Floría, P., Sánchez-Sixto, A., & Harrison, A. J. (2019). Application of the principal component waveform analysis to identify improvements in vertical jump performance. Journal of Sports Sciences, 37(4), 370–377. https://doi.org/10.1080/02640414.2018.1504602

Abstract

The purpose of this study was to determine the effects of training on the force-, velocity-, and displacement-time curves using principal component analysis (PCA) to examine the pre to post intervention changes. Thirty-four trained women basketball players were randomly divided into training and control groups. The training intervention consisted of full squats combined with repeated jumps. The effects of the intervention were analysed before and after the training period of 6 weeks by comparing the principal component scores. The magnitude of differences within-/between-group were calculated and expressed as standardised differences. After the intervention period, clear changes in principal components were observed in the training group compared to the control group. These were related to the execution of a vertical jump with a faster and deeper countermovement that was stopped with greater force. This resulted in greater force from the start of the upward movement phase which was maintained for a longer time. This increase in force throughout a greater range of motion increased the take-off velocity and consequently jumping height.

Introduction

The countermovement vertical jump is one of the tests most used by coaches and strength and conditioning professionals to evaluate the effect of a training program on athletes. Discrete variables are frequently used to evaluate the training effect on countermovement jump performance including measures such as, jump height (Glatthorn et al., 2011), peak power (Markovic, Mirkov, Knezevic, & Jaric, 2013), maximum velocity (Jimenez-Reyes, Pareja-Blanco, Rodriguez-Rosell, Marques, & Gonzalez-Badillo, 2016), relative impulse (Kirby, Mcbride, Haines, & Dayne, 2011) or peak force (González-Badillo, Marquez, & Marques, 2010). While these parameters have merit, the data reduction from a continuous series to a discrete measure, discards a large amount of data which could be useful for understanding performance or training adaptations (Deluzio, Harrison, Coffey, & Caldwell, 2014; Preatoni et al., 2013). The analysis of continuous biomechanical variables based on time series data could facilitate the evaluation of differences in the shape or pattern of the waveform without severe loss the important information (Deluzio et al., 2014; Preatoni et al., 2013). Despite the merits of time series analysis, only a few studies (Cormie, McBride, & McCaulley, 2008, 2009; Flería, Gómez-Landero, Suárez-Arrones, & Harrison, 2016; Richter, O'Connor, Marshall, & Moran, 2014a, 2014b) have analysed the variations in the patterns of the force-, velocity- and displacement-time curves (i.e. waveforms) to evaluate jumping skill. These studies have observed differences in the waveform patterns between groups of different performance levels or changes in response to training (Cormie et al., 2009; Floría et al., 2016). All studies that applied continuous analysis, have facilitate the identification of movement phases where differences between groups occur and provide knowledge about the biomechanics underlying the vertical jump. Understanding the nature and direction of changes in waveforms in more detail can have implications for the planning of training programs. Optimization of training programs can improve overall jump ability in various ways by inducing specific changes in the waveforms (Cormie et al., 2009), therefore, more studies are needed to examine how the waveforms change in response to training interventions.

Principal component analysis (PCA) is an orthogonal transformation technique that converts several correlated variables into a smaller number of uncorrelated variables called principal components (Deluzio et al., 2014). Few studies have used PCA to identify performance related features in the force-time curves (Richter et al., 2014a, 2014b), although these studies used PCA as an intermediate step within the process of analysis namely, analysis of characterizing phases. The utility of PCA in identifying patterns in the variance of continuous data sets has been demonstrated in skills such as walking (Deluzio & Astephen, 2007), cutting (O'Connor & Bottum, 2009), gymnastics long-swing (Williams et al., 2016) and Nordic skiing (Gløersen, Myklebust, Hallén, & Federolf, 2017). In these studies, PCA was often used to differentiate groups (Deluzio & Astephen, 2007) or to identify key features of the movement patterns (Gløersen et al., 2017; Williams et al., 2016).

Given the general utility of PCA, it is likely that the technique could be used to evaluate the effects of training interventions on athletic performance. This could provide coaches and athletes a greater understanding of the information contained in continuous waveform data and avoid the need to create and interpret discrete variables which attempt to explain variations in continuous phenomenon (Williams et al., 2016). Consequently, there is a need to evaluate the utility and feasibility of applying PCA techniques as tool to monitor training and performance of athletes. The purpose of this study was to determine the effects of a training intervention on the shape and amplitude of the force-, velocity- and displacement-time curves. To achieve this, the PCA technique was used to assess differences between training and control groups after 6 weeks of a complex training (i.e.

combined weight and plyometric exercises) by examining the pre to post intervention changes on the force-, velocity- and displacement-time curves of the vertical jump.

Methods

Participants

Thirty-four trained women basketball players participated in this study. All participants had a minimum basketball training age of 5 years and had prior experience in jumping tasks. The participants were randomly divided into two groups: training and control. The training group consisted of 17 females aged 23.10 ± 2.94 years (mean ± SD), with a mass of 60.40 ± 11.69 kg and a height of 1.68 ± 0.09 m. The control group consisted of 17 females aged 23.21 ± 4.34 years (mean ± SD), with a mass of 64.99 ± 8.87 kg and a height of 1.69 ± 0.06 m. No participants had suffered any musculoskeletal within 6 months before participation in this study. The study had ethical approval from the local University Research Ethics Committee and all the participants provided informed consent before participation.

Testing protocol

Participants performed a familiarization session, and this ended when participants demonstrated correct and consistent execution of the countermovement jump test and assigned training exercises. The countermovement jump tests were carried out 72 hours before and after the 6-week of training intervention.

Countermovement jump test

Immediately before testing, all participants performed 10 minutes of general warm up including, 2 minutes of low-intensity aerobic exercise, dynamic stretching exercises and one set of 6 sub-maximal jumps. After the warm up, the participants performed 5 maximal countermovement jumps and the importance of jumping as high as possible was emphasized. The participants retained the arms akimbo position from the start until the completion of the landing phase in the jumps. The countermovement jump test was executed on a force plate (Quattro Jump, Kistler Instrument AG, Winterthur, Switzerland) sampling at 500 Hz. The jump with the greatest height was selected for analysis.

