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## Improving the Specificity of Vertical Stiffness Measurement in Depth Jump Landings

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IMPROVING THE SPECIFICITY OF VERTICAL STIFFNESS MEASUREMENT  
IN DEPTH JUMP LANDINGS

by

Miles A. Mercer

A Plan B thesis submitted in partial fulfillment  
of the requirements for the degree

of

Master of Science

in

Health and Human Movement

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## ABSTRACT

Greater lower extremity stiffness has been shown to increase bilateral jump height through stretch-shortening cycle optimization. Currently, there are two established methods for estimating vertical stiffness ( $K_{\text{vert}}$ ) of the human body, which is a variant of lower extremity stiffness. The validity of these methods for estimating  $K_{\text{vert}}$  in non-cyclical human movements has been questioned recently due to the complex physiological and neuromotor factors that support stiffness regulation in the muscle-tendon complex. The purpose of the present study was to improve the specificity of  $K_{\text{vert}}$  measurement using direct derivation of vertical ground reaction force (GRF) and center of mass displacement ( $d_{\text{CoM}}$ ) data that correspond with the landing phase of depth jumping (DJ). Twenty NCAA Division I basketball athletes (male = 9, female = 11; age =  $19.9 \pm 1.1$  years; mass =  $82.6 \pm 13.9$  kg; height =  $188.6 \pm 11.3$  cm) attended a single data collection session. Participants performed three successful trials of depth jumps (DJ) from drop heights of 0.51m, 0.66m, and 0.81m. DJ performance was measured using 2-dimensional video recordings and force platform dynamometry.  $K_{\text{vert}}$  was estimated using conventional methods as a ratio of maximum GRF to either  $d_{\text{CoM}}$  corresponding to the time point of maximum GRF ( $K_{\text{vert1}}$ ) or maximum  $d_{\text{CoM}}$  displacement ( $K_{\text{vert2}}$ ). GRF and  $d_{\text{CoM}}$  data were then interpolated using a Lagrange polynomial, yielding 1000 equally spaced data points in the  $d_{\text{CoM}}$  domain. Interpolated data were passed through a Savistky-Golay polynomial filter. Following interpolation,  $K_{\text{vert1}}$  and  $K_{\text{vert2}}$  were estimated a second time to evaluate for signal distortion. The new estimation method ( $K_{\text{vertNew}}$ ) was then calculated through first central difference derivation of interpolated GRF data with respect to interpolated  $d_{\text{CoM}}$  data. Simple linear regression models were fit to GRF and  $d_{\text{CoM}}$  data using  $K_{\text{vert1}}$  and  $K_{\text{vert2}}$  values. The validity of  $K_{\text{vert1}}$  and  $K_{\text{vert2}}$  was evaluated using Root Mean Square Error (RMSE) and coefficients of determination ( $R^2$ ) returned

from the linear models. Segmented linear regression was then fit to interpolated GRF and  $d_{CoM}$  data. The validity of  $K_{vertNew}$  was evaluated using RMSE and  $R^2$  values returned from the segmented linear models. One-way repeated measures ANOVAs were conducted to evaluate for main effects of estimation method on  $K_{vert}$ , RMSE, and  $R^2$ . Post-hoc comparisons were made using Bonferroni-adjusted paired  $t$ -tests. There were significant main effects of estimation method on  $K_{vert}$  ( $p < 0.001$ ), RMSE ( $p < 0.001$ ), and  $R^2$  values ( $p < 0.001$ ).  $K_{vert1}$  and  $K_{vert2}$  were significantly lower than peak  $K_{vertNew}$  ( $p < 0.001$ ) and significantly greater from mean  $K_{vertNew}$  ( $p < 0.001$ ).  $K_{vert1}$  and  $K_{vert2}$  were not affected by the interpolation technique ( $p = 1.0$ ). RMSE values were significantly greater for  $K_{vert1}$  and  $K_{vert2}$  when compared with  $K_{vertNew}$ .  $R^2$  values returned from the segmented linear models were significantly greater than values returned from the simple linear models constructed using  $K_{vert1}$  and  $K_{vert2}$  data.  $K_{vertNew}$  appears to be a feasible method for estimating  $K_{vert}$  in DJ landings.  $K_{vertNew}$  may also provide greater specificity and address the threats to validity associated with conventional estimation methods.

## INTRODUCTION

Mechanical stiffness is defined as the resistance of an object or body to a change in length when placed under mechanical stress (Brughelli & Cronin, 2007). In humans, stiffness affords a quantitative measurement of body elastic properties and is thought to influence several variables relating to human movement (i.e., elastic energy storage and utilization, sprint kinematics, and rate of force development (RFD) (Brughelli & Cronin, 2007; Struzik & Zawadzki, 2016). Lower extremity stiffness is observed to enhance, or at least have a major influence on, the performance of functional movements such as walking, running, and jumping (Brazier et al., 2014; Brughelli & Cronin, 2007; Brughelli & Cronin, 2008; Butler, Crowell, & Davis, 2003). For instance, greater lower extremity stiffness is suggested to increase bilateral jump height through stretch-shortening cycle (SSC) optimization (Brughelli & Cronin, 2007; Butler et al., 2003).

