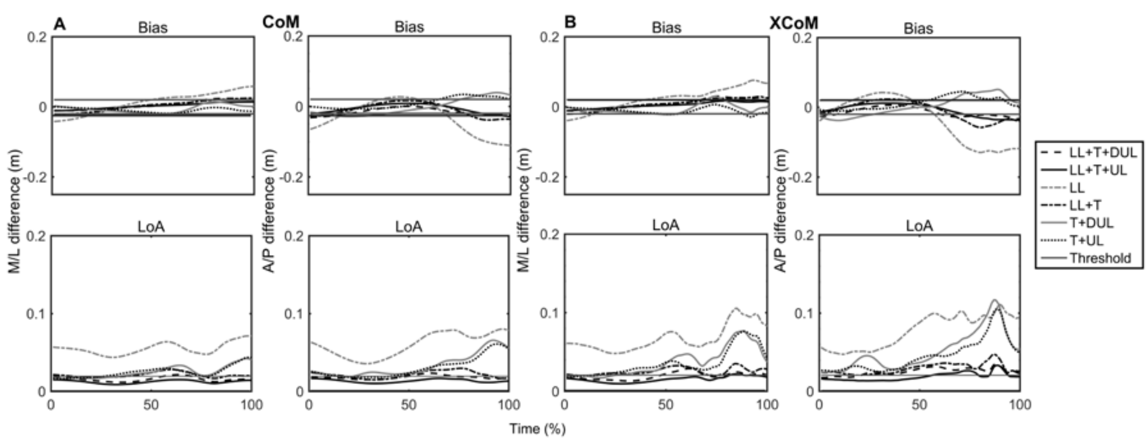

Figure 4. (A) shows the difference of CoM trajectories, whereas (B) shows the differences of XCoM trajectories in M/L (left panels) and A/P (right panels) directions between FB kinematic model and selective model reductions during tennis serve.

Appendix A: CoM bias and LoA's in vertical direction.

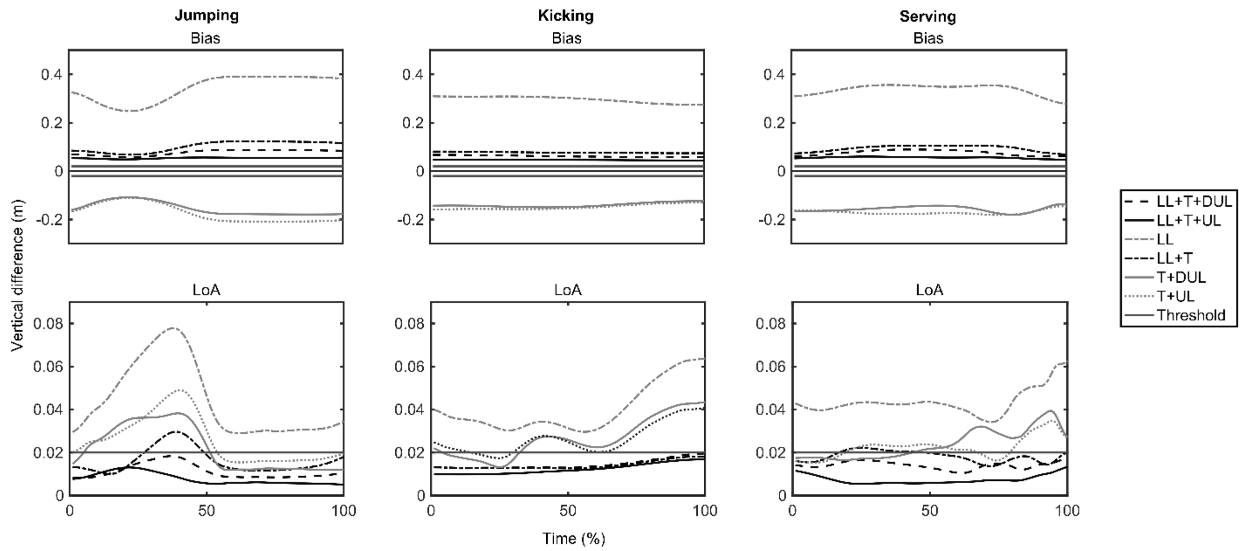

Figure A-1: bias and limits of agreement for trajectories of CoM representations in vertical direction

Appendix B: (X)CoM trajectories

In this appendix the trajectories of (X)CoM representations in Anterior-Posterior and Medio-Lateral direction for the full-body model and the six model reductions are provided.