Isoinertial progressive resistance test

This test was used to determine the relative resistance for the full squat performed by the participants. Before testing, participants performed various joint-mobilizations, 5 repetitions of unresisted full squats and 2 sets of 5 repetitions with 10 kg resistance. The assessment consisted in an isoinertial test with progressively increasing resistances using the full squat exercise performed in a Smith machine (Multipower Fitness Line, Peroga, Murcia, Spain). González-Badillo et al. (2015) provide a complete description of this test procedure. A dynamic measurement system (T-Force System, Ergotech, Murcia, Spain) controlled the mean bar propulsive velocity of each repetition. Participants performed the upward movement phase of the full squat at maximal velocity and the downward movement phase at a controlled mean velocity (0.5-0.65 $m \cdot s^{-1}$). The initial resistance load was 17 kg and this was progressively increased; the test ended when participants reached a 1 $m \cdot s^{-1}$ (0.96-1.04 $m \cdot s^{-1}$) mean propulsive velocity in the upward movement phase (González-Badillo et al., 2015). Participants executed three repetitions for each resistance and were allowed three minutes rest between each series.

Training program

The warm up consisted of 7 minutes of standard activities (i.e. jogging and joint-mobilization exercises), 2 sets of full squats and 2 sets of jumps. The training group performed 12 sessions on non-consecutive days during the 6-week training intervention. The training group performed full squats in the Smith machine (Multipower Fitness Line, Peroga, Spain) with a relative resistance and rebound jumps using body weight as the overload with an emphasis on short contact time and maximum jump height. The relative resistances of the full squat lifted by each participant were assigned according to the movement mean propulsive velocity of the bar during the initial isoinertial progressive squat resistance test. The resistances of the full squats were recalculated for each subsequent session. Between the full squat sets, the players had 3 minutes rest and 1 minute rest was provided between the rebound jump sets.

Data analysis

Force-time data of the countermovement jumps from the force plate were analysed by the impulse method (Linthorne, 2001). The net impulse was obtained by integrating the net vertical force with respect to time, from 2 s prior to the first movement of the participant (Floría et al., 2016; Street, McMillan, Board, Rasmussen, & Heneghan, 2001). Subsequently, the centre of mass vertical velocity was calculated by dividing the net impulse by the participant´s body mass. The vertical centre of mass displacement was derived by integrating the vertical centre of mass velocity.

Statistical analyses

All calculations, data normalization and PCA were carried out in Matlab (The MatlabWorks Inc., Natic, MA, USA). To prepare the data for the PCA, the dataset of each parameter was normalized to 501 points using a piecewise linear length normalization procedure (Helwig, Hong, Hsiao-Wecksler, & Polk, 2011). This technique expands or compresses the time axis to ensure temporal alignment at points of interest (Sadeghi et al., 2000). Three points of interest were identified which defined two sub-phases of the jump. The downward phase was defined from start of the movement to the lowest centre of mass position and the upward phase was from lowest centre of mass position to instant of take-off. This allowed all force-, velocity-, displacement-, and RFD-time curves to be expressed over normalized periods of percentage time, such that individual data could be aligned to identifiable events. Three separate PCA were conducted to identify dominant modes of variation within the force-, velocity-, and displacement-time waveforms. The PCA approach used for this study was based on the methods of Deluzio et al (2014). For each parameter (force, velocity, and displacement) a matrix was created (68 x 501) containing the time series data of all participants' jumps (34 participants x 2 sessions x 501 time points per jump). The PCA of these matrices resulted in eigenvector components, eigenvalues and scores. The eigenvector components contain principal component loading vectors indicating the direction of variance in the data set. The eigenvalues indicated the amount of variation in the data explained by a given principal component. The scores indicated the degree to which the shape of individual waveform deviated from the average pattern. To aid in the biomechanical interpretation of results of PCA, single plots with two waveforms $\vec{x}_H$ and $\vec{x}_L$ were created (Deluzio et al., 2014). $\vec{x}_H$ and $\vec{x}_L$ represent waveforms corresponding to a high and low score of the principal component obtained by adding and subtracting a scalar multiple of the eigenvector component, u_R, to the average waveform, $\overline{x}$. A convenient scalar multiple is one standard deviation of the corresponding principal component scores, SD($\vec{z}_i$):

$$\vec{x}_H = \overline{x} + SD(\overrightarrow{z_i}) \times \overline{u}_i$$

$$\vec{x}_L = \overline{x} - SD(\overrightarrow{z_i}) \times \overline{u}_i$$

The differences between training and control groups (independent variables) were analysed before and after the training period of 6 weeks by comparing the principal component scores. A criterion of 95% of variance explained was used to determine the number of principal components extracted for statistical analysis (Deluzio et al., 2014). The magnitude of differences within-/between-group were calculated and expressed as standardised differences (Cohen, 1977). The interpretation criteria for the standardised differences were: trivial = 0.00-0.19; small = 0.20-0.59; moderate = 0.60-1.19; large = 1.20-1.90; very large = 2.00-4.00 and nearly perfect >4.00 (Hopkins, Marshall, Batterham, & Hanin, 2009). Confidence intervals (90%) and probabilities that true effect was substantially positive or negative were estimated according to Hopkins et al (2009). The scale for interpreting the probabilities for a mechanistic effect based on the 90% confidence limits were: <1%, almost certainly not; >1-5%, very unlikely; >5-25%, unlikely; >25-75%, possibly; >75-95%, likely; >95-99%, very likely and >99%, almost certainly. When the positive and negative values were both >5%, the inference was classified as unclear (Batterham & Hopkins, 2006). All calculations were completed using a predesigned spreadsheet (Hopkins, 2006).

Results

The training group highlighted a most likely, moderate increase in jump height after the six-week training intervention in comparison with the control group (with chances of greater/similar/lower values of 100/0/0%). PCA performed on force-, velocity- and displacement-time datasets separately, highlighted that between two and six principal components accounted for 97 ± 0.35% of the total variance within each of the datasets (Table 1). Of the principal components retained, five, at least one for each dataset, highlighted clear changes in the training group in comparison with the control group after the intervention period (Table 1).

