Tracking the Reliability of Force Plate-Derived Countermovement Jump Metrics Over Time in Female Basketball Athletes: A Comparison of Principal Component Analysis vs. Conventional Methods

Running Head: Countermovement Jump Reliability in Female Basketball Athletes

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ABSTRACT

BACKGROUND: Establishing the reliability of countermovement jump (CMJ) metrics over multiple weeks can be important in understanding and tracking changes in jump performance over time. However, a limited number of key performance indicators are generally retained for ease of interpretation. Fortunately, CMJ metrics are often highly correlated, which offers the potential to summarize key jump aspects using principal component analysis (PCA). **PURPOSE:** The objective of this study was to assess and compare the week-to-week (i.e., week 1 vs. week 2, week 2 vs. week 3, etc.) vs. preseason (i.e., *n*th-week vs. average of the 7-weeks) reliability of CMJ metrics, relative to principal components (PCs). **METHODS:** Thirteen varsity female basketball athletes completed 17 weeks of CMJ testing (i.e., off-season (4 weeks), pre-season (7 weeks), and in-season (6 weeks)). The PCA was developed from all data collected, but only results of the pre-season PC scores were examined for reliability purposes. **RESULTS:** It was found that both methods displayed comparable reliability, such that 11/18 CMJ metrics and 3/6 PCs displayed excellent weekly reliability (ICC≥0.9), while 17/18 of the CMJ metrics and 5/6 of the PCS displayed excellent reliability when assessed longitudinally. PCs 1-4 explained 83% of the variance in the data relating to force measures, braking metrics, jump power measures, and between-limb differences, respectively. **CONCLUSION:** These findings support the use of PCA in routine longitudinal athletic monitoring, as this technique retains valuable performance information and summarizes distinct aspects of the jump, providing a more holistic assessment of performance and indication of injury susceptibility.

KEY WORDS athlete monitoring, injury prevention, athlete performance, asymmetry, between-limb differences, longitudinal

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INTRODUCTION

The CMJ is the most frequently used testing protocol to assess vertical jump performance in competitive athletic populations (Heishman et al. 2020; Heishman, Miller, et al. 2019; Schuster, Bove, and Little 2020). Not only is it one of the most comprehensive tests for quantifying neuromuscular performance and fatigue (Doeven et al. 2018; Gathercole et al. 2015; Heil, Loffing, and Büsch 2020), but when integrated with force plates, it has the ability to measure propulsive, braking, or landing forces (Barker, Harry, and Mercer 2018; Heishman, Daub, et al. 2019; Kavanaugh et al. 2018; McMahon et al. 2018), as well as the potential between limb differences that may exist when using dual force-plates (Bishop, Turner, and Read 2018; Heishman, Daub, et al. 2019; Impellizzeri et al. 2007). Moreover, this methodology is minimally invasive, leading to exceptional compliance rates in athletes (Schuster et al. 2020). Nevertheless, the ultimate utility of this assessment for tracking athletic performance is dependent on the reliability of the variety of performance metrics obtained overtime, as well as the ability of coaching staff, medical practitioners, and athletes to interpret these data in a time-efficient manner.

While there are no shortage of studies assessing the reliability of CMJ testing protocols and commonly defined performance metrics, this cannot be said for the variety of individual between-limb difference metrics that can be meaningfully assessed. For instance, common metrics such as jump height (JH), peak propulsive power, the modified reactive strength index (RSI mod), and countermovement depth (CMD) have been widely studied and shown to display good to excellent inter-day reliability (ICC = 0.85-0.98) (Aoki et al. 2017; Byrne et al. 2017; Cormack et al. 2008; Gathercole et al. 2015; Heishman et al. 2020). Alternatively, in the limited number of studies assessing the reliability of inter-limb asymmetry CMJ metrics, the results have been highly variable (ICC = 0.47-0.93) (Heishman, Daub, et al. 2019; Impellizzeri et al. 2007; Menzel et al. 2013; Pérez-Castilla et al. 2021). This variation in the reliability of data may be related to many factors (e.g., aspect of CMJ asymmetry examined, athletic population, testing protocols, etc.) (Sarabon et al. 2020; Virgile and Bishop 2021), but one important characteristic of inter-limb asymmetry that can at times be neglected is the direction of the asymmetry, otherwise known as limb dominance (Bishop et al. 2019, 2020). For instance, if the magnitude of asymmetry is reported in isolation (as an absolute value), fluctuations in limb dominance would ultimately be missed (Bishop et al. 2019, 2020). This is especially important in sports such as basketball, where a variety of left and right dominant movements, combined with repetitive vertical jumping, may cause fluctuations in limb dominance (Bishop et al. 2019, 2020). Finally, most assessments of reliability simply compare assessments at two time-points but fail to understand how consistent these measures may be over multiple days or weeks (Cormack et al. 2008; Heishman et al. 2020; Heishman, Daub, et al. 2019; Menzel et al. 2013; Pérez-Castilla et al. 2021). Overall, it is imperative to understand the reliability of CMJ asymmetry metrics with respect to both magnitude and direction as measured over multiple assessments, as they would be in practice for an athletic population, and to do so in addition to the more commonly assessed CMJ metrics.

In addition to establishing adequate levels of reliability, there is the need to facilitate the interpretation and "red flagging" of changes across the potentially large number of CMJ metrics. This is especially important when many athletes are being assessed repeatedly over the course of the season. Previous research has suggested specific variables can serve as key performance indicators (KPIs) such as: JH, RSI mod, peak power, etc. to monitor athletic performance (Barker et al. 2018; Byrne et al. 2017; Heishman et al. 2020; Heishman, Miller, et al. 2019; Schuster et al. 2020). However, isolating key variables may cause coaching staff and practitioners to miss important underlying aspects of the jump that may be contributing to sub-optimal performance or predisposing athletes to a greater risk of lower extremity injury. Thankfully, however, it is well-documented that many CMJ metrics are highly correlated to each other (Barker et al. 2018; Floría, Sánchez-Sixto, and Harrison 2019; Harry et al. 2021; Lachlan et al. 2021). Specifically, metrics related to jump height or power have been shown to display significant correlations, while those related to inter-limb asymmetry have displayed greater independence (Harry et al. 2021). These findings support the potential to summarize metrics into a reduced number of CMJ components, which may make the monitoring process easier for practitioners without losing any value. For instance, grouping of interrelated biomechanical metrics using techniques such as principal component analysis (PCA) may better describe independent aspects of jumping movement patterns, by summarizing several correlated biomechanical metrics as one overarching jump score (e.g., overall jump asymmetry) (Floría et al. 2019; Lachlan et al. 2021; Markovic et al. 2004; Welch et al. 2019), while still retaining biomechanical metrics that are otherwise neglected when the focus is placed on specific KPIs. Thus, this technique offers the potential to "red flag" changes across a larger number of CMJ metrics, and provides an actionable means of assessing what overarching components of movement (i.e., braking, propulsive or landing phase during the CMJ) or performance (e.g., force production, rate of force development (RFD), etc.) can be improved upon or rectified to reduce the relative risk of injuries and optimize performance. While this may provide an effective method for coaching staff to quickly and easily track CMJ performance, there is currently no information on the reliability of such analyses, especially in a longitudinal setting.

Therefore, our two objectives of this study were to (i) determine the week-to-week vs. multi-week (i.e., 7-weeks of preseason training) reliability of CMJ metrics and limb dominance, and (ii) similarly determine the week-to-week vs. multi-week (i.e., 7-weeks of preseason training) reliability of newly derived composite PCs that summarize specific aspects of the jump. Based on previous findings, we hypothesized that the commonly reported CMJ metrics (e.g., JH, RSI mod, peak power, etc.) would display excellent week-to-week reliability (Aoki et al. 2017; Byrne et al. 2017; Cormack et al. 2008; Gathercole et al. 2015; Heishman et al. 2020), while the asymmetry metrics would display much lower, but acceptable levels of week-to-week reliability (Heishman, Daub, et al. 2019; Impellizzeri et al. 2007; Menzel et al. 2013; Pérez-Castilla et al. 2021). Additionally, we expected to see improved reliability when these metrics were assessed in a multi-week fashion (i.e., across the entire preseason). As for the newly derived PCs, we hypothesized that we would find two primary components relating to jump power (PC1) and asymmetry (PC2), with the reliability being superior to the individual biomechanical metrics themselves, in both the week-to-week and entire preseason reliability analyses.