The literature has established several variants of lower extremity stiffness, which include vertical stiffness ( $K_{\text{vert}}$ ), leg stiffness ( $K_{\text{leg}}$ ), and joint stiffness ( $K_{\text{joint}}$ ).  $K_{\text{vert}}$  and  $K_{\text{leg}}$  are linear measures of lower extremity stiffness, while  $K_{\text{joint}}$  is a measure of rotational stiffness.  $K_{\text{vert}}$  is defined as human body resistance to center of mass (CoM) displacement when placed under stress from ground reaction force (GRF), while  $K_{\text{leg}}$  is defined as resistance to a change in leg length when placed under stress from GRF (Brazier et al., 2014; Maloney & Fletcher, 2018). Current convention is to estimate  $K_{\text{vert}}$  as a ratio of maximum GRF to either CoM displacement corresponding to the time point of maximum GRF (Equation 1;  $K_{\text{vert1}}$ ) or maximum CoM displacement (Equation 2;  $K_{\text{vert2}}$ ). The estimation of  $K_{\text{leg}}$  is similar, but includes change in leg length ( $\Delta L$ ) as the denominator variable in place of CoM displacement (Equation 3).  $K_{\text{joint}}$  is calculated by the ratio of joint moment ( $J_m$ ) to angular joint displacement ( $J_d$ ) and has been

shown to influence  $K_{leg}$  and  $K_{vert}$  in running and hopping movements (Brughelli & Cronin, 2007; Brughelli & Cronin, 2008; Butler et al. 2003; Serpell, Ball, Scarvell, & Smith 2012).

$$(1) K_{vert1} = \frac{F_{max}}{\Delta y}$$

where  $K_{vert}$  = vertical stiffness,  $F_{max}$  = maximum GRF, and  $\Delta y$  = CoM displacement corresponding to the time point of  $F_{max}$ .

$$(2) K_{vert2} = \frac{F_{max}}{\Delta y_{max}}$$

where  $K_{vert}$  = vertical stiffness,  $F_{max}$  = maximum GRF, and  $\Delta y_{max}$  = maximum CoM displacement.

$$(3) K_{leg} = \frac{F_{max}}{\Delta L}$$

where  $K_{leg}$  = leg stiffness,  $F_{max}$  = maximum GRF, and  $\Delta L$  = change in leg length.

$$(4) K_{joint} = \frac{J_M}{J_D}$$

where  $K_{joint}$  = joint stiffness,  $J_M$  = joint Moment, and  $J_d$  = joint displacement.

To estimate  $K_{vert}$  and  $K_{leg}$  (Equations 1-3), the human body is modelled as an ideal spring-mass, with stiffness modelled as a constant linear ratio of stress ( $\sigma$ ) to strain ( $\epsilon$ ) (Equation 5; Brughelli et al., 2008; Butler et al., 2003; Maloney & Fletcher, 2018). Ideal spring-mass models yield point measure estimates of  $K_{vert}$  and  $K_{leg}$  that are assumed to represent lower extremity stiffness with acceptable validity. Prior literature supports ideal spring-mass models of lower extremity stiffness in cyclical human movements, such as walking, running, and repetitive jumping (Butler et al., 2003; Cavagna, Franzetti, Heglund, & Williems, 1987; Maloney & Fletcher, 2018; Padua et al., 2006). For instance, ideal spring-mass estimates of  $K_{vert}$  have been validated against criterion GRF-CoM displacement curves in running ( $r = 0.96$ , Cavagna et al.,

1988) and repetitive jumping ( $r = 0.99$ , Padua et al., 2006). In addition, moderate to strong reliabilities are observed for ideal spring-mass estimates of  $K_{\text{vert}}$  and  $K_{\text{leg}}$  in running ( $ICC = 0.87-0.98$ ) and repetitive jumping ( $ICC = 0.61-0.98$ ; Maloney & Fletcher, 2018).

$$(5) K = \sigma/\varepsilon$$

where  $K$  = stiffness,  $\sigma$  = stress,  $\varepsilon$  = strain.

Validity of the ideal spring-mass assumption may not generalize to non-cyclical human movements (Maloney & Fletcher, 2018; Struzik & Zawadski, 2016). For instance, Maloney & Fletcher (2018) suggest that  $K_{\text{vert}}$  and  $K_{\text{leg}}$  values from repetitive jumping misrepresent the complexity of stiffness recruitment strategies involved in performing ‘maximal athletic tasks’. This notion is supported by Struzik & Zawadski (2016), who contend that point measure estimates of  $K_{\text{vert}}$  are quasi-valid in single-repetition maximal effort jumping. In cyclical movements, humans adopt a relatively constant level of  $K_{\text{vert}}$  to gain mechanical efficiency. The mechanical efficiency of single-repetition, maximal effort tasks is not as crucial to performance, thus the stiffness recruitment strategy is typically more variable and dependent on the body’s prediction and response to the mechanical load applied. Struzik & Zawadski (2016) improved the validity of  $K_{\text{vert}}$  estimation in countermovement jumping (CMJ) by fitting separate linear models to GRF-CoM displacement data corresponding with the countermovement and take-off phases. This approach returned valid estimates of  $K_{\text{vert}}$  ( $R^2 = 0.96-0.97$ ) that were substantially different from  $K_{\text{vert}}$  values obtained using  $K_{\text{vert}1}$  (-53-58%) and  $K_{\text{vert}2}$  (+60-79%; Struzik & Zawadski, 2016). Accordingly, results by Struzik & Zawadski (2016) suggest a need to evaluate the validity of generalizing the ideal spring-mass assumption to maximal effort jumping movements, such as CMJ and depth jumping (DJ).

