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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.

1. 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

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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 [1,5–8]. 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.

2. Methods

2.1. 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).

2.2. 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.

2.3. 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 Fig. 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).

2.4. 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.

3. 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 Figs. 2–4 .

3.1. 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