MATERIALS AND METHODS

Experimental Approach to the Problem

A repeated-measures design was used to assess the reliability of week-to-week vs. full 7-week preseason for force plate measured CMJ metrics and composite PCs. While our study was only examining the reliability of pre-season data, we collected data during a five-month period (from August to December, 2021) which consisted of four-weeks of off-season, seven-weeks of pre-season, and six-weeks of in-season CMJ testing that were used to build our PCA model. A total of 18 CMJ metrics were obtained from each jump. These consisted of JH, CMD, time to takeoff, RSI mod, peak braking power, and peak propulsive power, as well as the left and right components, asymmetry, and limb dominance for peak braking force, peak propulsive force, average braking RFD, and peak landing force. The force and power variables were chosen due to their relation to explosive performance and athletic trainability (Byrne et al. 2017; Kavanaugh et al. 2018; Schuster et al. 2020), while the strategy metrics (i.e., time to takeoff, CMD, and RSI mod) were chosen to provide insight into how the outcome was accomplished (Barker et al. 2018; Barker, Siedlik, and Mercer 2021; Heishman, Miller, et al. 2019). Additionally, inter-limb asymmetry metrics, along with the respective component parts of the asymmetry index, were chosen due to the implications to sport performance and risk of injury (Bishop et al. 2018; McGrath et al. 2016); similarly, peak landing forces (i.e., left and right peak landing force) were included given that the most frequent mechanism of injury in basketball relates to improper landings from vertical jumping or during change-of-direction tasks (i.e., cutting and pivoting) (Agel et al. 2007; Hewett et al. 2005; Noyes et al. 1983). Therefore, a total of 17 weekly CMJ testing sessions were completed to build the PCA model and examine the week-to-week vs. full 7-week pre-season reliability of these dependent variables and composite jump PCs.

Subjects

Based on a priori sample size calculation with an estimate r>0.80 ± 0.3 over 7 collections, a minimum of 12 participants were required (Shoukri, Asyali, and Donner 2004). Therefore, our sample consisted of 13 collegiate female basketball athletes (age 20 ± 1.5 years, height 178 ± 9.2 cm, mass 72.3 ± 11.6 kg, and training experience at the collegiate basketball level 3.2 ± 1.4 years). All participants were free of any musculoskeletal injury that would perturb their ability to fully participate in vertical jump testing, and the sample was exclusively comprised of female basketball athletes enrolled at our institution and were actively participating and competing on the women's basketball team. Subjects were familiar with routine CMJ testing as this protocol is a weekly assessment conducted in their strength and conditioning program. Prior to study commencement, all participants were informed of the potential risks, benefits, and study protocol. Participants were made fully aware of their ability to withdraw from the study at any time. Written consent was obtained from all athletes who participated in this study. This study was reviewed and approved by the university research ethics board. Separately and in addition to the approval from the university research ethics board, our plan of study was approved by the coaching staff of the basketball team.

Procedures

CMJ testing was completed once per week for a total of 17 weeks during the 2021-2022 female basketball competitive season. Testing was completed during three consecutive phases of training: off-season (4 weeks), pre-season (7 weeks), and in-season (6 weeks). CMJ testing was conducted on Monday mornings prior to any sport-specific practices or strength and conditioning sessions to ensure that athletes were fully rested and jump performance would not be affected by neuromuscular fatigue. All athletes had a minimum of 24 hours rest between any prior competition or training when completing weekly CMJ testing to ensure that they were provided with sufficient rest between any form of fatiguing exercise and maximal jump testing.

Prior to CMJ testing itself, participants completed a 10-minute dynamic warm-up to prepare the neuromuscular system. This dynamic warm-up was led by coaching staff and was the same for all athletes. Two portable force platforms (Hawkin Dynamics, Westbrook, ME, USA) were utilized to collect the 18 biomechanical variables of interest at a sampling frequency of 1000 Hz; this method of biomechanical assessment during vertical jump testing has been deemed valid when compared to the in-laboratory gold standard (Lake et al. 2018; Walsh et al. 2006). Subjects were instructed to stand still with feet shoulder width apart on the dual force plates and allow for proper establishment of body weight calculation. Additionally, subjects were told to self-select CMD, as this has been said to allow for fluid movement as would regularly be seen when jumping in competition, without tampering with the reliability of the metrics obtained (Gathercole et al. 2015; Heishman et al. 2020). Athletes were then verbally cued to jump as high as possible, while also completing the movement as quickly as possible, to effectively utilize a stretch-shortening cycle and mimic explosive performance that occurs in game (Barker et al. 2018; Gathercole et al. 2015; Harry et al. 2021). All jumps were completed with hands placed on hips, and without an arm-swing (Heishman et al. 2020; Impellizzeri et al. 2007). No instructions were provided for the landing phase of the CMJ aside from ensuring that both feet made contact with the force platform prior to concluding the downward motion of this phase of movement and, subsequently, returning to an upright standing position (Harry et al. 2021). This was accomplished by providing synchronous visual feedback of bilateral weight distribution on either a monitor or portable device in front of the athletes (Heishman et al. 2020). Additionally, jumps were visually monitored by the research team such that those attempts in which an athlete was unable to land with both feet on the force platform or was unable to return to an upright standing position to conclude the trial were identified as mistrials, discarded, and the attempt was then repeated after the provision of sufficient rest (Barker et al. 2018; Harry et al. 2021). Athletes completed 3 jumps per day, with a minimum of 30-seconds rest between each trial. Subsequently, the average of these 3 jumps were used to determine CMJ metrics for each weekly session, as this has been shown to be preferable to using the best jump approach (i.e., retaining and utilizing the best jump for analysis as determined by JH) (Bishop et al. 2019). However, if an individual jump had a JH which deviated by ≥20% within a session, then this specific jump attempt was removed from the computation of the sessional average and, as such, was ultimately excluded from statistical analyses. This only occurred for 2 of the 663 total jumps (i.e., 3 jumps x 17 weeks x 13 athletes), and as such nearly all of the following CMJ metrics are computed as weekly assessments as an average of 3 jumps.

Countermovement Jump Metrics

We included a total of 18 CMJ metrics computed from ground reaction force data in the manufacturer provided software (Hawkin Dynamics, Westbrook, ME, USA). First, common measures of overall jump performance and power were included such as JH, CMD, time to takeoff, RSI mod, peak braking power, and peak propulsive power. These metrics provide insight into explosive performance and lower-extremity force producing capabilities (Byrne et al. 2017; Kavanaugh et al. 2018; Schuster et al. 2020), while also highlighting the strategy utilized to achieve the outcome (Barker et al. 2018, 2021; Heishman, Miller, et al. 2019). The impulse-momentum theorem and take-off velocity were used to derive JH, rather than flight time, as this has been previously noted as the gold standard (Heishman et al. 2020; McMahon et al. 2018). Data smoothing and the identification of key time instances (e.g., take-off, etc.) were completed by the manufacturer provided software (Hawkin Dynamics, Westbrook, ME, USA), which has been demonstrated to possess low percent errors when compared to traditional methods (Merrigan et al. 2022).

Additionally, we included a series of commonly assessed metrics related to between-limb asymmetry force production (Heishman et al. 2020; Heishman, Daub, et al. 2019; Impellizzeri et al. 2007; Pérez-Castilla et al. 2021). These included the values from each limb, as well as the asymmetry and limb dominance for peak braking force, peak propulsive force, average braking RFD, and peak landing force. Asymmetry metrics were calculated using an asymmetry index and the following formula: Asymmetry Index = $\frac{Left - Right}{Left + Right} * 100$. As such, biomechanical asymmetry metrics are reported using both the magnitude and directional differences between limbs, with a positive value indicating left dominance, and a negative value indicative of right legged dominance. Additionally, a measure of limb dominance was computed to assess only directional bias (i.e., binary variable of left vs. right without the magnitude of between-limb differences).

Principal Component Analysis

A PCA was used to create a new set of linearly uncorrelated variables to summarize the original 18 dependent variables. To best map the relationships between these original CMJ metrics, the PCA was developed from all data collected across the 5-month study period (i.e., 4 weeks of off-season, 7 weeks of pre-season, and 6 weeks of in-season training). This resulted in 221 total weekly observations of each of the 18 CMJ metrics (i.e., 13 athletes x 17 sessions). Further, although the PCA was derived using data from the entire 5-month collection period, only results of the PC scores from the 7-weeks of pre-season are examined for reliability and presented in this study. The PCA was completed using the "pca" function in MATLAB R2021a (MathWorks, Inc., Natick, MA, USA) following the standardization of variables (i.e., mean of 0 and standard deviation of 1). In general, this function utilizes the singular value decomposition approach to consolidate commonalities between the original biomechanical variables by uniquely loading (i.e., rotating) them onto new variables (i.e., PCs). Therefore, the newly developed PCs utilize commonalities between all original biomechanical variables, but they themselves are orthogonal (i.e., uncorrelated) to each other. Further, these newly developed PCs are derived in order of maximum variance explained in the data and presented in descending order from PC1 to n-PC. The magnitude and direction of biomechanical variable loading on each PC is presented in Table 3, along with a colour-coded scale with darker shades of yellow signifying increasingly more negative loadings and deeper shades of blue signifying increasingly more positive loadings. Standardization of input variables was required given the varying scales of our biomechanical variables (Bartholomew 2002; Jolliffe and Cadima 2016). The first n-PCs explaining at least 90% of variance were retained for the analysis (Bartholomew 2002; Jolliffe and Cadima 2016). Additionally, the use of a PCA as a data reduction tool was justified given the highly correlated nature of these data (e.g., each variable was significantly correlated with 12-17 other variables in the dataset; Supplementary Table 1).

