DOES THE METHOD OF MEASURING CENTRE OF MASS DISPLACEMENT AFFECT VERTICAL STIFFNESS CALCULATION IN SINGLE-LEG HOPPING?

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The purpose of this study was to compare vertical stiffness values calculated from two kinetic and two kinematic estimations of the vertical displacement of the centre of mass. Twenty recreationally active male and female participants completed one 15 s single-leg hopping trial at 2.2 Hz with vertical stiffness calculated for the first 10 complete hop cycles. Vertical displacement was estimated using double integration (DI), first principle (FP), sacral marker cluster (SMC) and segmental analysis (SA) methods. Bland-Altman plots demonstrated the SA and DI methods to have a small bias (0.92 kN/m) and tight 95% limits of agreement (-1.16 to 3.08 kN/m). In contrast, the SMC and FP methods underestimated and overestimated vertical stiffness, respectively. These findings suggest the SA and DI methods can be used interchangeably to calculate vertical stiffness.

KEY WORDS: agreement, lower limb, Bland-Altman, double integration.

INTRODUCTION: Lower limb stiffness is often measured during tasks of locomotion such as walking, running and hopping and has been suggested to influence a number of performance and injury risk characteristics (Butler, Crowell III, & Davis, 2003). Thus a consistent and accurate calculation of lower limb stiffness is of interest to many researchers and sports practitioners. Specifically, during on-the-spot-hopping vertical stiffness is calculated as the quotient of maximal ground reaction force and vertical centre of mass (COM) displacement (Butler et al., 2003). Ground reaction forces can be directly measured from a force platform, however it is not possible to measure the exact position of the COM. A number of methods have been developed to estimate vertical displacement of the COM, each with specific advantages and disadvantages (Hébert-Losier & Eriksson, 2014; Hobara, Inoue, Kobayashi, & Ogata, 2014; Ranavolo et al., 2008). However the accuracy of different methods for the calculation of vertical displacement may be task dependant (Ranavolo et al., 2008). Therefore, it remains unknown whether vertical COM displacements derived from different methods provides similar calculations of vertical stiffness during single-leg hopping. This remains problematic for the interpretation and comparison of new and existing research. The purpose of this study was to compare vertical stiffness values calculated from using two kinetic and two kinematic estimations of the vertical displacement of the COM during single-leg hopping.

METHODS: Following a warm-up and familiarisation period (Hobara, Inoue, Omuro, Muraoka, & Kanosue, 2011), twenty healthy recreationally active male and female participants completed 15 s of on-the-spot single-leg hopping on a force platform. Hopping was performed barefoot on the participants self-selected dominant leg (Padua et al., 2006) at 2.2 Hz controlled by an audible digital metronome. Kinetic (AMTI, Gen 5, USA) and kinematic data (NDI, Optotrak, Canada) were collected synchronously at 1500 Hz and 150 Hz (First Principles software, Version 1.2.4), respectively. Consistent with previous research, a seven-segment model was used to model the trunk (G. Wu et al., 2005), pelvis, thigh, shank (Ball, 2011), hindfoot, forefoot (W. L. Wu et al., 2000) and hallux (Stebbins, Harrington, Thompson, Zavatsky, & Theologis, 2006) of the hopping leg.

Kinetic data were dual-pass filtered with a low pass Butterworth filter with a 50 Hz cut-off. Kinematic data were interpolated using a spline interpolation for up to a maximum gap of 10 frames and dual-pass filtered using a fourth order Butterworth filter with an 8 Hz cut-off (Hobara et al., 2011)(Visual 3D, Version 4). Derived variables calculated were vertical stiffness and vertical displacement of the COM during the flight and loading phases. All COM displacement measures were derived using a sacral marker cluster (SMC), segmental analysis (SA), double integration (DI) and first principles (FP) methods as the mean of the first 10 hop cycles that were within 5% of the set hopping frequency (Microsoft Office Excel, 2007).