DJ, in particular, is a skillful movement requiring the performance of a maximal jump upwards that immediately succeeds landing impact from a self-initiated drop. Stiffness recruitment strategies in DJ are complex and involve pre-activation of core and lower extremity skeletal muscle during the drop phase (Galindo et al., 2009; Helm et al., 2020; Helm, Freyler, Waldvogel, Gollhofer, & Ritzmann, 2019; Kamibayashi & Muro, 2006; Santello, 2005). Skeletal muscle pre-activation is decidedly variable and important for optimizing lower extremity stiffness in anticipation of the timing and magnitude of landing impact GRFs (Helm et al., 2020; Helm et al., 2019; Santello, 2005). Moreover, pre-activation is thought to prepare short latency spinal reflexes for rapid adjustment of lower extremity stiffness in response to landing impact GRF (Kamibayashi & Muro, 2006; Santello, 2005).

When considering the complexity of stiffness recruitment strategies in DJ, there is a need to explore methods for estimating  $K_{\text{vert}}$  that address the potential threats to validity associated with conventional ideal spring-mass models. With time-series interpolation, it may be possible to derive  $K_{\text{vert}}$  directly from GRF and CoM displacement data. In theory, direct derivation may yield valid estimates of  $K_{\text{vert}}$ , however, the feasibility and validity of this approach have not been formally investigated. Thus, the purpose of this study is to evaluate a method for estimating  $K_{\text{vert}}$  ( $K_{\text{vertNew}}$ ) that involves direct derivation of GRF and CoM displacement data corresponding with the landing phase of DJ. We hypothesized that  $K_{\text{vert}}$  would not behave as an ideal spring-mass, thus  $K_{\text{vert1}}$  and  $K_{\text{vert2}}$  would not yield valid estimates of  $K_{\text{vert}}$  during DJ landings. We also hypothesized that  $K_{\text{vertNew}}$  could be a feasible approach for improving the validity of  $K_{\text{vert}}$  estimation in DJ landings.



## METHODOLOGY

### Study Design

A single cohort, repeated measures experimental design was used to compare the differences between the validity of conventional methods for estimating  $K_{\text{vert}}$  and a proposed method that involves direct derivation of GRF and CoM displacement data in depth jump landings.

### Participants

Twenty NCAA Division I basketball athletes (male = 9, female = 11; age =  $19.9 \pm 1.1$  years; mass =  $82.6 \pm 13.9$  kg; height =  $188.6 \pm 11.3$  cm) volunteered to participate in this investigation. Athletes were required to have no recent history of lower extremity injury (<12 months) requiring surgical intervention and were actively training in a pre-season strength and conditioning program. Participants were recruited on a volunteer basis and were required to provide written consent on an informed consent document approved by the University's Institutional Review Board.

### Experimental Procedures

Participants were asked to report to a Human Performance Laboratory for a single data collection session conducted in the morning. Participants were required to wear practice attire, which included a t-shirt, athletic shorts, and court shoes. Each session lasted approximately 1 hour. Upon arrival to the laboratory, participants completed an approximate 15 minute warm-up that included a brief jog and dynamic exercises including jumping jacks, high knees, lateral shuffle, and carioca. Participants rested for approximately 5 minutes and then completed a familiarization of the DJ technique.

Familiarization of the study procedures consisted of visual demonstration of the DJ technique by a member of the research team and participant practice. Participants were allowed an unrestricted number of practice trials, yet were asked to practice jumping from each drop height a minimum of three times. Generally, participants performed three to five practice trials at each drop height in familiarization. Prior to each practice trial, participants were instructed with the following standard verbal cue: “Step forward off the box with your preferred foot, land with both feet hitting the ground simultaneously, and then jump upwards as quickly and as high as possible.” Practice trials were monitored by a member of the research team, with corrective verbal feedback provided, if necessary. Most commonly, corrective feedback was provided if participants stepped down instead of forward off the box or if they paused excessively during landing impact.

After completing familiarization, participants rested for 20 minutes and then completed three successful trials of DJ from drop heights of 0.51m, 0.66m, and 0.81m. For each trial, participants self-initiated the drop phase while standing atop a custom plyometric box (0.51m x 0.66m x 0.81m). The order of drop heights was randomized for each participant, with all three trials performed before advancing to the subsequent height. Participants rested for approximately 1 minute between trials and 5 minutes between drop height conditions. Prior to each trial, participants were instructed with the same standard verbal cue provided in familiarization. Arm motion was not restricted to maximize the ecological validity of dependent measures. Trials were monitored visually by a member of the research team to ensure that participants landed from the drop phase with full foot contact on a force platform (Model FP4080, Bertec Corporation, Columbus, OH, USA). The leading edge of the force platform was positioned 0.30m in front of the plyometric box and the force platform was recessed to be flush

with the laboratory floor. Force platform hardware was calibrated before testing and zeroed before each jump condition.

## **Data Analyses**

### *2-dimensional Videography*

Reflective markers were affixed to participants according to segment endpoint locations specified by the 14-segment de Leva (1996) anthropometric model. Video recordings of each DJ trial were captured using a high-speed camera (300 Hz; Model EX-F1, Casio, Shibuya, Tokyo, Japan). The camera was located 5 m from the right perspective of participants and aligned perpendicular to the sagittal movement plane. The camera was levelled and secured at a height of 0.67 m above the laboratory floor. Video recordings were digitized in Kinovea (version 0.8.27) to estimate vertical segment endpoint trajectories. Digitization began approximately 1 second prior to movement initiation and ended when participants left the ground for the rebound jump.