Statistical Analyses

To address the first research objective, the reliability of CMJ metrics (n = 18) were assessed week-to-week and across the entire pre-season using an intraclass correlation coefficient ($ICC_{3,k}$) with 95% confidence intervals, standardized error of the measurement (SEM), and minimum detectable change (MDC_{95}) (Baumgartner and Chung 2001; Weir 2005). Week-to-week reliability assessments were computed between subsequent weeks (i.e., week 1 vs. week 2, week 2 vs. week 3, etc.), with the average of these 6 weekly comparisons (i.e., 6 $ICC_{3,2}$) reported as the depiction of the reliability expected from week-to-week. Alternatively, the reliability across the entire pre-season was determined with all 7-week measurements compared in a single assessment ($ICC_{3,7}$). Reliability of limb dominance metrics were compared similarly, but with the use of a kappa coefficient, given their categorical nature (Viera and Garrett 2005). Finally, to address our second research objective, we applied the similar procedure using $ICC_{3,2}$ and $ICC_{3,7}$ to determine the reliability of the PCs scores week-to-week and over the entire pre-season, respectively. We interpreted ICCs as poor (<0.5), moderate (0.5-0.75), good (0.75-0.89), and excellent (>0.9) (Koo and Li 2016) and kappa coefficients as trivial (0-0.2), fair (0.21-0.4), moderate (0.41-0.6), substantial (0.61-0.8), nearly perfect (0.81-

0.99), and perfect (1) (Viera and Garrett 2005). All statistical analyses were performed using MATLAB R2021a (MathWorks, Inc., Natick, MA, USA).

RESULTS

Countermovement Jump Metrics

The group mean and standard deviations for all pre-season CMJ metrics, including limb dominance measures, are presented in Table 1. The results of the week-to-week and entire preseason reliability analyses are also presented in Table 1. It was found that all but two variables displayed good to excellent week-to-week reliability (ICC>0.75), with 11/18 displaying excellent reliability (ICC>0.9). The two variables that displayed lower week-to-week reliability were peak landing force asymmetry (ICC = 0.73) and right peak landing force (ICC = 0.48). Reliability was improved when CMJ metrics were examined over the entire preseason, such that 17/18 CMJ metrics displayed excellent reliability (ICC>0.9) and right peak landing force displayed good reliability (ICC = 0.84). While measures of limb dominance displayed a similar trend of improved reliability when examined across the entire preseason, the overall the levels of reliability for these dichotomized variables were generally lower when compared to the continuous measures of asymmetry (Table 2).

Table 1 about here

Table 2 about here

Principal Component Analysis

The PCA resulted in 6 PCs which accounted for 92% of the variance in our dataset. The correlation between the original biomechanical metrics and the PCs are presented in Table 3, while the loading coefficients are presented in Supplementary Table 2 and highlight the most important variables with respect to each PC. While these loadings represent complex relationships between the individual CMJ metrics used in the PCA, we can make some general interpretations as to the meaning of each PC. We found that PC1 was loaded with a variety of metrics as would be expected for PC1, but was most heavily on the force metrics, signifying a “Force Component”. PC2 was loading most heavily on the braking metrics, in addition to RSI mod, signifying a “Braking Component”. PC3 was loading most heavily on the power metrics, in addition to JH. Alternatively, PC4 appeared to be focused on the asymmetry metrics, signifying an “Asymmetry Component”. The final 2 PCs only accounted for an additional 9% of the variance and were related to a specific CMD and right landing force pattern (PC5), as well as a jump strategy component (PC6).

The results of the week-to-week and entire preseason reliability analyses for the PCs are presented in Table 4. The first 3 PCs displayed excellent week-to-week reliability, with the remaining 3 PCs displayed moderate reliability. Similar to the individual CMJ metrics, reliability was improved when examined across the preseason, with all PCs demonstrating good to excellent reliability (ICC = 0.89–0.99). Additionally, the individual PC scores for all athletes across all 7 weeks of the pre-season are presented in Figure 1.

Table 3 about here

Table 4 about here

*Figure 1 about here (***Figure 1.** Principal component scores for each athlete across the 7-week preseason, as well as individually plotted minimum detectable change ranges for PC4.)

Figure 2 about here (**Figure 2.** Representative weekly force-time curves for Athlete 11, illustrating the asymmetrical landing pattern occurring on weeks 4 and 6. This large asymmetry resulted in PC4 falling outside the minimum detectable change range (showing in Figure 1), even though other asymmetry measures (week 4 plot) remained relatively normal.)

DISCUSSION AND IMPLICATIONS

The primary purpose of this study was to assess the week-to-week reliability and multi-week reliability of preseason CMJ and limb dominance metrics. Additionally, we aimed to examine these same forms of reliability across newly derived composite PCs that summarize CMJ metrics. The findings of this investigation were 3-fold. First, nearly all CMJ metrics and limb dominance estimates displayed good to excellent week-to-week reliability. Second, the reliability was augmented when CMJ metrics were assessed together across the entire preseason. Finally, the reliability of newly derived PCs were at least as good as that of standard CMJ metrics, regardless of whether reliability was being assessed on a week-to-week basis or over the course of an entire training period (i.e., preseason). Overall, these findings suggest that PCs can offer a simple and reliable method to identify holistic changes in jump performance and ultimately support “red flagging” a jumping session which may require a deeper dive into specific CMJ metrics and potential biomechanical deficiencies.

Weekly vs. Preseason Reliability and Levels of Agreement in Limb Dominance

While many studies have assessed the reliability of both standard and inter-limb asymmetry CMJ metrics cross-sectionally, our results demonstrated that longitudinal assessment may result in superior reliability, especially for asymmetry metrics. In the present investigation, metrics that have been previously established as KPIs (i.e., JH, RSI mod, and peak propulsive power) displayed good to excellent reliability (ICC = 0.89-0.99), irrespective of whether they were assessed weekly or over the course of the entire 7-week preseason training period. These findings are in line with previous research which has demonstrated the excellent reliability of these KPIs (ICC = 0.85-0.98) (Aoki et al. 2017; Byrne et al. 2017; Cormack et al. 2008; Gathercole et al. 2015; Heishman et al. 2020). However, to the best of our knowledge, our study is the first of its kind to demonstrate the reliability of such KPIs in a longitudinal setting across an entire preseason.

In the present study, inter-limb asymmetry metrics displayed improved reliability when assessed longitudinally (ICC = 0.92-0.98), rather than weekly (ICC = 0.73-0.94). Interestingly, the inter-limb asymmetry metric that demonstrated the largest improvement in reliability when assessed longitudinally was peak landing force asymmetry (ICC = 0.73 and 0.93, weekly and longitudinally, respectively). Given this metric relates to the most frequent mechanism of injury in basketball (i.e., excessive load placed on the lower-extremities and improper or uneven dissipation of force when landing from high volume of jumping), improving the reliability in this manner is highly relevant. Discordant with our findings, Pérez-Castilla et al. (Pérez-Castilla et al. 2021) reported moderate to good reliability of asymmetry metrics (ICC = 0.63-0.77), while Heishman et al. (Heishman, Daub, et al. 2019) reported that only 4 of 16 CMJ asymmetry metrics assessed in their study displayed excellent inter-session reliability (ICC>0.9). In the study conducted by Heishman and colleagues (Heishman, Daub, et al. 2019), the 4 asymmetry metrics that were also included in our study (i.e., asymmetry for peak braking force, peak propulsive force, average braking RFD, and peak landing force) displayed moderate to excellent reliability (ICC = 0.91, 0.82, 0.73, and 0.82). Although this study conducted by Heishman and colleagues (Heishman, Daub, et al. 2019) presented interesting differences in reliability between CMJ protocols (i.e., with and without an arm swing), controlled for both time of day, and controlled for the impact of training load on jump performance, similar to Pérez-Castilla et al. (Pérez-Castilla et al. 2021), the best jump method was utilized and the inter-session reliability was comparing only 2 weekly testing sessions. In another study conducted by Menzel and colleagues (Menzel et al. 2013), which assessed the correlation of inter-limb asymmetry present in the CMJ vs. isokinetic strength in male professional soccer players, the best jump approach was used once again and only 2 weekly CMJ assessments were conducted. Similar to the present study, Impellizzeri et al. (Impellizzeri et al. 2007) utilized an average jump method to characterize CMJ metrics and found the reliability of bilateral strength asymmetry (i.e., bilateral difference in vertical peak force) to be excellent (ICC = 0.91). This study conducted by Impellizerri and colleagues (Impellizzeri et al. 2007) had a much larger sample size relative to the present study (n = 60), but differed in both the biological sex of the subjects, as well as the homogeneity of competitive sport participation (e.g., soccer, track and field, basketball, fencing, and alpine skiing). In contrast to most other studies assessing the reliability of CMJ inter-limb asymmetry, our results displayed excellent reliability for all but one asymmetry variable (i.e., week-to-week peak landing force asymmetry). The improved reliability of CMJ inter-limb asymmetry metrics in our study can be attributed to the fact that inter-limb asymmetry is a highly variable metric, and the use of an average value for the metrics across the 3 CMJ attempts, as well as the longitudinal nature of our study, enabled a more accurate assessment of both intra-individual normative asymmetries and inter-individual differences in asymmetry. Further, the MDCs of asymmetry metrics observed over the entire preseason (MDC = 2-12%) provide an acceptable level of sensitivity with respect to commonly defined 10-15% thresholds (Bishop et al. 2018). Alternatively, the MDCs for the week-to-week assessment (MDC = 3-22%) suggests that asymmetry changes would likely need to be substantially larger before it could be detected on a weekly basis.