Vertical stiffness was calculated for each method as the quotient of maximal ground reaction force (N) and vertical displacement of the COM during loading (m) (Butler et al., 2003). The SMC method estimated the vertical displacement of the COM during the flight and loading phases by calculating the vertical displacement of the centre of the sacral marker cluster (Ranavolo et al., 2008). The SA method involved the calculation of the COM of the seven modelled upper and lower limb segments by default within Visual 3D (Version 4) using the location and masses of each segment. Vertical displacement of the COM was then calculated during the flight and loading phases. Double integration of the vGRF curve was used to estimate the vertical displacement of the COM during both flight and loading phases for the DI method (Butler et al., 2003; Hébert-Losier & Eriksson, 2014). The FP method used Newton's Laws of motion (Hall, 2007) to estimate the vertical displacement of the COM during the flight and loading phases (equation (1)–(3)). First the vertical displacement of the COM during the falling period of the flight phase (z_f) was calculated as:

$$z_f = (1/2)\times g\times(t_f/2)^2 \quad (1)$$

Following, the velocity of the COM at IC (v_i) was determined by:

$$v_i = (2\times g\times z_f)^{1/2} \quad (2)$$

Lastly, the vertical displacement of the COM during the loading phase (z_l) was calculated by:

$$z_l = [(v_i+v_f)/2]\times t_l \quad (3)$$

Where g was the acceleration due to gravity (-9.81 m.s^{-2}), t_f was the total time of the flight phase (s), and v_f was the velocity of the COM at peak force (0 m.s^{-1}).

To quantify the agreement between methods, Bland-Altman plots were created by plotting the mean difference (bias) against the mean result of each method pair (Bland & Altman, 1986). The 95% limits of agreement (LoA) were estimated as the mean difference ± 1.96 of the standard deviation of the difference (Bland & Altman, 1999).

RESULTS AND DISCUSSION: The main finding of this investigation revealed the SA and DI methods produced similar calculations of vertical stiffness during single-leg hopping. Bland-Altman plots revealed only a small bias (0.92 kN/m) and tight 95% LoA (-1.16 to 3.08 kN/m) between the SA and DI methods for the calculation of vertical stiffness (Figure 1). Further, Bland-Altman plots also revealed no increasing or decreasing trend between the size of the difference (bias) and the mean score of the SA and DI methods. Therefore, the current results suggest the SA and DI methods can be used interchangeably for the calculation of vertical stiffness during single-leg hopping. Although the DI method only requires a force platform and thus use outside of the laboratory is possible, the SA method is able to provide additional data such as three dimensional positions of the COM. Further, due to built-in calculations within common software such as Visual3D (Visual 3D, Version 4) the simplistic nature of the SA method and the increased availability and use of three dimensional motion capture equipment within human movement laboratories supports the use of the SA method.

In contrast, Bland-Altman plots revealed a large bias in vertical stiffness between the SMC and the SA (2.52 kN/m) and DI (3.48 kN/m) methods with an increasing bias trend as mean values increased (Figure 1). Therefore, the SMC method underestimated vertical stiffness with the size of the bias increasing as stiffness values increased and thus is not appropriate for the calculation of vertical stiffness during single-leg hopping at 2.2 Hz. The underestimation of vertical stiffness is due to an overestimation of vertical displacement of the COM which may be caused by a number of factors including pelvic tilt, clothing and skin movement artefact, all of which would be expected to be amplified during tasks with greater movement such as hopping or jumping at lower frequencies. However, the SMC may be an appropriate method for the calculation of vertical stiffness for tasks with less displacement, for example hopping at higher frequencies. Although future research is required to determine whether an increasing trend remains present during tasks when the vertical displacement of the COM is less.

The FP method overestimated vertical stiffness compared to all other methods with Bland-Altman plots revealing a large bias between the FP method and the SMC (21.46 kN/m), SA (18.94 kN/m) and DI (17.98 kN/m) methods (Figure 1). When compared to the SMC, SA and DI methods the FP method also demonstrated an increasing bias as mean values increased. The overestimation of the FP method for the calculation of vertical stiffness may be due to the assumptions required to calculate the vertical displacement of the COM during loading. When using the FP method it is assumed maximum velocity of the COM occurs at IC followed by a linear decrease to zero at peak vGRF. This assumption is incorrect as downward maximum vertical velocity of the COM is not reached until after IC when force equals body weight (Blickhan, 1989) and therefore vertical velocity of the COM during loading will be largely underestimated. Thus compared to other methods that do not rely on this assumption, the FP method will underestimate vertical displacement of the COM during loading causing vertical stiffness to be overestimated.