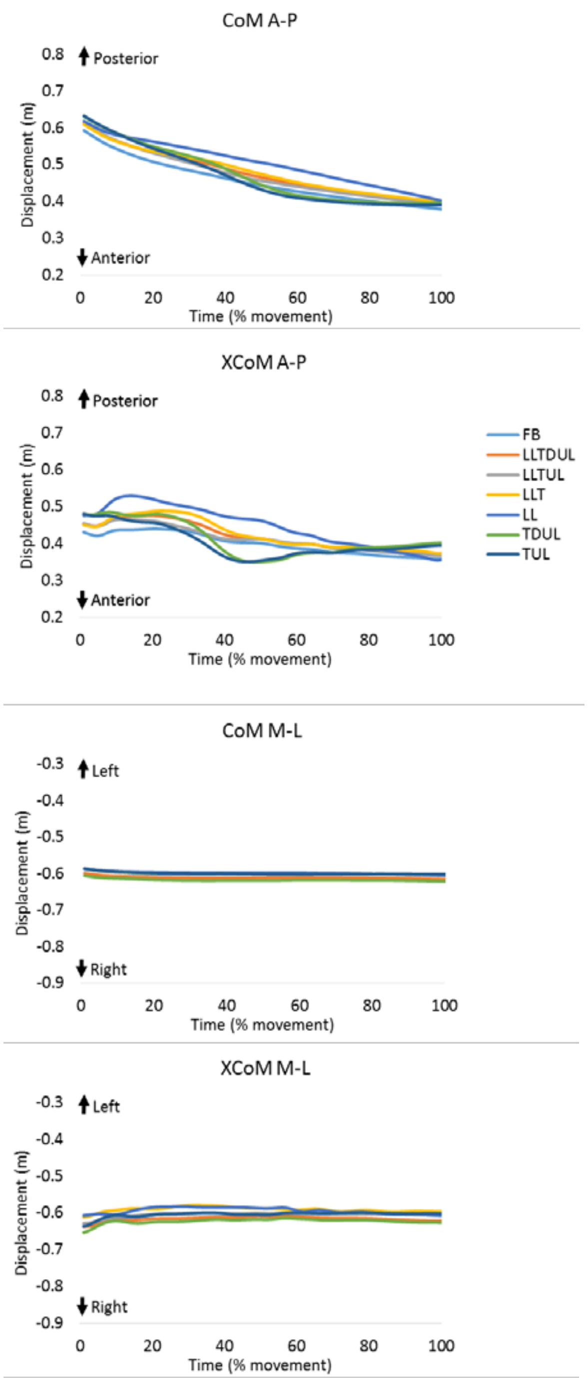

Figure B-1: (X)CoM trajectories in anterior-posterior (A-P) and medio-lateral (M-L) direction for jumping