In addition to the asymmetry metrics depicting magnitude and direction (Table 1), we also demonstrated similar trends for measures of limb dominance (i.e., directionality alone; Table 2). Specifically, the multi-week assessments of reliability for this binary categorical variable (i.e., left v right) ranged from substantial to nearly perfect (Kappa = 0.73–0.85), which was similar but superior to week-to-week measures (Kappa = 0.63–0.83). Additionally, these results are noticeably higher than those seen in other studies reporting on the level of agreement in limb dominance for the CMJ in athletic populations (Bishop et al. 2019, 2020; Bishop, Abbott, et al. 2022). These findings may be attributed to the use of a bilateral CMJ in the present study, rather than a unilateral CMJ protocol, which has often been the case in previous literature aimed at adjudicating the variance of the direction of asymmetry during vertical jump tasks (Bishop et al. 2019, 2020). The performance of a bilateral CMJ has been reported to be more stable than the unilateral CMJ (Bishop, Abbott, et al. 2022), which is likely the underpinning difference between the present levels of agreement statistics, and those reported in other studies (Bishop et al. 2019, 2020; Bishop, Abbott, et al. 2022). In accordance with our hypothesis, the levels of agreement in limb dominance for CMJ asymmetry metrics was greater when assessed longitudinally, which in line with the results of the other individual CMJ metrics, as well as PC scores.

PCs vs. CMJ Metrics

Previous research has demonstrated the capacity to use a PCA to improve the interpretation of CMJ metrics (Floría et al. 2019; Lachlan et al. 2021; Markovic et al. 2004), but this is the first study to demonstrate the reliability of the resulting PCs. In doing so, this work supports the use of PCs to summarize CMJ ability and define more holistic jump metrics. Even though our results are contrary to our hypothesis that all PCs would yield superior reliability when compared to traditional CMJ metrics, it was found that the reliability of the PCs was at least equivalent to the conventional reliability methods. Specifically, PC1, PC2, and PC3 described aspects of force production, the braking phase of the CMJ, and jump power, respectively, with excellent reliability, irrespective of the week-to-week or entire preseason approach (ICCs = 0.92–0.99). Alternatively, PC4 almost exclusively described overall jump asymmetry and, similar to the individual asymmetry metrics, this PC displayed superior reliability with the entire preseason reliability method (ICC = 0.73 and 0.93, respectively). While the remaining PCs explained only a small portion of remaining variance, PC6 was clearly related to a movement strategy that displayed excellent reliability over the entire preseason (ICC = 0.9). While similar components summarizing performance and strategy have previously been observed (Floría et al. 2019; Lachlan et al. 2021; Markovic et al. 2004), this is the first demonstration of a unique asymmetry component. Overall, these summarizing PCs, combined with the derived MDC estimates, provide an excellent method to identify and "red flag" meaningful changes in CMJ performance overtime. As a demonstration of this, individual PC scores for all 13 subjects for the first 4 PCs throughout the 7 preseason weeks are displayed in Figure 1, with dashed lines for PC4 MDCs. In doing so, we can subsequently describe an example of how these data may be utilized or interpreted in day-to-day practice.

Utility of PCs Demonstrated Through Case Use Example

To demonstrate the utility of incorporating PCs into routine athletic monitoring, we will examine Figure 1 and Figure 2 to highlight asymmetrical CMJ patterns in an athlete. First, we can see that variability exists for many athletes and PCs as one may expect, but by overlaying MDC ranges, specifically presented for PC4 in Figure 1, we can provide an indication of when a detectable change has occurred. In examining these asymmetry MDCs in Figure 1, we can see that athlete 11 demonstrates deviations beyond their intra-individual averages for weeks 4 and 6. These PC scores breach the upper bounds of the MDC, subsequently "red flagging" these weeks for having changes in asymmetry which require further examination. This further examination may be in the form of the individual CMJ metrics, or the ground reaction force traces themselves. Figure 2 highlights the change that occurred by presenting a representative ground reaction force trace for a CMJ from each week of the preseason, along PC scores and individual asymmetry metrics. Specifically, we can see that these deviant weeks were driven entirely by highly asymmetrical peak impact landings (56% in week 4 and 48% in week 6). In general, the athlete shows a tendency to land with greater left limb force, but the increased values observed in weeks 4 and 6 demonstrate an increase above and beyond the MDCs for peak landing force asymmetry presented in Table 1. Therefore, the examination of PC scores for all athletes in Figure 1 allowed us to easily "red flag" certain weeks and subsequently point the root of this deviation. Nevertheless, identifying the underlying mechanism of a change may still require multi-week trends (Bishop et al. 2018; Heil et al. 2020) and the awareness of context (i.e., training cycle or weekly load) or psychological state (i.e., sleep, pain, exertion, anxiety, etc.). Further, while this demonstration was conducted within our preseason data, it would be most advantageous to apply a similar method to longitudinal monitoring after defining baseline values and MDCs over multiple weeks. This longitudinal application would allow for monitoring potential in-season changes, which might be expected and of importance since lower limb biomechanics, including asymmetry, have demonstrated significant differences across a competitive season (Bishop, Read, et al. 2022; Fort-Vanmeerhaeghe et al. 2021; Häkkinen 1993). Lastly, it is important to note that our 95% MDCs provide a conservative estimate of change, but lower values could be derived to allow for more sensitive change metrics (i.e., 80% MDC or 90% MDC vs. 95% MDC; (Charlton et al. 2021)). Overall, these findings support the reliability of the CMJ PCs and their use as a method to summarize and "red flag" changes in CMJ performance which may help to refer an athlete for further investigation, assessments, or modifications to training for maximizing performance and minimizing injury risk.