Force

After the intervention period, clear changes in principal components 4 and 5 were observed in the training group compared to the control group (Figure 1). Unclear changes were observed in the remaining principal components retained. Principal components 4 and 5 explained 6% and 4% of the variance observed in the force-time data, respectively. Following the intervention, moderately high scores in principal components 4 and 5 were likely and very likely in the training group compared with the control group (84/13/3% and 95/4/1%) (Figure 2). These differences were interpreted by examining the shape of the eigenvector components simultaneously with waveforms that represented extreme values of each principal component (Figure 3). The peaks in the eigenvector components of principal component 4 were achieved in the downward–upward transition period (~70%) and in the last portion of the movement (~97%). Similar features were captured by principal component 5, where high eigenvector components were achieved in the last moments of movement (~97%). In summary, the training intervention increased the scores of principal components 4 and 5 in the experimental group.

Table 1. Principal components (PC) scores (mean ± SD) for training and control group and standardized differences (effect size; ±90% confidence limits) within-/between-group.

	% Variation within data explained	Training Group			Control Group			Differences in change observed for Training group compared Control group
		Pre	Post	Effect Size Pre-Post	Pre	Post	Effect Size Pre-Post	
Height jump (m)		0.37 ± 0.05	0.40 ± 0.06	0.67; ±0.23	0.37 ± 0.04	0.37 ± 0.03	0.07; ±0.16	0.71; ±0.30
Force								
PC1	39%	1.32 ± 2.82	0.73 ± 4.01	-0.20; ±0.59	-1.25 ± 1.98	-0.81 ± 2.01	0.21; ±0.49	0.37; ±0.71
PC2	26%	0.41 ± 2.82	0.36 ± 2.31	-0.02; ±0.40	-0.35 ± 2.58	-0.41 ± 2.12	-0,02; ±0.26	0.00; ±0.48
PC3	18%	-0.11 ± 1.37	-0.31 ± 2.72	-0.14; ±0.74	0.33 ± 1.66	0.09 ± 2.22	-0,14; ±0.36	-0.02; ±0.78
PC4	6%	-0.08 ± 1.09	0.52 ± 1.45	0.53; ±0.42	-0.21 ± 0.96	-0.24 ± 0.98	-0,03; ±0.54	0.61; ±0.69
PC5	4%	-0.26 ± 0.87	0.46 ± 1.03	0.78; ±0.52	-0.05 ± 0.89	-0.15 ± 0.65	-0,11; ±0.45	0.91; ±0.69
PC6	3%	-0.17 ± 0.79	-0.02 ± 1.05	0.18; ±0.54	0.10 ± 0.71	0.10 ± 0.64	0,00; ±0.36	0.19; ±0.18
Velocity								
PC1	56%	-1.28 ± 2.57	-0.72 ± 4.15	0.21; ±0.63	1.21 ± 2.37	0.79 ± 2.40	-0,17; ±0.47	0.35; ±0.72
PC2	25%	-0.02 ± 1.81	-0.99 ± 2.50	-0.51; ±0.44	0.50 ± 1.92	0.50 ± 1.75	0,00; ±0.29	-0.51; ±0.52
PC3	12%	-0.12 ± 1.06	0.35 ± 1.99	0.42; ±0.58	-0.05 ± 0.98	-0.18 ± 1.43	-0,13; ±0.43	0.59; ±0.74
PC4	3%	0.00 ± 0.66	-0.19 ± 0.55	-0.27; ±0.41	0.09 ± 0.81	0.11 ± 0.67	0,02; ±0.51	-0.28; ±0.68
Displacement								
PC1	78%	-0.09 ± 0.58	-0.28 ± 0.85	-0.31; ±0.51	0.17 ± 0.75	0.19 ± 0.62	0,02; ±0.30	-0.31; ±0.56
PC2	19%	-0.13 ± 0.29	0.12 ± 0.47	0.83; ±0.67	0.03 ± 0.30	-0.02 ± 0.33	-0,17; ±0.45	0.98; ±0.78

Elevated scores in principal components 4 and 5 were associated with higher forces at the start and end of the upward phase of the vertical jump.