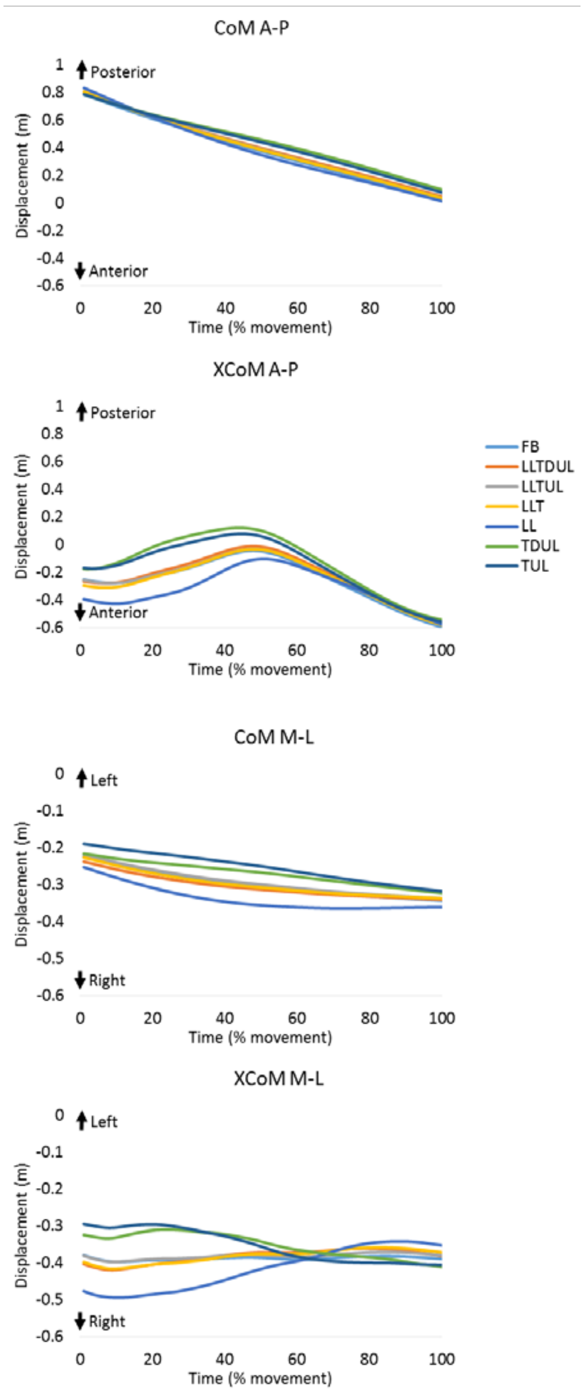

Figure B-2: (X)CoM trajectories in anterior-posterior (A-P) and medio-lateral (M-L) direction for kicking (right footed)

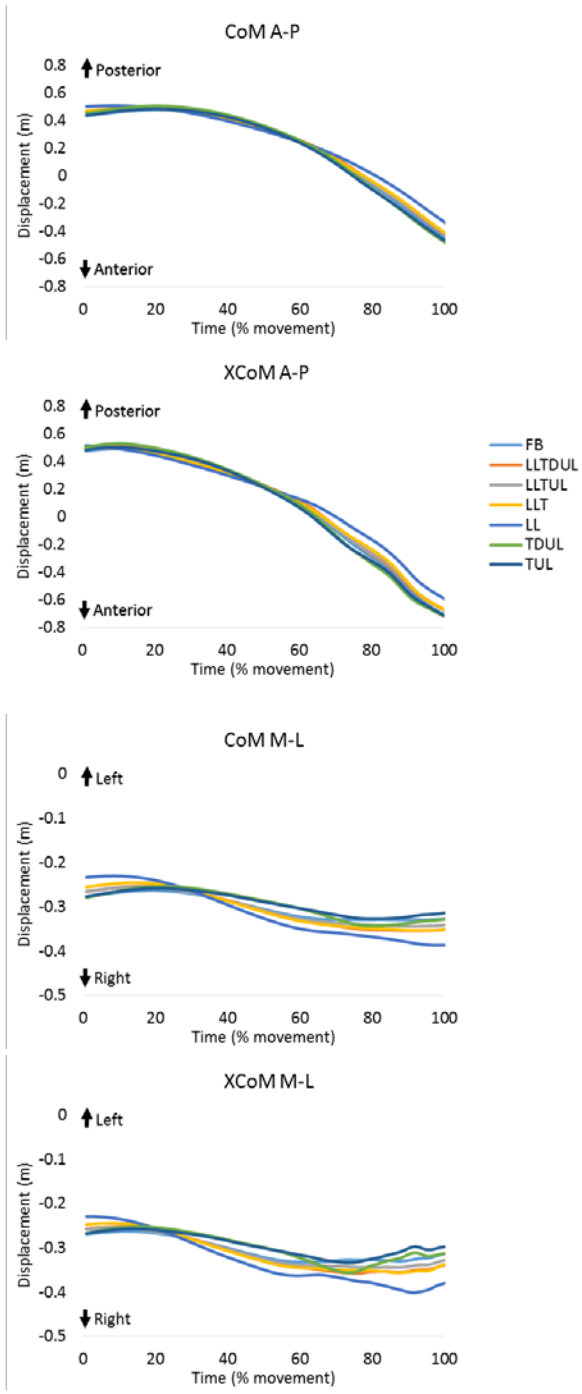

Figure B-3: (X)CoM trajectories in anterior-posterior (A-P) and medio-lateral (M-L) direction for a tennis serve (right-handed)