There were several limitations to the present investigation. Firstly, the sample consisted of a homogenous group of female collegiate basketball athletes, which potentially limits the generalizability of these findings to the male counterpart or other competitive sporting populations. While we acknowledge that the PCs defined in this work are specific to the current sample and dataset, the conclusions drawn related to their reliability and utility support the definition of more holistic PC metrics to identify changes in CMJ performance. Second, while the sample size used for the reliability analyses was relatively small (n = 13), given that 17 weekly CMJ testing sessions were conducted across a 5-month study period, we had an impressive 221 total sessions to derive CMJ metric interrelationships within the PCA. Third, although the use of PCA provides a much more holistic outlook of jump performance, this is only part of the picture of overall load and stress experienced by the athlete, and without other tasks taken into consideration (e.g., strength, on-court assessments, etc.) and forms of stress (i.e., psychological stress), the true image of athletic performance and injury susceptibility cannot be adequately represented. Fourth, while PC4 provides a nice measure of overall jump asymmetry with adept sensitivity to detect change per guidelines for thresholds related to sport performance and injury risk (i.e., 10-15%) (Bishop et al. 2018; Parkinson et al. 2021), inter-limb asymmetry is highly task specific (Keogh et al. 2022; Sarabon et al. 2020; Virgile and Bishop 2021). Thus, this field or lab-based assessment as a surrogate measure of asymmetry present during jumping might vary substantially as compared to what is truly experienced on-court in a highly dynamic and ever-changing game environment. Fifth, due to the observational nature of the present investigation and to ensure standardization between phases of training, the maximum affordable hours of rest prior to CMJ testing across the five-month study period was a 24-hour window. While other studies have demonstrated that a greater time period between training and testing may be required to mitigate the affects of neuromuscular fatigue on vertical jump performance (Chatzinikolaou et al. 2014; Pliauga et al. 2015), the study design employed in the present investigation precluded the ability to provide rest periods of this magnitude, and thus may be inherently impacted by residual levels of neuromuscular fatigue. Sixth, given that our sample consisted exclusively of elite female athletes, it is possible that the effects of the menstrual cycle may have affected jump performance and neuromuscular function (Ansdell et al. 2019). However, recent systematic reviews have suggested that the effect of the menstrual cycle on exercise performance are inconclusive and trivial (McNulty et al. 2020; Meignié et al. 2021). Another limitation of the current work is that our PC model was built on variation between athletes, while a more sensitive model could exist if built individually on each athlete. Unfortunately, this would require a large number of jumps (e.g., 50-100) from each athlete in a short period of time (e.g., preseason). Additionally, this alternative approach may result in unique PC profiles for some athletes that require separate interpretations. Given the purpose of red flagging changes, this may not be necessary. Lastly, the average JH (i.e., 0.23m) in our sample was lower than those traditionally seen in other studies that have assessed vertical jump performance in competitive athletic populations. However, these findings are in line with a review conducted by Ziv and Lidor (Ziv and Lidor 2009), which demonstrated that female basketball athletes had mean vertical JH ranging from 0.25-0.48m, of which the higher values of this spectrum were derived from CMJ tests that incorporated an arm swing (i.e., did not isolate lower-extremity power production).

CONCLUSION

Common CMJ metrics obtained from force plate systems that are often referred to as KPIs offer highly reliable metrics to assess and track athlete explosivity and power (e.g., JH, RSI mod, peak propulsive power, etc.) during vertical jumping. Asymmetry CMJ metrics, which also appear to be generally reliable, may be beneficial in identifying between-limb differences present during jumping in athletes. Additionally, the assessment of these CMJ metrics, especially those related to between-limb asymmetry, will benefit from multi-week collections. This benefit comes in the form of improved baseline estimates of CMJ performance and the ability to define MDC values to highlight longitudinal changes which surpass measurement error in the system. Moreover, a PCA can be used to effectively summarize these data into a smaller number of reliable metrics (i.e., PCs) to holistically assess and track CMJ performance. Therefore, this method offers a unique opportunity to easily “red flag” changes in CMJ performance amongst the many CMJ metrics and across a potentially large cohort of athletes. Incorporating such methodologies with other lab-, field-, and sport-specific performance assessments, along with measures of psychological state can help to better define meaningful changes in student-athletes in a longitudinal setting over the course of an entire or multiple competitive seasons. Together, these data and advanced methodologies can help support trainers, coaches, and athletes in assessing, tracking, and potentially correcting training deficiencies, augmenting athletic performance, preventing impeding injuries, or improving return-to-play protocols.

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Table 1. Countermovement jump (CMJ) week-to-week vs. full preseason reliability.

CMJ Metrics	**Mean (SD)**		**ICC**	**95% CI**	**SEM**	**MDC**
Jump Height (m)	0.23 (0.04)	Week-to-Week	0.96	(0.84, 0.99)	9.03x10^{-3}	0.03
		Full Preseason	0.99	(0.97, 0.99)	5.1x10^{-3}	0.01
CMD (m)	-0.27 (0.03)	Week-to-Week	0.89	(0.63, 0.97)	0.01	0.03
		Full Preseason	0.96	(0.91, 0.98)	6.9 x10^{-3}	0.02
Time to Takeoff (s)	0.82 (0.17)	Week-to-Week	0.88	(0.62, 0.96)	0.04	0.11
		Full Preseason	0.97	(0.93, 0.99)	0.02	0.06
Peak Braking Power (W)	-1022.82 (295.99)	Week-to-Week	0.94	(0.79, 0.98)	75.23	208.53
		Full Preseason	0.98	(0.96, 0.99)	39.86	110.5
Peak Propulsive Power (W)	2912.05 (312.03)	Week-to-Week	0.96	(0.88, 0.99)	60.0	166.23
		Full Preseason	0.99	(0.97, 1.00)	34.33	95.16
Peak Braking Force Asym. (%)	-2.83 (7.35)	Week-to-Week	0.94	(0.81, 0.98)	1.77	4.92
		Full Preseason	0.98	(0.95, 0.99)	1.08	2.98
Left Peak Braking Force (N)	731.36 (147.42)	Week-to-Week	0.97	(0.89, 0.99)	26.34	73.01
		Full Preseason	0.99	(0.98, 1.00)	15.16	42.03
Right Peak Braking Force (N)	770.86 (128.52)	Week-to-Week	0.94	(0.78, 0.98)	30.15	83.57
		Full Preseason	0.98	(0.95, 0.99)	19.28	53.44
Peak Propulsive Force Asym. (%)	-2.47 (4.20)	Week-to-Week	0.91	(0.71, 0.97)	1.25	3.47
		Full Preseason	0.97	(0.93, 0.99)	0.76	2.11
Left Peak Propulsive Force (N)	777.68 (132.38)	Week-to-Week	0.98	(0.93, 0.99)	19.67	54.53
		Full Preseason	0.99	(0.99, 1.00)	10.56	29.28
Right Peak Propulsive Force (N)	812.48 (103.85)	Week-to-Week	0.96	(0.87, 0.99)	20.9	57.92
		Full Preseason	0.98	(0.97, 0.99)	13.31	36.9
Ave Braking RFD Asym. (%)	-0.11 (13.73)	Week-to-Week	0.91	(0.70, 0.97)	4.12	11.42
		Full Preseason	0.97	(0.94, 0.99)	2.39	6.62
Left Ave Braking RFD (N/s)	2335.79 (801.09)	Week-to-Week	0.87	(0.57, 0.96)	284.15	787.62

		Full Preseason	0.95	(0.90, 0.98)	177.61	492.31
Right Ave Braking RFD (N/s)	2359.88 (803.73)	Week-to-Week	0.86	(0.50, 0.96)	299.07	828.99
		Full Preseason	0.94	(0.87, 0.98)	195.17	540.99
Peak Landing Force Asym. (%)	-1.85 (15.31)	Week-to-Week	0.73	(0.11, 0.92)	7.94	22.0
		Full Preseason	0.92	(0.82, 0.97)	4.41	12.21
Left Peak Landing Force (N)	1079.65 (307.83)	Week-to-Week	0.91	(0.72, 0.97)	90.32	250.37
		Full Preseason	0.97	(0.94, 0.99)	53.89	149.39
Right Peak Landing Force (N)	1092.23 (187.94)	Week-to-Week	0.48	(0.00, 0.84)	135.51	375.62
		Full Preseason	0.84	(0.66, 0.94)	75.19	208.41
RSI mod (Jump Height/Contact Time)	0.29 (0.06)	Week-to-Week	0.89	(0.66, 0.97)	0.02	0.05
		Full Preseason	0.97	(0.94, 0.99)	9.3x10^{-3}	0.03

CMJ = countermovement jump; ICC = intraclass correlation coefficient; CI = confidence interval; SEM = standard error of the measurement; MDC = minimum detectable change; CMD = countermovement depth; Asym. = asymmetry; Ave = average; RFD = rate of force development; RSI mod = the modified reactive strength index.

Table 2. Week-to-week vs. full preseason levels of agreement in limb dominance (i.e., direction of CMJ asymmetry)

CMJ Asymmetry Metrics		**Kappa Coefficients**	**95% CI**	**SEM**
Peak Braking Force Asymmetry	Week-to-Week	0.83	(0.51, 1.00)	0.16
	Full Preseason	0.85	(0.61, 1.00)	0.13
Peak Propulsive Force Asymmetry	Week-to-Week	0.67	(0.28, 1.00)	0.20
	Full Preseason	0.73	(0.31, 1.00)	0.21
Ave Braking RFD Asymmetry	Week-to-Week	0.63	(0.23 0.98)	0.21
	Full Preseason	0.76	(0.49, 0.98)	0.14
Peak Landing Force Asymmetry	Week-to-Week	0.69	(0.35, 1.00)	0.17
	Full Preseason	0.76	(0.44, 1.00)	0.16

CMJ = countermovement jump; CI = confidence interval; SEM = standard error of the measurement; Ave = average; RFD = rate of force development.

Table 3. Summary of variable loading on principal components (e.g., correlation between original variables and principal component scores). The magnitude and direction of the relationships found are indicated using a colour coded scale, such that the relationships become increasingly more negative with darker shades of yellow, while the relationships become increasingly more positive with deeper shades of blue.