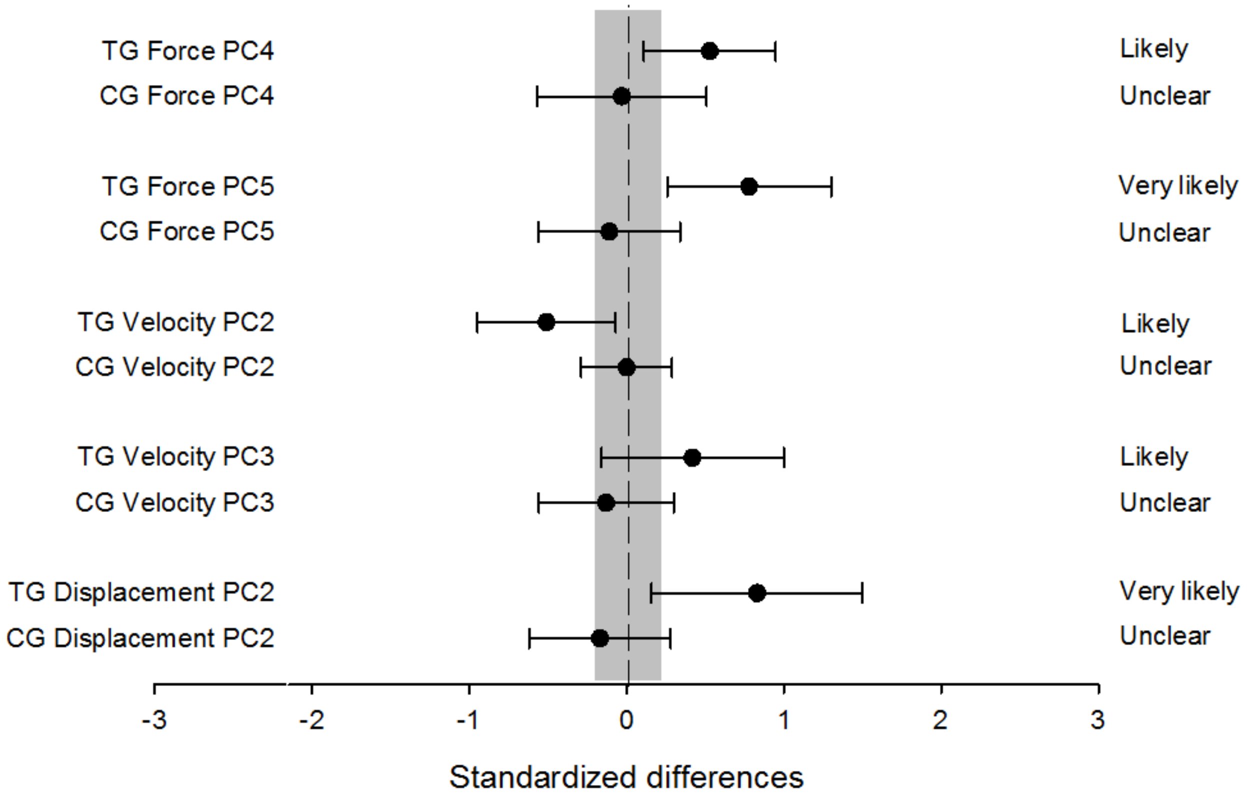

Figure 1. Within-group standardized differences for principal component (PC) scores in force-, velocity and displacement-time profiles. Bars indicate uncertainty in the true mean changes with 90% confidence intervals. Trivial area was calculated from the smallest worthwhile change.

Velocity

The scores of principal components 2 and 3 highlighted interpreted changes in the training group in comparison to the control group after the intervention period (Figure 1). The rest of the principal components retained, highlighted unclear changes. Principal components 2 and 3 explained the 25% and 12% of the variance observed in the velocity-time patterns, respectively. Following the intervention, small changes in principal components 2 and 3 were likely in the training group compared with the control group (1/15/84% and 81/15/4%) (Figure 2). The peak of the eigenvectors of principal component 2 corresponded to the instant of peak downward velocity during the countermovement (Figure 3). The peak of the eigenvectors of principal component 3 was achieved at the instant of peak upward velocity. After the intervention period, the training group decreased scores of principal component 2 while increasing the principal component 3 scores compared with the control group. Lower scores in principal component 2 were associated with high peaks of downward velocity, while high scores in principal component 3 were associated with high peaks of upward velocity.

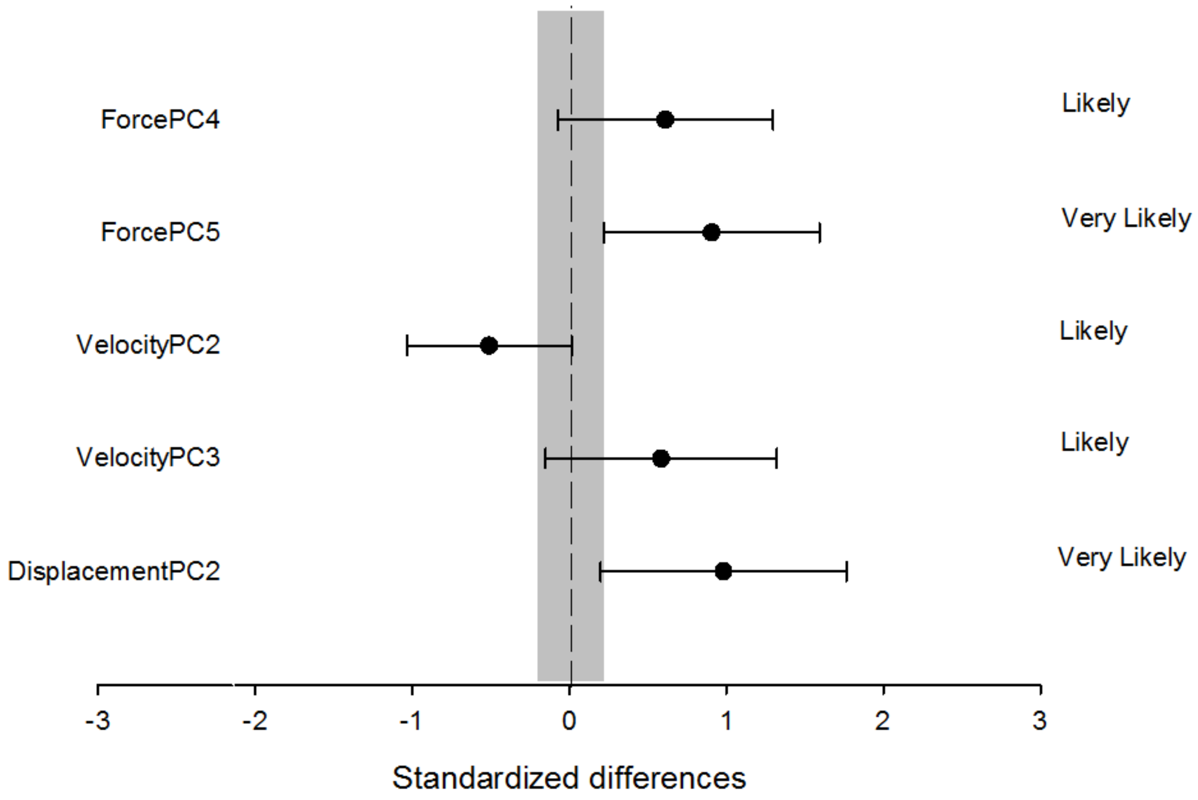

Figure 2. Between-group standardized differences for principal component (PC) scores in force-, velocity and displacement-time profiles. Bars indicate uncertainty in the true mean changes with 90% confidence intervals. Trivial area was calculated from the smallest worthwhile change.