Vertical segment endpoint trajectories were passed through a low-pass, recursive, 4th order Butterworth filter set to a 6 Hz cut-off frequency in MATLAB (The Mathworks, Natick, MA, USA). Vertical whole-body CoM trajectories were estimated in accordance with the de Leva (1996) anthropometric model. Vertical whole-body CoM velocities were then estimated from first central difference derivation of vertical whole-body CoM trajectories. Vertical landing impact velocity ( $v_i$ ) was specified as the maximum downward velocity value.

### *Force Platform Dynamometry*

GRF data were sampled at 1000 Hz using a tri-axial force platform and processed in MATLAB. GRF data were passed through a low-pass, recursive, 4th order Butterworth filter set

to a cut-off frequency of 300 Hz. Using methods described previously (Louder, Bressel, Nardoni, & Dolny, 2019), GRF data were pared to begin at the time instant of landing from the drop phase and end at the time instant of rebound jump take-off using a RFD method described previously (Louder et al., 2019). The change in whole-body CoM velocity ( $v$ ) was estimated through numerical integration (trapezoidal rule) of filtered GRF data (Equation 6). True whole-body CoM velocity ( $v_{CoM}$ ) was estimated by removing  $v_i$  from  $v$  signals (Equation 7). Whole-body CoM displacement ( $d_{CoM}$ ) was then estimated through numerical integration (trapezoidal rule) of  $v_{CoM}$  data (Equation 8).

$$(6) \ v = \frac{\int(GRF-BW)}{mass}$$

$$(7) \ v_{CoM} = v - v_i$$

$$(8) \ d_{CoM} = \int v_{CoM}$$

### *K<sub>vert</sub> Estimation*

All estimations of  $K_{vert}$  were performed in MATLAB. First,  $K_{vertNew}$  was estimated from filtered GRF and  $d_{CoM}$  data using Equations 1 and 2. Next, in a custom Microsoft Excel spreadsheet (Microsoft Corporation, Redmond, WA, USA), filtered GRF and  $d_{CoM}$  data were interpolated using a Lagrange polynomial (Equation 9). The interpolation technique yielded 1000 data points for GRF and  $d_{CoM}$  that were equally spaced in the displacement domain. Interpolated GRF and  $d_{CoM}$  data was then smoothed using a Savitzky-Golay filter, which is a digital polynomial filter that can be applied to non-time-series signals. The Savitzky-Golay filter was specified to fit a moving 6<sup>th</sup> order polynomial to a window size of 75 data points. Furthermore, filter parameters were selected based on a visual inspection of filtered data, which optimized the removal of noise and preserved the tendency of the signal. To evaluate for distortion of GRF and

$d_{CoM}$  data post-interpolation,  $K_{vert}$  was estimated a second time using  $K_{vert1}$  and  $K_{vert2}$  estimation methods. Lastly,  $K_{vertNew}$  was estimated through first central difference derivation of interpolated GRF data with respect to interpolated  $d_{CoM}$  data. Peak and mean values were then taken from  $K_{vertNew}$  data.

$$(9) \quad GRF_{new} = GRF_{d-1} \times \frac{(d_{new}-d)(d_{new}-d_{+1})}{(d_{-1}-d)(d_{-1}-d_{+1})} + GRF_d \times \frac{(d_{new}-d_{-1})(d_{new}-d_{+1})}{(d-d_{-1})(d-d_{+1})} + \\ GRF_{d+1} \times \frac{(d_{new}-d_{-1})(d_{new}-d)}{(d_{+1}-d_{-1})(d_{+1}-d)}$$

In MATLAB, linear regression models were fit to pre- and post-interpolated GRF and  $d_{CoM}$  data using  $K_{vert}$  values estimated from Equations 1 and 2 (Equation 10). For all linear models, Root Mean Square Error (RMSE) and the coefficient of determination ( $R^2$ ) were computed to give an evaluation of model performance.

$$(10) \quad GRF = K_{vert} * d_{CoM}$$

Interpolated GRF and  $d_{CoM}$  data were passed through segmented linear regression in RStudio (version 1.1.456). The maximum number of breakpoints was set to 10, which allowed for a maximum of 11 linear segments to be fit to the data. The selection of optimal breakpoints was performed iteratively and was based on minimization of the Bayesian Information Criterion ( $\alpha = 0.05$ ). RMSE and  $R^2$  were computed from segmented models to give an evaluation of model performance.

### Statistical Analyses

The effect of estimation method on  $K_{vert}$  was evaluated using a one-way Repeated Measures Analysis of Variance (RMANOVA; [Pre- $K_{vert1}$   $\times$  Post- $K_{vert1}$   $\times$  Pre- $K_{vert2}$   $\times$  Post- $K_{vert2}$   $\times$  peak  $K_{vertNew}$   $\times$  mean  $K_{vertNew}$ ]). The effect of estimation method on the RMSE and  $R^2$  returned

from linear models was evaluated using separate one-way RMANOVAs ([Pre- $K_{\text{vert}1}$   $\times$  Post- $K_{\text{vert}1}$   $\times$  Pre- $K_{\text{vert}2}$   $\times$  Post- $K_{\text{vert}2}$   $\times$   $K_{\text{vertNew}}$ ]). Following observation of main effects, post-hoc analyses were performed using paired  $t$ -tests and a Bonferroni adjustment. Statistical analyses were performed using RStudio (version 1.1.456) and all hypothesis tests were conducted using a type I error threshold of 0.05.

## RESULTS

### Central Tendency and Dispersion

Central tendency and dispersion results for  $K_{\text{vert}}$ , RMSE, and  $R^2$  are presented in

Table 1.

Table 1. Central tendency and dispersion results.