CMJ Metrics Included	**PC1**	**PC2**	**PC3**	**PC4**	**PC5**	**PC6**
Jump Height	-0.56	0.58	0.49	0.02	-0.13	0.22
CMD	0.57	-0.26	-0.45	0.04	0.44	0.41
Time to Takeoff	-0.47	-0.56	0.37	0.29	0.02	-0.28
Peak Braking Power	-0.71	-0.48	0.00	0.12	0.32	0.11
Peak Propulsive Power	0.62	0.36	0.50	0.30	0.04	0.08
Peak Braking Force Asymmetry	0.44	-0.68	0.24	-0.42	-0.16	0.16
Left Peak Braking Force	0.96	-0.03	0.07	-0.11	-0.17	-0.12
Right Peak Braking Force	0.79	0.48	-0.12	0.18	-0.05	-0.27
Peak Propulsive Force Asymmetry	0.56	-0.53	0.35	-0.38	-0.16	0.01
Left Peak Propulsive Force	0.97	-0.10	0.09	0.03	-0.02	-0.12
Right Peak Propulsive Force	0.90	0.19	-0.11	0.25	0.10	-0.16
Ave Braking RFD Asymmetry	0.38	-0.77	0.02	-0.28	0.01	0.11
Left Ave Braking RFD	0.88	0.16	-0.16	-0.24	-0.05	0.07
Right Ave Braking RFD	0.58	0.67	-0.22	-0.14	-0.03	0.07
Peak Landing Force Asymmetry	0.57	-0.39	0.11	0.59	-0.15	0.29
Left Peak Landing Force	0.73	-0.11	0.42	0.31	0.25	0.15
Right Peak Landing Force	0.17	0.41	0.45	-0.43	0.60	-0.19
RSI mod	-0.22	0.83	0.20	-0.17	-0.12	0.41
% Var. Exp. Individually	43	23	9	8	5	4
Total Cumulative % Var. Exp.	43	66	75	83	88	92

CMJ = countermovement jump; PC = principal component; CMD = countermovement depth; Ave = average; RFD = rate of force development; RSI mod = the modified reactive strength index; Var. Exp. = percent variance explained.

Table 4. Principal component week-to-week vs. full preseason reliability.

PCs		ICC	95% CI	SEM	MDC
PC 1	Week-to-Week	0.96	(0.86, 0.99)	0.52	1.45
	Full Preseason	0.99	(0.98, 1.00)	0.29	0.82
PC 2	Week-to-Week	0.93	(0.77, 0.98)	0.57	1.58
	Full Preseason	0.97	(0.95, 0.99)	0.34	0.93
PC 3	Week-to-Week	0.92	(0.74, 0.98)	0.33	0.92
	Full Preseason	0.97	(0.94, 0.99)	0.21	0.57
PC 4	Week-to-Week	0.73	(0.09, 0.92)	0.65	1.70
	Full Preseason	0.93	(0.85, 0.97)	0.33	0.92
PC 5	Week-to-Week	0.64	(0.00, 0.89)	0.47	1.31
	Full Preseason	0.89	(0.77, 0.96)	0.26	0.73
PC 6	Week-to-Week	0.74	(0.14, 0.92)	0.47	1.30
	Full Preseason	0.90	(0.79, 0.97)	0.29	0.80

ICC = intraclass correlation coefficient; CI = confidence interval; SEM = standard error of the measurement; MDC = minimum detectable change; PC = principal component.

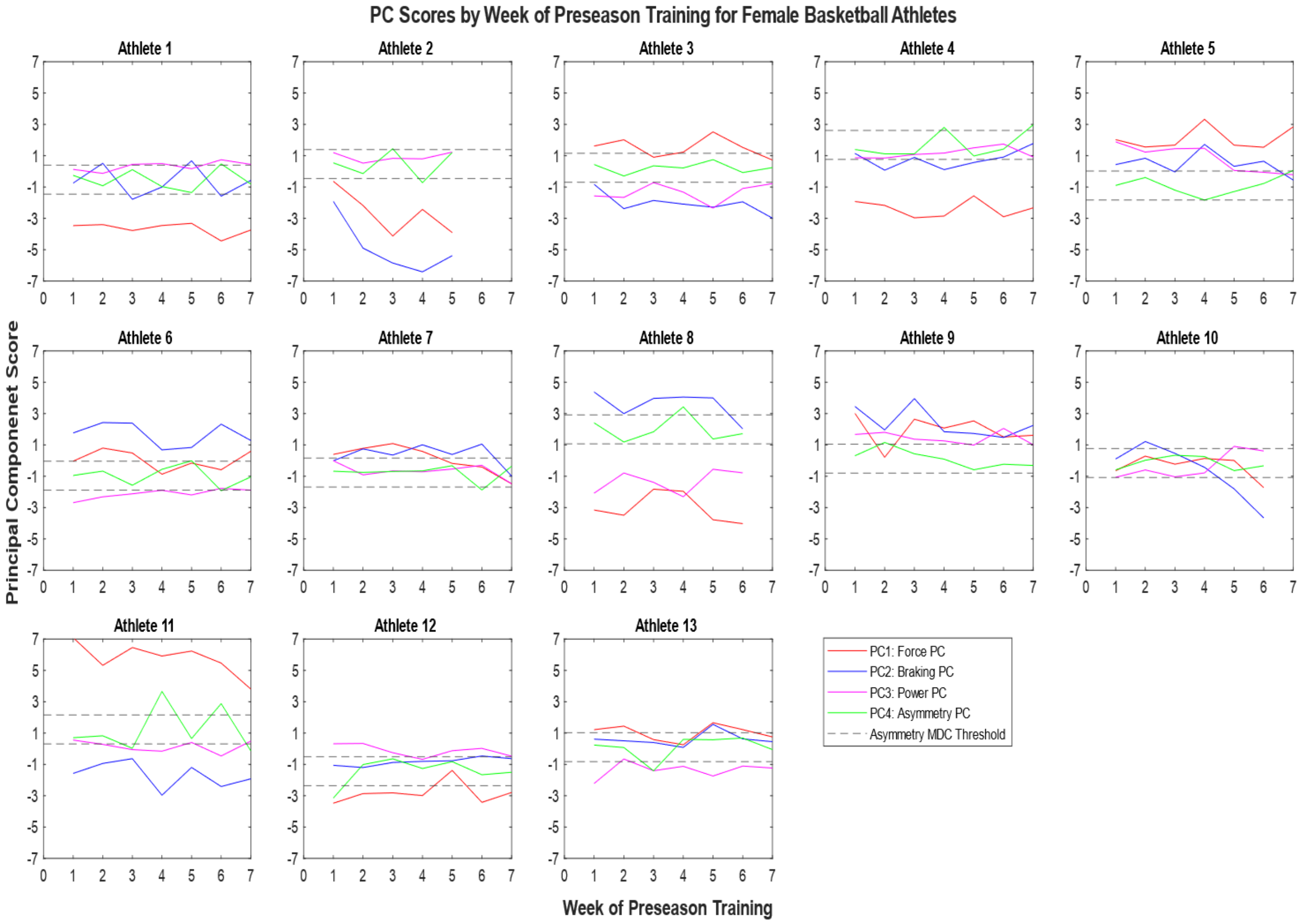

Figure 1. Principal component scores for each athlete across the 7-week preseason, as well as individually plotted minimum detectable change ranges for PC4.