Displacement

Of the two principal components that explained 95% of the variance in the displacement-time waveform, only principal component 2 highlighted clear changes in the training group compared with the control group (Figure 1). This PC explained the 19% of the variation of data. Following the intervention, moderately high scores in principal component 2 were very likely in the training group compared with the control group (95/4/1%) (Figure 2) and two peaks in the eigenvector components waveform were achieved during and at the end of the downward movement (Figure 3). After the intervention period, the training group increased the scores of principal component 2 compared to the control group and high scores in principal component 2 were associated with a higher rate of descent of the mass centre and a deeper countermovement.

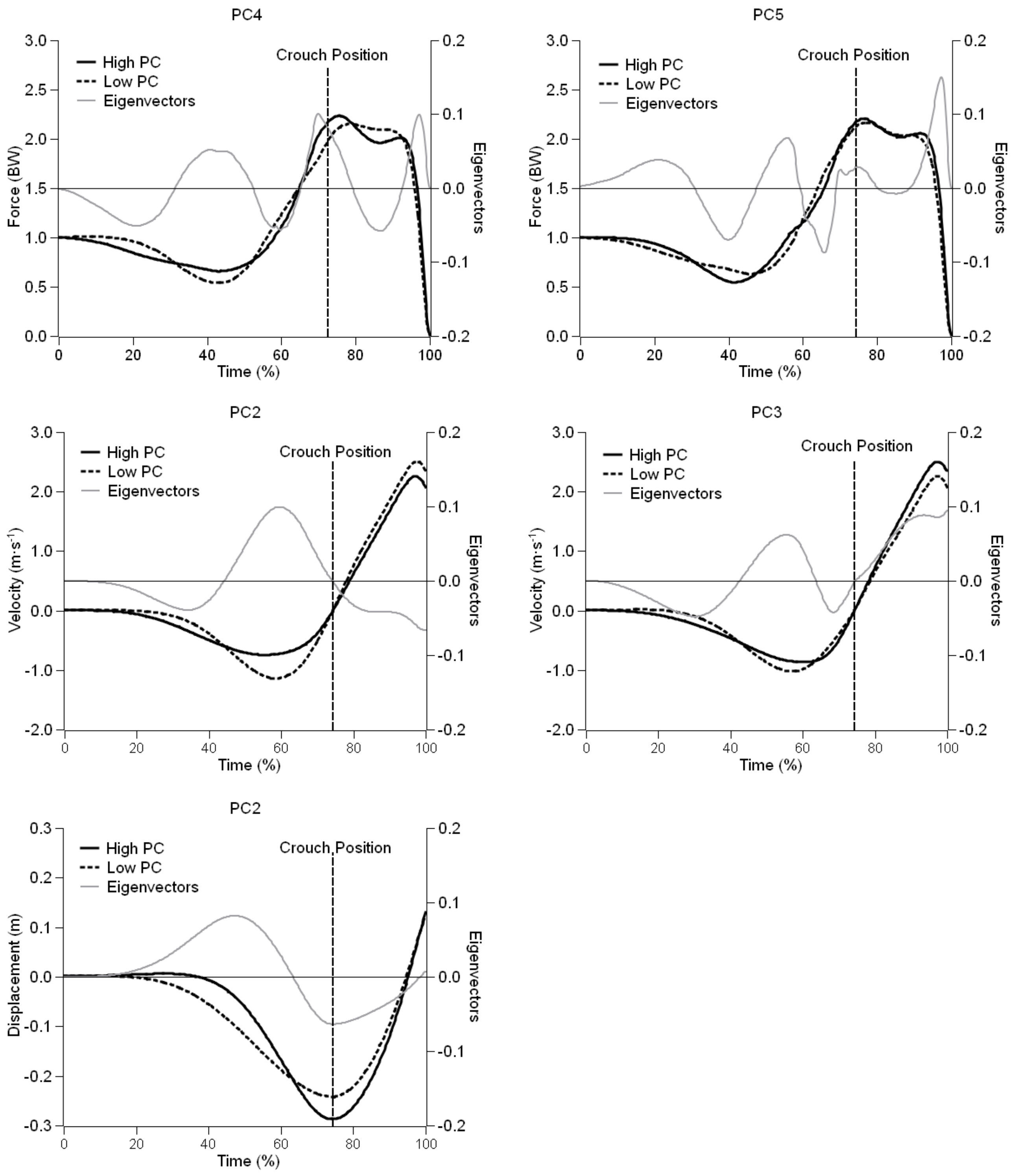

Figure 3. Principal component (PC) and loading vector contributions to force-, velocity and displacement-time profiles. In all cases, high scorers for each PC are the black solid lines and low scorers are the black dashed lines. The grey solid line represents PC loading vector which is added to and subtracted from the average waveform to represent the waveforms of high and low scorers.

Discussion

The main finding in this study was that PCA proved to be a useful tool to evaluate improvements in vertical jump performance following a training intervention since it was able to identify differences in the shape of the waveform data associated with an increase in the countermovement jump height. Parameters such as, force applied in the downward-upward transition, force applied in the last portion of movement, downward velocity or countermovement depth have been related to the improvement of the vertical jump performance after a training intervention (Aragón-Vargas & Gross, 1997; Cormie et al., 2009; Cormie, McGuigan, & Newton, 2010; Floría et al., 2016; González-Badillo et al., 2010; Kollias, Hatzitaki, Papaiakovou, & Giatsis, 2001). The findings related to performance improvements in the training group were consistent with established knowledge of the vertical jump. This concordance of results reinforces the validity of the PCA as a tool to detect changes caused by training and this is a relevant finding in sports sciences that could extend beyond the specific application to the vertical jump.

The interpretation of the PCA results was based on the analysis of the peaks of the eigenvector component series data (Deluzio et al., 2014). As eigenvector component values approach zero, they contribute very little to the main component score, while larger eigenvector components are more important to a particular principal component. Higher eigenvectors (>0.08) were associated with single discrete events such as downward peak velocity, upward peak velocity or countermovement depth. Previous studies have related these variables to vertical jump performance (Floría et al., 2016; González-Badillo et al., 2010), however, high eigenvector components were also associated with high forces in the last moments of the upward movement which cannot be associated with a specific discrete event. Although the interpretation of the PCA was based on the eigenvector component peaks, a specific eigenvector component value was not established as a threshold which was sufficiently high to indicate change. Therefore, further research is recommended to establish criteria to allow the interpretation of the PCA results by coaches and athletes and facilitate wider use of waveform data analysis.