Estimation Method	$K_{\text{vert}}$ ( $\text{N} \cdot \text{m}^{-1}$ )	RMSE (N)	$R^2$
Pre- $K_{\text{vert}1}$	19117.73 $\pm$ 7649.17	665.45 $\pm$ 360.66	.87 $\pm$ .09
Pre- $K_{\text{vert}2}$	11869.30 $\pm$ 5527.19	1126.73 $\pm$ 601.77	.41 $\pm$ .29
Post- $K_{\text{vert}1}$	19308.11 $\pm$ 7318.59	664.79 $\pm$ 355.38	.86 $\pm$ .09
Post- $K_{\text{vert}2}$	11851.02 $\pm$ 5543.20	908.52 $\pm$ 429.20	.52 $\pm$ .30
Mean $K_{\text{vertNew}}$	7307.23 $\pm$ 3785.95		
Peak $K_{\text{vertNew}}$	81222.99 $\pm$ 34471.44	$K_{\text{vertNew}}$ 49.02 $\pm$ 42.90	1.00 $\pm$ .01

*Note:* Data corresponds with the performance of depth jump landings from drop heights of 0.51, 0.66, and 0.81m. Jumps were performed by a mixed-sex sample of NCAA Division I basketball athletes. Data are averaged across sex and drop height.  $K_{\text{vert}1}$  = vertical landing stiffness estimated by taking a ratio of maximum GRF to CoM displacement corresponding to the time point of maximum GRF.  $K_{\text{vert}2}$  = vertical landing stiffness estimated by taking a ratio of maximum GRF to maximum CoM displacement. Pre- and post- values correspond with estimates taken before and following Lagrange polynomial interpolation of GRF and CoM data, respectively.  $K_{\text{vertNew}}$  = vertical landing stiffness estimated from first central difference derivation of GRF data with respect to CoM data. Data are reported as mean  $\pm$  SD.

**$K_{\text{vert}}$**

There was a significant main effect of estimation method on  $K_{\text{vert}}$  ( $F = 137.2$ ;  $p < 0.001$ ). Post-hoc comparisons revealed no significant differences between the pre- and post-interpolation values for  $K_{\text{vert1}}$  and  $K_{\text{vert2}}$  ( $p = 1.00$ ). All other post-hoc comparisons were significant ( $p < 0.001$ ; Table 2). Notably,  $K_{\text{vert1}}$  values were significantly greater than  $K_{\text{vert2}}$  values ( $p < .001$ ; Tables 1 and 2). In addition,  $K_{\text{vert1}}$  and  $K_{\text{vert2}}$  values were significantly greater than mean  $K_{\text{vertNew}}$  values ( $p < .001$ ; Tables 1 and 2) and significantly smaller than peak  $K_{\text{vertNew}}$  values ( $p < .001$ ; Tables 1 and 2).

Table 2. Post-hoc comparisons -  $K_{\text{vert}}$  ( $\text{N} \cdot \text{m}^{-1}$ )

Estimation Method	Pre- $K_{\text{vert1}}$	Pre- $K_{\text{vert2}}$	Post- $K_{\text{vert1}}$	Post- $K_{\text{vert2}}$	Mean $K_{\text{vertNew}}$	Peak $K_{\text{vertNew}}$
Pre- $K_{\text{vert1}}$	-	$p < 0.001$	$p = 1.0$	$p < 0.001$	$p < 0.001$	$p < 0.001$
Pre- $K_{\text{vert2}}$	-	-	$p < 0.001$	$p = 1.0$	$p < 0.001$	$p < 0.001$
Post- $K_{\text{vert1}}$	-	-	-	$p < 0.001$	$p < 0.001$	$p < 0.001$
Post- $K_{\text{vert2}}$	-	-	-	-	$p < 0.001$	$p < 0.001$
Mean $K_{\text{vertNew}}$	-	-	-	-	-	$p < 0.001$

*Note:*  $p$ -values correspond with Bonferroni-adjusted pairwise comparisons of  $K_{\text{vert}}$  derived using different estimation methods.  $K_{\text{vert}}$  values were estimated from depth jump landings performed at drop heights of 0.51, 0.66, and 0.81m. Jumps were performed by a mixed-sex sample of NCAA Division I basketball athletes (male = 9; female = 11).  $K_{\text{vert}}$  values were averaged across sex and drop height.  $K_{\text{vert1}}$  = vertical landing stiffness estimated by taking a ratio of maximum vertical ground reaction force (GRF) to whole-body center of mass displacement ( $d_{\text{CoM}}$ ) corresponding to the time point of maximum GRF.  $K_{\text{vert2}}$  = vertical landing stiffness estimated by taking a ratio of maximum GRF to maximum  $d_{\text{CoM}}$ . Pre- and post- values correspond with estimates taken before and following a Lagrange polynomial interpolation of GRF and  $d_{\text{CoM}}$  data, respectively.  $K_{\text{vertNew}}$  = vertical landing stiffness estimated from first central difference derivation of GRF data with respect to  $d_{\text{CoM}}$  data.