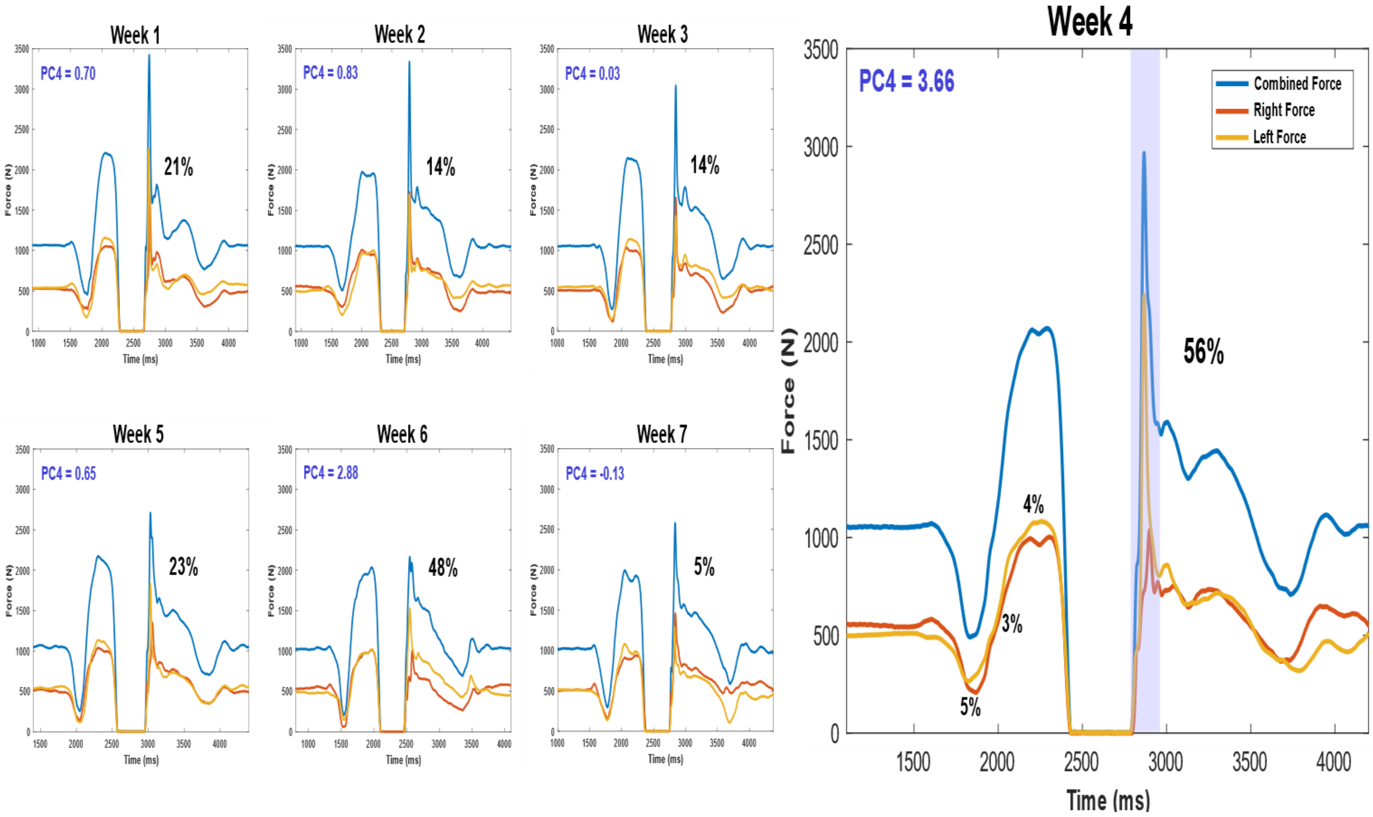

Figure 2. Representative weekly force-time curves for Athlete 11, illustrating the asymmetrical landing pattern occurring on weeks 4 and 6. This large asymmetry resulted in PC4 falling outside the minimum detectable change range (showing in Figure 1), even though other asymmetry measures (week 4 plot) remained relatively normal.)

Supplementary Table 1. Correlations between force plate-derived biomechanical metrics obtained from countermovement jump testing in a cohort of female collegiate basketball athletes across a competitive season. The magnitude and direction of the relationships found are indicated using a colour coded scale, such that the relationships become increasingly more negative with darker shades of yellow, while the relationships become increasingly more positive with deeper shades of blue.

	JH	CMD	TTTo	PBP	PPP	PBF Asym	L PBF	R PBF	PPF Asym	L PPF	R PPF	Ave BRFD Asym	L Ave BRFD	R Ave BRFD	PLF Asym	L PLF	R PLF	RSI mod
JH	1.00 (1.00, 1.00)	-0.64 (-0.71, -0.55) ***	0.13 (-0.01, 0.26)	0.14 (0.00, 0.27)	0.13 (-0.01, 0.27)	-0.48 (-0.58, -0.36) ***	-0.52 (-0.62, -0.42) ***	-0.27 (-0.39, -0.14) ***	-0.45 (-0.55, -0.33) ***	-0.58 (-0.67, -0.49) ***	-0.49 (-0.59, -0.37) ***	-0.60 (-0.68, -0.51) ***	-0.41 (-0.52, -0.28) ***	0.00 (-0.14, 0.13)	-0.42 (-0.53, -0.30) ***	-0.29 (-0.41, -0.16) ***	0.21 (0.08, 0.34) **	0.80 (0.75, 0.85) ***
CMD	-0.64 (-0.71, -0.55) ***	1.00 (1.00, 1.00)	-0.34 (-0.46, -0.21) ***	-0.08 (-0.21, 0.06)	0.14 (0.00, 0.27) *	0.30 (0.17, 0.42) ***	0.40 (0.27, 0.51) ***	0.25 (0.12, 0.38) ***	0.24 (0.11, 0.37) ***	0.50 (0.39, 0.59) ***	0.50 (0.39 ,0.59) ***	0.43 (0.31, 0.53) ***	0.54 (0.43, 0.63) ***	0.27 (0.14, 0.40) ***	0.42 (0.30, 0.53) ***	0.39 (0.27, 0.50) ***	-0.06 (-0.20, 0.07)	-0.33 (-0.45, -0.20) ***
TTTo	0.13 (-0.01, 0.26)	-0.34 (-0.46, -0.21) ***	1.00 (1.00, 1.00)	0.63 (0.54, 0.71) ***	-0.25 (-0.38, -0.12) ***	0.12 (-0.02, 0.25)	-0.40 (-0.51, -0.28) ***	-0.56 (-0.65, -0.46) ***	0.01 (-0.12, 0.15)	-0.33 (-0.45, -0.21) ***	-0.45 (-0.56, -0.33) ***	0.16 (0.02, 0.29) *	-0.57 (-0.65, -0.46) ***	-0.69 (-0.75, -0.60) ***	0.06 (-0.08, 0.20)	-0.09 (-0.23, 0.04)	-0.22 (-0.34, -0.08) **	-0.46 (-0.56, -0.34) ***
PBP	0.14 (0.00, 0.27)	-0.08 (-0.21, 0.06)	0.63 (0.54, 0.71) ***	1.00 (1.00, 1.00)	-0.51 (-0.60, -0.39) ***	-0.07 (-0.20, 0.07)	-0.72 (-0.78, -0.65) ***	-0.80 (-0.85, -0.75) ***	-0.19 (-0.32, -0.05) **	-0.61 (-0.69, -0.51) ***	-0.67 (-0.74, -0.58) ***	0.03 (-0.11, 0.16)	-0.72 (-0.78, -0.64) ***	-0.71 (-0.77, -0.63) ***	-0.20 (-0.33, -0.06) **	-0.39 (-0.51, -0.27) ***	-0.24 (-0.36, -0.10) ***	-0.25 (-0.38, -0.12) ***
PPP	0.13 (-0.01, 0.27)	0.14 (0.00, 0.27) *	-0.25 (-0.38, -0.12) ***	-0.51 (-0.60, -0.39) ***	1.00 (1.00, 1.00)	0.03 (-0.11, 0.17)	0.58 (0.47, 0.66) ***	0.63 (0.53, 0.70) ***	0.23 (0.10, 0.36) ***	0.65 (0.56, 0.72) ***	0.67 (0.59, 0.74) ***	-0.09 (-0.23, 0.05)	0.43 (0.31, 0.54) ***	0.40 (0.27, 0.51) ***	0.40 (0.28, 0.51) ***	0.64 (0.55, 0.71) ***	0.32 (0.19, 0.44) ***	0.24 (0.11, 0.37) ***
PBF Asym	-0.48 (-0.58, -0.36) ***	0.30 (0.17, 0.42) ***	0.12 (-0.02, 0.25)	-0.07 (-0.20, 0.07)	0.03 (-0.11, 0.17)	1.00 (1.00, 1.00)	0.53 (0.42, 0.62) ***	-0.14 (-0.27, 0.00) *	0.84 (0.79, 0.87) ***	0.48 (0.37, 0.58) ***	0.11 (-0.03, 0.25)	0.79 (0.74, 0.84) ***	0.35 (0.22, 0.46) ***	-0.14 (-0.27, 0.00)	0.37 (0.24, 0.48) ***	0.35 (0.22, 0.46) ***	-0.04 (-0.18, 0.10)	-0.46 (-0.57, -0.35) ***
L PBF	-0.52 (-0.62, -0.42) ***	0.40 (0.27, 0.51) ***	-0.40 (-0.51, -0.28) ***	-0.72 (-0.78, -0.65) ***	0.58 (0.47, 0.66) ***	0.53 (0.42, 0.62) ***	1.00 (1.00, 1.00)	0.76 (0.70, 0.82) ***	0.64 (0.55, 0.72) ***	0.96 (0.94, 0.97) ***	0.83 (0.78, 0.87) ***	0.40 (0.28, 0.51) ***	0.86 (0.82, 0.89) ***	0.54 (0.44, 0.63) ***	0.49 (0.38, 0.59) ***	0.63 (0.54, 0.71) ***	0.15 (0.01, 0.28) *	-0.24 (-0.37, -0.10) ***
R PBF	-0.27 (-0.39, -0.14) ***	0.25 (0.12, 0.38) ***	-0.56 (-0.65, -0.46) ***	-0.80 (-0.85, -0.75) ***	0.63 (0.53, 0.70) ***	-0.14 (-0.27, 0.00) *	0.76 (0.70, 0.82) ***	1.00 (1.00, 1.00)	0.09 (-0.04, 0.23)	0.74 (0.68, 0.80) ***	0.89 (0.86, 0.92) ***	-0.12 (-0.26, 0.01)	0.75 (0.69, 0.81) ***	0.76 (0.69, 0.81) ***	0.29 (0.16, 0.41) ***	0.48 (0.37, 0.58) ***	0.22 (0.09, 0.35) **	0.06 (-0.08, 0.20)