The results demonstrated that the force-time data varied with training. Changes in the waveforms were associated with higher forces at the end of countermovement and the latter part of upward movement. The positive effect on the jump performance of increasing both the eccentric load and force during the latter part of upward movement has been reported previously (Bobbert & Mackay, 1986; Floría et al., 2016; Moran & Wallace, 2007). The observed changes in the force-time pattern in the present study could be influenced by the type of training used in the intervention. This training was based on rebound jumps and full squats, which some authors describe as complex training (Arabatzi, Kellis, & Saèz-Saez De Villarreal, 2010). The exercises used were intended to increase force application in deep crouch positions (full squats) and force expression at a high speed (rebound jumps with short contact time and maximum height). Further studies are needed to determine whether different training methods can produce similar changes in the force-time waveform or if these changes are influenced by the specific type of training used in this intervention.

The performance improvement in the vertical jump induced by strength training was accompanied by changes in the shape of the velocity-time curve. Two different principal components (PC2 and PC3) were judged to be associated to the training intervention and each principal component was related to a different mechanism. PC2-velocity was related to improvements in the stretch-shortening cycle where a faster downward movement was related with a larger upward-velocity. PC3-velocity was related to more effective propulsion, since the velocity increases only occurred during the upward movement phase. Figure 4 report the individual scores the principal components 2 and 3 of the velocity-time curve. This graph highlights how participants are divided into four possibilities: 1) Improvements in the countermovement (participants included in the quadrant "positive effects PC2”), 2) improvements in propulsion (participants included in the quadrant "positive effects PC3”), 3) improvements simultaneously (participants included in the quadrant "positive effects PC2 & PC3”), and 4) no effects or negative effects. A single participant demonstrated positive effects in PC2 and PC3, while four and three participants showed positive effects only in PC2 and PC3, respectively. Figure 4 displays how PCA could be used effectively to identify individual adaptations to training to personalize future training focused on the rectifying individual deficiencies.

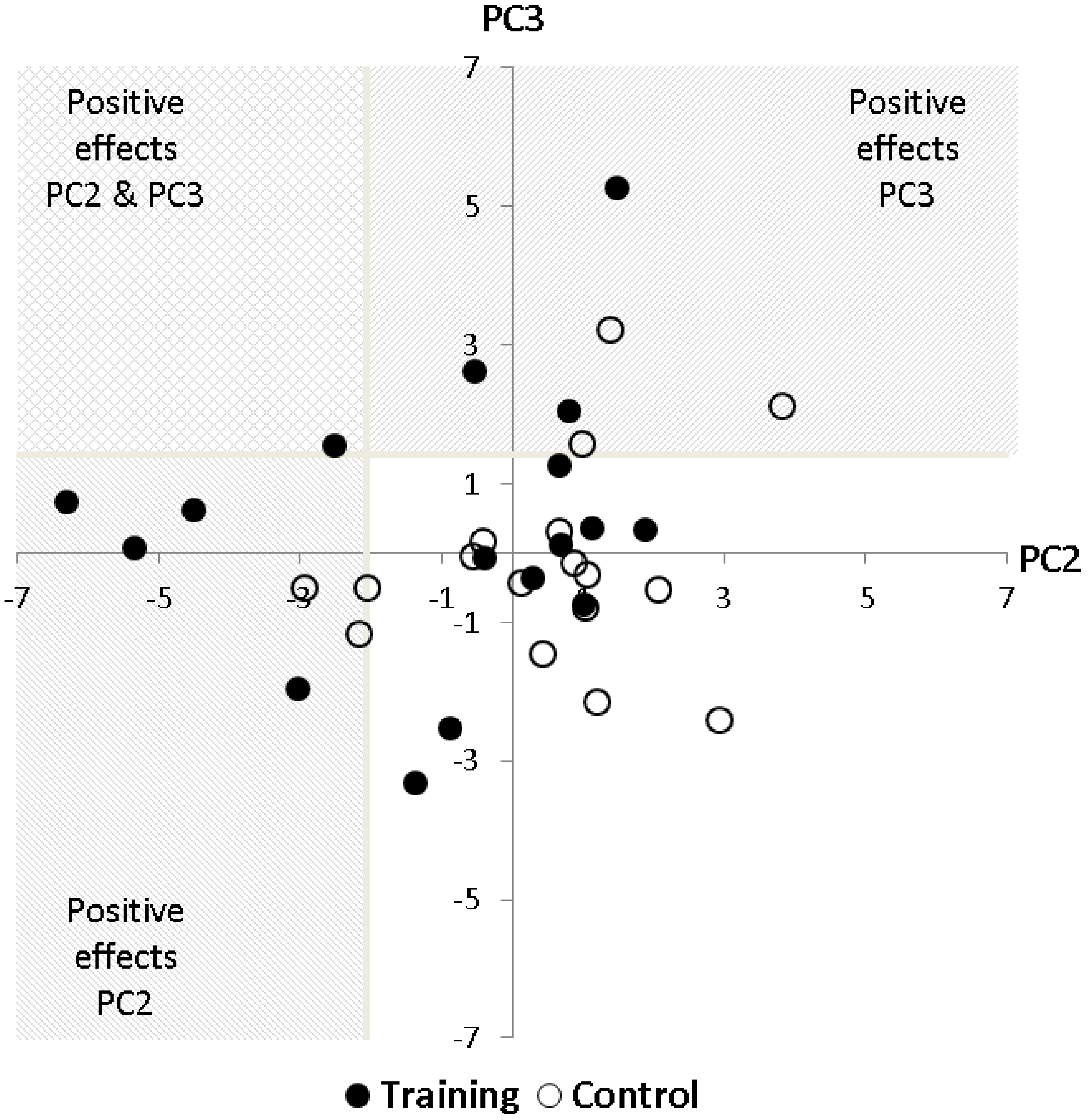

Figure 4. Individual PC scores values for PC2-velocity versus PC3-velocity. The striped areas were calculated from the standard deviation of the principal component