## RSME

There was a significant main effect of estimation method on RMSE ( $F = 141.0$ ,  $p < 0.001$ ). Post-hoc comparisons revealed no significant differences between the RMSE returned from linear models constructed using pre- and post-interpolation  $K_{\text{vert1}}$  values ( $p = 1.00$ ; Table 3). All other post-hoc comparisons were significant ( $p < 0.001$ ; Table 3). Notably, RMSE values

returned from linear models constructed using  $K_{\text{vert1}}$  values were significantly smaller than for models constructed using  $K_{\text{vert2}}$  values ( $p < 0.001$ ; Tables 1 and 3). In addition, RMSE values returned from linear models constructed using  $K_{\text{vert1}}$  and  $K_{\text{vert2}}$  values were significantly greater than RMSE values returned from segmented linear models ( $p = < 0.001$ ; Tables 1 and 3). Lastly, RMSE values returned from linear models constructed using pre-interpolated  $K_{\text{vert2}}$  values were significantly greater than RMSE values returned from models that were constructed using post-interpolated  $K_{\text{vert2}}$  values ( $p < 0.001$ ; Tables 1 and 3).

Table 3. Post-hoc comparisons – RMSE (N)

Estimation Method	Pre- $K_{\text{vert1}}$	Pre- $K_{\text{vert2}}$	Post- $K_{\text{vert1}}$	Post- $K_{\text{vert2}}$	Segmented Regression
Pre- $K_{\text{vert1}}$	-	$p < 0.001$	$p = 1.0$	$p < 0.001$	$p < 0.001$
Pre- $K_{\text{vert2}}$	-	-	$p < 0.001$	$p < 0.001$	$p < 0.001$
Post- $K_{\text{vert1}}$	-	-	-	$p < 0.001$	$p < 0.001$
Post- $K_{\text{vert2}}$	-	-	-	-	$p < 0.001$

*Note:* :  $p$ -values correspond with Bonferroni-adjusted pairwise comparisons of RMSE returned from linear models of ground reaction force (GRF) and whole-body center of mass displacement ( $d_{\text{CoM}}$ ). Linear models were constructed from  $K_{\text{vert}}$  derived using different estimation methods.  $K_{\text{vert}}$  values were estimated from depth jump landings performed at drop heights of 0.51, 0.66, and 0.81m. Jumps were performed by a mixed-sex sample of NCAA Division I basketball athletes (male = 9; female = 11). RMSE values were averaged across sex and drop height.  $K_{\text{vert1}}$  = vertical landing stiffness estimated by taking a ratio of maximum GRF to  $d_{\text{CoM}}$  corresponding to the time point of maximum GRF.  $K_{\text{vert2}}$  = vertical landing stiffness estimated by taking a ratio of maximum GRF to maximum  $d_{\text{CoM}}$ . Pre- and post- values correspond with estimates taken before and following a Lagrange polynomial interpolation of GRF and  $d_{\text{CoM}}$  data, respectively.

## $R^2$

There was a significant main effect of estimation method on  $R^2$  ( $F = 141.0$ ,  $p < 0.001$ ). All post-hoc comparisons were significant ( $p < 0.001$ ; Table 4). Notably,  $R^2$  values returned from linear models constructed using  $K_{\text{vert1}}$  values were significantly greater than for models constructed using  $K_{\text{vert2}}$  values ( $p < 0.001$ ; Tables 1 and 4).  $R^2$  values returned from linear models created using  $K_{\text{vert1}}$  and  $K_{\text{vert2}}$  were significantly smaller than  $R^2$  values returned from



linear models created using  $K_{\text{vertNew}}$  ( $p < 0.001$ ; Table 4).  $R^2$  values returned from linear models created using pre- $K_{\text{vert2}}$  were significantly smaller than  $R^2$  values returned from post- $K_{\text{vert2}}$  ( $p < 0.001$ ; Tables 1 and 4).

Table 4. Post-hoc comparisons –  $R^2$

Estimation Method	Pre- $K_{\text{vert1}}$	Pre- $K_{\text{vert2}}$	Post- $K_{\text{vert1}}$	Post- $K_{\text{vert2}}$	Segmented Regression
Pre- $K_{\text{vert1}}$	-	$p < 0.001$	$p < 0.001$	$p < 0.001$	$p < 0.001$
Pre- $K_{\text{vert2}}$	-	-	$p < 0.001$	$p < 0.001$	$p < 0.001$
Post- $K_{\text{vert1}}$	-	-	-	$p < 0.001$	$p < 0.001$
Post- $K_{\text{vert2}}$	-	-	-	-	$p < 0.001$

*Note:*  $p$ -values correspond with Bonferroni-adjusted pairwise comparisons of  $R^2$  returned from linear models of ground reaction force (GRF) and whole-body center of mass displacement ( $d_{\text{CoM}}$ ). Linear models were constructed from  $K_{\text{vert}}$  derived using different estimation methods.  $K_{\text{vert}}$  values were estimated from depth jump landings performed at drop heights of 0.51, 0.66, and 0.81m. Jumps were performed by a mixed-sex sample of NCAA Division I basketball athletes (male = 9; female = 11).  $R^2$  values were averaged across sex and drop height.  $K_{\text{vert1}}$  = vertical landing stiffness estimated by taking a ratio of maximum GRF to  $d_{\text{CoM}}$  corresponding to the time point of maximum GRF.  $K_{\text{vert2}}$  = vertical landing stiffness estimated by taking a ratio of maximum GRF to maximum  $d_{\text{CoM}}$ . Pre- and post- values correspond with estimates taken before and following a Lagrange polynomial interpolation of GRF and  $d_{\text{CoM}}$  data, respectively.