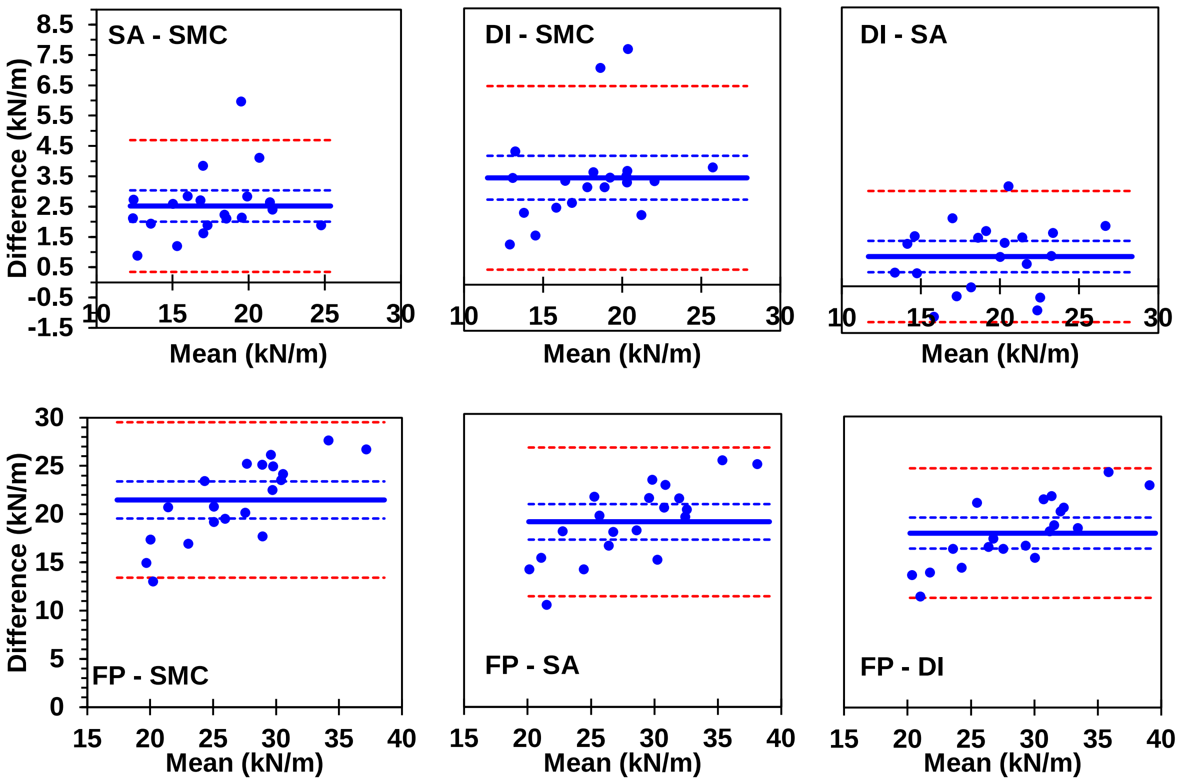

Figure 1: Bland-Altman plots for the comparison of vertical stiffness between the sacral marker cluster (SMC), segmental analysis (SA), double integration (DI) and first principles (FP) methods. Horizontal solid line = mean difference; inside dashed lines = 95% confidence intervals; and outside dashed lines = 95% limits of agreement.

CONCLUSION: This study highlights that the calculation of vertical stiffness is sensitive to the method used to estimate vertical displacement of the COM. This finding has implications for researchers and for interpretation of the scientific literature by practitioners. The current study suggests vertical stiffness calculated from the SA and DI estimations of COM vertical displacement can be appropriately compared and either method used to calculate vertical stiffness during single-leg hopping. However, the SMC and FP methods underestimated and overestimated calculated vertical stiffness values respectively, with the difference between methods increasing as the magnitude of vertical stiffness increased. Due to the invariable bias between the SA and DI methods over a range of vertical stiffness values, the SA and DI methods are suggested to be equally as representative of a measure of vertical stiffness over a greater range of values than the SMC and FP methods when assuming motion to be modelled as a spring-mass. Therefore, it is recommended that either the SA or DI methods be used to calculate vertical stiffness during single-leg hopping at 2.2 Hz.

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