The results highlighted that the waveform of the displacement of centre of mass with respect to time was also modified after training which improved the vertical jump performance. Two notable features were observed, a rapid downward movement and a deeper crouch position. The rapid descent is related to the downward peak velocity discussed above. Previous studies have linked a deeper countermovement with increases in vertical jump performance (Bobbert, Gerritsen, Litjens, & Van Soest, 1996; Floría et al., 2016; Kirby et al., 2011; McBride, Triplett-Mcbride, Davie, & Newton, 1999; Moran &

Wallace, 2007; Ugrinowitsch, Tricoli, Rodacki, Batista, & Ricard, 2007). These results suggest that a deeper crouch position increases the distance over which the athlete can apply force. Consequently, if the force is maintained at submaximal values, the work and power outputs will increase, resulting in increased height jumped.

It is recognised that this study has certain limitations. One of the main disadvantages of the principal component waveform analysis is the need for all datasets to have exactly the same number of points making time normalization is necessary. This makes it impossible to find differences in the execution time, which is important in the jump performance since this is determined by the impulse (Kirby et al., 2011). This study has tried to resolve this disadvantage by analysing the vertical centre of mass displacement. An increase in the execution time without reducing the velocity could be achieved by increasing the range over which the force is applied. In this way, an athlete could increase the time without modifying the force applied, resulting in an increase in the impulse. To facilitate the interpretation of the results, this study executed three different PCAs one by each parameter (force, velocity and displacement), this could be considered a limitation. A PCA that includes all the parameters in a single matrix could potentially yield information on the interrelation between parameters to determine which of them could be more related to the performance improvement after the training intervention; however, this would compound the interpretation of results and compromise their use by coaches and strength and conditioning professionals.

This study provides novel insight into the evaluation and monitoring of performance for coaches and strength and conditioning professionals. The PCA was able to detect changes in the force-, velocity and displacement-time profiles after a training intervention focused on increasing the vertical jump performance. This demonstrated that the analysis of continuous data series could provide a valid alternative to discrete measure analysis which has been widely used previously (González-Badillo et al., 2010; Jimenez-Reyes et al., 2016; Kirby et al., 2011; Markovic et al., 2013). The improvements in the jump performance after the training were related to the execution of a vertical jump with a faster and deeper countermovement that was stopped with a greater amount of force. This resulted in greater force from the start of the upward movement phase which was maintained for a longer time. This increase in force throughout a greater range of motion increased the take-off velocity and consequently jumping height was increased. Although these results are important for understanding the biomechanics factors underlying improvements in vertical jump performance, it was not possible to determine which of these factors specifically had the greatest influence on the increase in jump height. Further examination of relationships that exist between these factors and their degree of influence on performance could be of considerable benefit to coaches and athletes in designing specific training interventions.

References

Arabatzi, F., Kellis, E., & Saèz-Saez De Villarreal, E. (2010). Vertical jump biomechanics after plyometric, weight lifting, and combined (weight lifting + plyometric) training. *Journal of Strength and Conditioning Research*, *24*(9), 2440–2448. https://doi.org/10.1519/JSC.0b013e3181e274ab

Aragón-Vargas, L. F., & Gross, M. M. (1997). Kinesiological factors in vertical jump performance: Differences among individuals. *Journal of Applied Biomechanics*, *13*, 24–44.

Batterham, A. M., & Hopkins, W. G. (2006). Making meaningful inferences about magnitudes. *International Journal of Sports Physiology and Performance*, *1*(1), 50–57.

Bobbert, M. F., Gerritsen, K. G. M., Litjens, M. C. A., & Van Soest, A. J. (1996). Why is countermovement jump height greater than squat jump height? *Medicine and Science in Sports and Exercise*, *28*(11), 1402–1412.

Bobbert, M. F., & Mackay, M. (1986). Biomechanical analysis of drop and countermovement jumps. *European Journal of Applied Physiology and Occupational Physiology*, *54*, 566–573.

Cohen, J. (1977). The t test for means. In *Statistical Power Analysis for the Behavioral Sciences* (pp. 19–74). New York, NY: Academic Press.

Cormie, P., McBride, J. M., & McCaulley, G. O. (2008). Power-time, force-time, and velocity-time curve analysis during the jump squat: Impact of load. *Journal of Applied Biomechanics*, *24*(2), 112–120.

Cormie, P., McBride, J. M., & McCaulley, G. O. (2009). Power-time, force-time, and velocity-time curve analysis of the countermovement jump: Impact of training. *Journal* *of Strength and Conditioning Research*, *23*(1), 177–186.

Cormie, P., McGuigan, M. R., & Newton, R. U. (2010). Changes in the eccentric phase contribute to improved stretch-shorten cycle performance after training. *Medicine and Science in Sports and Exercise*, *42*(9), 1731–1744. https://doi.org/10.1249/MSS.0b013e3181d392e8

Deluzio, K. J., & Astephen, J. L. (2007). Biomechanical features of gait waveform data associated with knee osteoarthritis. An application of principal component analysis. *Gait and Posture*, *25*(1), 86–93. https://doi.org/10.1016/j.gaitpost.2006.01.007

Deluzio, K. J., Harrison, A. J., Coffey, N., & Caldwell, G. E. (2014). The analysis of biomechanical waveform data. In D. G. E. Robertson, G. E. Caldwell, J. Hamill, G. Kamen, & S. N. Whittlesey (Eds.), *Research Methods in Biomechanics* (2nd ed., pp. 317–337). Champaign, IL: Human Kinetics.