## DISCUSSION

The purpose of the present investigation was to evaluate a method for estimating  $K_{\text{vert}}$  ( $K_{\text{vertNew}}$ ) that involves first central difference derivation of GRF and  $d_{\text{CoM}}$  data corresponding with the landing phase of DJ. In the present investigation,  $K_{\text{vert1}}$  and  $K_{\text{vert2}}$  values were similar with values reported previously in the literature (Dutto & Smith, 2002; Morin, Belli, & Dalleau 2005; Padua et al., 2006; Struzik & Zawadski, 2016).  $K_{\text{vert1}}$  values were significantly greater than  $K_{\text{vert2}}$  values, which suggests that  $K_{\text{vert1}}$  and  $K_{\text{vert2}}$  are not interchangeable and, more importantly, the results and conclusions drawn from investigations that report  $K_{\text{vert1}}$  values may not be comparable to those that report  $K_{\text{vert2}}$  values. Our linear regression models suggest that  $K_{\text{vert1}}$

provides a more valid estimate ( $RMSE = 665.45 \pm 360.66$ ;  $R^2 = .87 \pm .09$ ) than  $K_{vert2}$  ( $RMSE = 1126.73 \pm 601.77$  N;  $R^2 = 0.41 \pm 0.29$ ).  $K_{vert1}$  captures a point estimate that corresponds with the time period between landing impact and the expression of peak GRF. Since the expression of GRF peak occurs rapidly following impact,  $K_{vert1}$  values are limited to providing a partial representation of  $K_{vert}$  in DJ landings.

Struzik & Zawadski (2016) found that  $K_{vert}$  values differ between the countermovement and take-off phases of CMJ. From this, Struzik & Zawadski (2016) contend that assuming  $K_{vert}$  values expressed during the countermovement phase are the same as the take-off phase is an over-simplification that results in quasi-valid estimates of  $K_{vert}$ . Since the DJ technique is more complex than CMJ, it was not surprising that the linear models constructed from  $K_{vert2}$  values returned RMSE and  $R^2$  values that imply poor validity. DJ consists of a landing phase, amortization, and a take-off phase.  $K_{vert2}$  is estimated as a ratio of maximum GRF, which is typically expressed during the landing phase, to the maximum  $d_{CoM}$  expressed at amortization (Struzik & Zawadski, 2016). Consequently,  $K_{vert2}$  is a linear model of stiffness that is derived from data corresponding to different phases of the DJ. According to the ideal spring-mass assumption, maximum GRF and maximum  $d_{CoM}$  should be expressed at the same time. The observation that this doesn't occur is evidence of the threat to validity associated with ideal spring-mass modelling of DJ landings.

To estimate  $K_{vertNew}$ , GRF and  $d_{CoM}$  data were interpolated using a Lagrange polynomial, which provided equally spaced  $d_{CoM}$  data prior to taking the derivative. This approach has not been evaluated for feasibility, therefore we estimated  $K_{vert1}$  and  $K_{vert2}$  values using both pre- and post-interpolated GRF and  $d_{CoM}$  data.  $K_{vert1}$  and  $K_{vert2}$  values from pre- and

post-interpolated data were not different ( $p = 1.0$ ), suggesting that there was minimal signal distortion post-interpolation.

We compared mean and peak  $K_{\text{vertNew}}$  values against  $K_{\text{vert1}}$  and  $K_{\text{vert2}}$  values. In theory,  $K_{\text{vert1}}$  and  $K_{\text{vert2}}$  provide an estimate of mean  $K_{\text{vert}}$  since both methods model the body as an ideal spring-mass. In the present investigation,  $K_{\text{vert1}}$  and  $K_{\text{vert2}}$  were significantly greater than mean  $K_{\text{vertNew}}$  ( $p < 0.001$ ) and significantly lower than peak  $K_{\text{vertNew}}$  ( $p < 0.001$ ). These findings suggest that  $K_{\text{vertNew}}$  may provide a more valid representation of mean and peak  $K_{\text{vert}}$  in DJ landings due to the consistency with which  $K_{\text{vert1}}$  and  $K_{\text{vert2}}$  overestimate mean  $K_{\text{vertNew}}$  and underestimate peak  $K_{\text{vertNew}}$ . Furthermore, the RMSE and  $R^2$  values returned from the segmented linear regression models support the validity of  $K_{\text{vertNew}}$ . The segmented linear models returned significantly smaller RMSE values ( $p < 0.001$ ) and significantly greater  $R^2$  values ( $p < 0.001$ ) when compared against values returned from the simple linear models that were constructed using  $K_{\text{vert1}}$  and  $K_{\text{vert2}}$  data. These findings suggest that  $K_{\text{vert}}$  is not a consistent value during DJ landings and, thus, may be misrepresented by the single point-measure estimates provided by  $K_{\text{vert1}}$  and  $K_{\text{vert2}}$ . The RMSE and  $R^2$  results from our segmented models suggest that  $K_{\text{vertNew}}$  may be a valid and feasible approach for addressing this issue.

The results of the present investigation are not surprising when considering the physiological underpinnings that support stiffness regulation of the muscle-tendon complex. Hill-type models are often used to provide a simplistic representation of muscle mechanics. Generally, Hill-type models include a series elastic component (SEC) that acts in series with the contractile component (CC) and a parallel elastic component (PEC) that acts in parallel to the CC (Siebert, Rode, Herzog, Till, & Blickhan, 2007). The CC is sensitive to electro-chemical stimuli and produces active stiffness in response to neuromotor signaling. Active muscle stiffness is

explained by the cross-bridge theory, suggesting that the attachment of myosin heads on to the actin myofilament forms cross bridges that interact to produce force in the muscle.