Floría, P., Gómez-Landero, L. A., Suárez-Arrones, L., & Harrison, A. J. (2016). Kinetic and kinematic analysis for assessing the differences in counter-movement jump performance in rugby players. *Journal of Strength and Conditioning Research*, *30*(9), 2533–2539. https://doi.org/10.1519/JSC.0000000000000502

Glatthorn, J. F., Gouge, S., Nussbaumer, S., Stauffacher, S., Impellizzeri, F. M., & Maffiuletti, N. A. (2011). Validity and reliability of optojump photoelectric cells for estimating vertical jump height. *Journal of Strength and Conditioning Research*, *25*(2), 556–560. https://doi.org/10.1519/JSC.0b013e3181ccb18d

Gløersen, Ø., Myklebust, H., Hallén, J., & Federolf, P. (2017). Technique analysis in elite athletes using principal component analysis. *Journal of Sports Sciences*, 1–9. https://doi.org/10.1080/02640414.2017.1298826

González-Badillo, J. J., Marquez, M. C., & Marques, M. C. (2010). Relationship between kinematic factors and countermovement jump height in trained track and field athletes. *Journal of Strength and Conditioning Research*, *24*(12), 3443–3447. https://doi.org/10.1519/JSC.0b013e3181bac37d

González-Badillo, J. J., Pareja-Blanco, F., Rodríguez-Rosell, D., Abad-Herencia, J. L., Del Ojo-López, J. J., & Sánchez-Medina, L. (2015). Effects of velocity-based resistance training on young soccer players of different ages. *Journal of Strength and Conditioning Research*, *29*(5), 1329–1338. https://doi.org/10.1519/JSC.0000000000000764

Helwig, N. E., Hong, S., Hsiao-Wecksler, E. T., & Polk, J. D. (2011). Methods to temporally align gait cycle data. *Journal of Biomechanics*, *44*(3), 561–6. https://doi.org/10.1016/j.jbiomech.2010.09.015

Hopkins, W. G. (2006). Spreadsheets for analysis of controlled trials, with adjustment for a subject characteristic. *Sportscience*, *10*, 46–50.

Hopkins, W. G., Marshall, S. W., Batterham, A. M., & Hanin, J. (2009). Progressive statistics for studies in sports medicine and exercise science. *Medicine and Science in Sports and Exercise*, *41*(1), 3–12. https://doi.org/10.1249/MSS.0b013e31818cb278

Jimenez-Reyes, P., Pareja-Blanco, F., Rodriguez-Rosell, D., Marques, M. C., & Gonzalez-Badillo, J. J. (2016). Maximal velocity as a discriminating factor in the performance of loaded squat jumps. *International Journal of Sports Physiology and Performance*, *11*(2), 227–234. https://doi.org/10.1123/ijspp.2015-0217

Kirby, T. J., Mcbride, J. M., Haines, T. L., & Dayne, A. M. (2011). Relative net vertical impulse determines jumping performance. *Journal of Applied Biomechanics*, *27*, 207–214.

Kollias, I., Hatzitaki, V., Papaiakovou, G., & Giatsis, G. (2001). Using principal components analysis to identify individual differences in vertical jump performance. *Research Quarterly for Exercise and Sport*, *72*(1), 63–67. https://doi.org/10.1080/02701367.2001.10608933

Linthorne, N. P. (2001). Analysis of standing vertical jumps using a force platform. *American Journal of Physics*, *69*(11), 1198–1204. https://doi.org/10.1119/1.1397460

Markovic, S., Mirkov, D. M., Knezevic, O. M., & Jaric, S. (2013). Jump training with different loads: Effects on jumping performance and power output. *European Journal of Applied Physiology*, *113*(10), 2511–2521. https://doi.org/10.1007/s00421-013-2688-6

McBride, J. M., Triplett-Mcbride, T., Davie, A., & Newton, R. U. (1999). A comparison of strength and power characteristics between power lifters, Olympic lifters, and sprinters. *Journal of Strength and Conditioning Research*, *13*(1), 58–66.

Moran, K. a, & Wallace, E. S. (2007). Eccentric loading and range of knee joint motion effects on performance enhancement in vertical jumping. *Human Movement Science*, *26*(6), 824–40. https://doi.org/10.1016/j.humov.2007.05.001

O’Connor, K. M., & Bottum, M. C. (2009). Differences in cutting knee mechanics based on principal components analysis. *Medicine & Science in Sports & Exercise*, *41*(4), 867–878. https://doi.org/10.1249/MSS.0b013e31818f8743

Preatoni, E., Hamill, J., Harrison, A. J., Hayes, K., Van Emmerik, R. E. A., Wilson, C., & Rodano, R. (2013). Movement variability and skills monitoring in sports. *Sports Biomechanics*, *12*(2), 69–92. https://doi.org/10.1080/14763141.2012.738700

Richter, C., O’Connor, N. E., Marshall, B., & Moran, K. (2014a). Analysis of characterizing phases on waveforms: An application to vertical jumps. *Journal of Applied Biomechanics*, *30*(2), 316–321. https://doi.org/10.1123/jab.2012-0218

Richter, C., O'Connor, N. E., Marshall, B., & Moran, K. (2014b). Comparison of discrete-point vs. dimensionality-reduction techniques for describing performance-related aspects of maximal vertical jumping. *Journal of Biomechanics*, *47*(12), 3012–3017. https://doi.org/10.1016/j.jbiomech.2014.07.001

Sadeghi, H., Allard, P., Shafie, K., Mathieu, P. A., Sadeghi, S., Prince, F., & Ramsay, J. (2000). Reduction of gait data variability using curve registration. *Gait and Posture*, *12*(3), 257–64.

Street, G. M., McMillan, S., Board, W., Rasmussen, M., & Heneghan, J. M. (2001). Sources of error in determining countermovement jump height with the impulse method. *Journal of Applied Biomechanics*, *17*, 43–54.

Ugrinowitsch, C., Tricoli, V., Rodacki, A. L. F., Batista, M., & Ricard, M. D. (2007). Influence of training background on jumping height. *Journal of Strength and Conditioning Research*, *21*(3), 848–852.

Williams, G. K. R., Irwin, G., Kerwin, D. G., Hamill, J., Van Emmerik, R. E. A., & Newell, K. M. (2016). Coordination as a function of skill level in the gymnastics longswing. *Journal of Sports Sciences*, *34*(5), 429–439. https://doi.org/10.1080/02640414.2015.1057209