The traditional view is that the SEC and PEC contribute to muscle stiffness through passive storage of elastic energy. Furthermore, these passive components of muscle are thought to enhance the force output and metabolic efficiency of jumping movements that evoke a SSC action. Passive contributions to the SSC are traditionally believed to be due to the storage of elastic energy in tendon (Rassier, MacIntosh, & Herzog, 1999; Fukutani et al., 2021). Recently, Fukutani et al. (2021) discovered that titin, a structural protein embedded in the sarcomeres of muscle fibers, plays a complex role in regulating the passive stiffness of skeletal muscle. Fukutani et al. (2021) suggest that, in addition to storing elastic energy, the passive stiffness of titin is regulated through the presence of Calcium. According to Fukutani et al. (2021), the binding of Calcium to titin may increase the passive stiffness of skeletal muscle. Further, an increase in the passive stiffness of the sarcomere may result in residual force enhancement (RFE), which Fukutani et al. (2021) describe as an increase in muscle contraction Force occurring in absence of a stretch placed on the muscle.

In addition to muscle physiology, the neuromotor control of DJ adds an additional tier of complexity to stiffness regulation. During the DJ drop phase, the neuromotor system must correctly anticipate the expression of GRF by pre-activating skeletal muscle prior to landing impact. Pre-activation adjusts muscle stiffness to optimize the SSC enhancement of muscle performance and to prevent injury. Pre-activation during the drop phase of DJ is variable (Helm et al., 2019), leading to complex stiffness recruitment strategies expressed during landing. In the present investigation,  $K_{\text{vertNew}}$  data reflect this complexity and give evidence that  $K_{\text{vert}}$  may not be adequately measured by the point-measure estimates provided by  $K_{\text{vert1}}$  and  $K_{\text{vert2}}$ .

In jumping movements, the pre-activation of skeletal muscle is a fundamental component of the SSC action that provides a sufficient level of stiffness in the muscle-tendon complex upon landing. Pre-activation is thought to improve the utilization of stored elastic energy during the take-off phase of jumping (Helm et al., 2019). Further, greater musculotendinous stiffness is suggested to increase the storage and release of elastic energy from an SSC action, thereby enhancing performance of the jump (Helm et al. 2019). Thus,  $K_{\text{vert}}$  is observed to be an important variable in athletic performance, despite optimal levels of stiffness not being defined in the literature (Joseph, Bradshaw, Kemp, & Clark 2013).  $K_{\text{vert}1}$  and  $K_{\text{vert}2}$  are the conventional methods used to estimate  $K_{\text{vert}}$  across a variety of human movements. Results of the present investigation suggest that these methods are not sensitive to the subtle changes in  $K_{\text{vert}}$  that occur during the landing phase of DJ.

$K_{\text{vertNew}}$  is a new method proposed in the present investigation that may offer the potential to examine  $K_{\text{vert}}$  with greater specificity. By estimating  $K_{\text{vert}}$  through direct derivation of GRF and  $d_{\text{CoM}}$  data,  $K_{\text{vertNew}}$  may provide more valid estimates of peak and mean  $K_{\text{vert}}$ . Furthermore,  $K_{\text{vertNew}}$  may provide insight into the complex interplay between skeletal muscle pre-activation and spinal reflex regulation of muscle stiffness. For example, the Golgi Tendon Organ (GTO) causes muscle relaxation in response to tension, while the muscle spindle increases the tension of muscle in response to stretch (Mirzaei, Norasteh, Villarreal, & Asadi, 2014). If skeletal muscle pre-activation correctly anticipates the muscle stiffness required during landing impact, then  $K_{\text{vert}}$  may not be as variable during landing impact (e.g., less feedback from spinal reflexes).

There were several limitations in the present study. First, to estimate  $K_{\text{vertNew}}$ , GRF and  $d_{\text{CoM}}$  data were interpolated using a Lagrange polynomial. While the results of the present

study suggest that the GRF and  $d_{CoM}$  signals were not distorted, the Lagrange polynomial interpolation is a technique that hasn't been used previously in the  $K_{vert}$  literature. Interpolated data were then passed through a Savitsky-Golay filter. The filter parameters were somewhat arbitrary and based on visual inspection of data outputs. Future studies could focus on examining and optimizing the filter parameters for application in  $K_{vert}$  estimation. Lastly, segmented linear models were fit to interpolated GRF and  $d_{CoM}$  data. In the present investigation, a maximum of 11 linear segments were allowed to be fit to the data. Future studies could focus on optimizing the application of segmented regression for modelling  $K_{vert}$ .

## CONCLUSION

Modelling  $K_{vert}$  as an ideal spring-mass is an approach that has been validated in the literature for cyclical human movements, such as jogging, running, and repetitive hopping (Brughelli & Cronin 2008). The results of the present investigation provide evidence of the threats to validity associated with using  $K_{vert1}$  and  $K_{vert2}$  to model  $K_{vert}$  in DJ landings. Although  $K_{vert2}$  models stiffness from landing impact through amortization, the results of the present investigation suggest that it provides an estimate of mean  $K_{vert}$  with an unacceptable level of validity.  $K_{vert1}$  was observed to provide a more valid estimate of mean  $K_{vert}$ , however it only captures the stiffness expressed between landing impact and the time point of peak GRF. Results of the present investigation support the feasibility of estimating  $K_{vert}$  in DJ landings via direct derivation of GRF and  $d_{CoM}$  data. The proposed method,  $K_{vertNew}$ , appears to effectively address the threats to validity associated with  $K_{vert1}$  and  $K_{vert2}$  and may provide greater specificity into the complexity of stiffness regulation in DJ landings.

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