PPF Asym	-0.45 (-0.55, -0.33) ***	0.24 (0.11, 0.37) ***	0.01 (-0.12, 0.15)	-0.19 (-0.32, -0.05) **	0.23 (0.10, 0.36) ***	0.84 (0.79, 0.87) ***	0.64 (0.55, 0.72) ***	0.09 (-0.04, 0.23)	1.00 (1.00, 1.00)	0.65 (0.56, 0.72) ***	0.22 (0.08, 0.34) **	0.64 (0.55, 0.71) ***	0.41 (0.29, 0.52) ***	-0.04 (-0.18, 0.10)	0.36 (0.23, 0.47) ***	0.44 (0.32, 0.54) ***	0.08 (-0.06, 0.22)	-0.41 (-0.52, -0.29) ***
L PPF	-0.58 (-0.67, -0.49) ***	0.50 (0.39, 0.59) ***	-0.33 (-0.45, -0.21) ***	-0.61 (-0.69, -0.51) ***	0.65 (0.56, 0.72) ***	0.48 (0.37, 0.58) ***	0.96 (0.94, 0.97) ***	0.74 (0.68, 0.80) ***	0.65 (0.56, 0.72) ***	1.00 (1.00, 1.00)	0.88 (0.85, 0.91) ***	0.40 (0.28, 0.51) ***	0.79 (0.73, 0.84) ***	0.45 (0.33, 0.55) ***	0.57 (0.46, 0.65) ***	0.70 (0.62, 0.76) ***	0.14 (0.00, 0.27) *	-0.33 (-0.45, -0.20) ***
R PPF	-0.49 (-0.59, -0.37) ***	0.50 (0.39 ,0.59) ***	-0.45 (-0.56, -0.33) ***	-0.67 (-0.74, -0.58) ***	0.67 (0.59, 0.74) ***	0.11 (-0.03, 0.25)	0.83 (0.78, 0.87) ***	0.89 (0.86, 0.92) ***	0.22 (0.08, 0.34) **	0.88 (0.85, 0.91) ***	1.00 (1.00, 1.00)	0.13 (-0.01, 0.26)	0.76 (0.70, 0.81) ***	0.61 (0.51, 0.69) ***	0.49 (0.38, 0.59) ***	0.63 (0.54, 0.71) ***	0.15 (0.02, 0.29) *	-0.18 (-0.31, -0.04) *
Ave BRFD Asym	-0.60 (-0.68, -0.51) ***	0.43 (0.31, 0.53) ***	0.16 (0.02, 0.29) *	0.03 (-0.11, 0.16)	-0.09 (-0.23, 0.05)	0.79 (0.74, 0.84) ***	0.40 (0.28, 0.51) ***	-0.12 (-0.26, 0.01)	0.64 (0.55, 0.71) ***	0.40 (0.28, 0.51) ***	0.13 (-0.01, 0.26)	1.00 (1.00, 1.00)	0.34 (0.21, 0.45) ***	-0.33 (-0.44, -0.20) ***	0.37 (0.25, 0.49) ***	0.31 (0.18, 0.43) ***	-0.13 (-0.27, 0.01)	-0.62 (-0.69, -0.52) ***
L Ave BRFD	-0.41 (-0.52, -0.28) ***	0.54 (0.43, 0.63) ***	-0.57 (-0.65, -0.46) ***	-0.72 (-0.78, -0.64) ***	0.43 (0.31, 0.54) ***	0.35 (0.22, 0.46) ***	0.86 (0.82, 0.89) ***	0.75 (0.69, 0.81) ***	0.41 (0.29, 0.52) ***	0.79 (0.73, 0.84) ***	0.76 (0.70, 0.81) ***	0.34 (0.21, 0.45) ***	1.00 (1.00, 1.00)	0.75 (0.68, 0.80) ***	0.30 (0.17, 0.42) ***	0.49 (0.37, 0.58) ***	0.20 (0.06, 0.33) **	-0.02 (-0.16, 0.12)
R Ave BRFD	0.00 (-0.14, 0.13)	0.27 (0.14, 0.40) ***	-0.69 (-0.75, -0.60) ***	-0.71 (-0.77, -0.63) ***	0.40 (0.27, 0.51) ***	-0.14 (-0.27, 0.00)	0.54 (0.44, 0.63) ***	0.76 (0.69, 0.81) ***	-0.04 (-0.18, 0.10)	0.45 (0.33, 0.55) ***	0.61 (0.51, 0.69) ***	-0.33 (-0.44, -0.20) ***	0.75 (0.68, 0.80) ***	1.00 (1.00, 1.00)	0.01 (-0.13, 0.15)	0.23 (0.09, 0.36) **	0.30 (0.17, 0.42) ***	0.42 (0.30, 0.53) ***
PLF Asym	-0.42 (-0.53, -0.30) ***	0.42 (0.30, 0.53) ***	0.06 (-0.08, 0.20)	-0.20 (-0.33, -0.06) **	0.40 (0.28, 0.51) ***	0.37 (0.24, 0.48) ***	0.49 (0.38, 0.59) ***	0.29 (0.16, 0.41) ***	0.36 (0.23, 0.47) ***	0.57 (0.46, 0.65) ***	0.49 (0.38, 0.59) ***	0.37 (0.25, 0.49) ***	0.30 (0.17, 0.42) ***	0.01 (-0.13, 0.15)	1.00 (1.00, 1.00)	0.76 (0.70, 0.81) ***	-0.38 (-0.49, -0.26) ***	-0.40 (-0.51, -0.28) ***
L PLF	-0.29 (-0.41, -0.16) ***	0.39 (0.27, 0.50) ***	-0.09 (-0.23, 0.04)	-0.39 (-0.51, -0.27) ***	0.64 (0.55, 0.71) ***	0.35 (0.22, 0.46) ***	0.63 (0.54, 0.71) ***	0.48 (0.37, 0.58) ***	0.44 (0.32, 0.54) ***	0.70 (0.62, 0.76) ***	0.63 (0.54, 0.71) ***	0.31 (0.18, 0.43) ***	0.49 (0.37, 0.58) ***	0.23 (0.09, 0.36) **	0.76 (0.70, 0.81) ***	1.00 (1.00, 1.00)	0.29 (0.16, 0.41) ***	-0.20 (-0.33, -0.06) **
R PLF	0.21 (0.08, 0.34) **	-0.06 (-0.20, 0.07)	-0.22 (-0.34, -0.08) **	-0.24 (-0.36, -0.10) ***	0.32 (0.19, 0.44) ***	-0.04 (-0.18, 0.10)	0.15 (0.01, 0.28) *	0.22 (0.09, 0.35) **	0.08 (-0.06, 0.22)	0.14 (0.00, 0.27) *	0.15 (0.02, 0.29) *	-0.13 (-0.27, 0.01)	0.20 (0.06, 0.33) **	0.30 (0.17, 0.42) ***	-0.38 (-0.49, -0.26) ***	0.29 (0.16, 0.41) ***	1.00 (1.00, 1.00)	0.31 (0.18, 0.43) ***
RSI mod	0.80 (0.75, 0.85) ***	-0.33 (-0.45, -0.20) ***	-0.46 (-0.56, -0.34) ***	-0.25 (-0.38, -0.12) ***	0.24 (0.11, 0.37) ***	-0.46 (-0.57, -0.35) ***	-0.24 (-0.37, -0.10) ***	0.06 (-0.08, 0.20)	-0.41 (-0.52, -0.29) ***	-0.33 (-0.45, -0.20) ***	-0.18 (-0.31, -0.04) *	-0.62 (-0.69, -0.52) ***	-0.02 (-0.16, 0.12)	0.42 (0.30, 0.53) ***	-0.40 (-0.51, -0.28) ***	-0.20 (-0.33, -0.06) **	0.31 (0.18, 0.43) ***	1.00 (1.00, 1.00)

Abbreviations: JH = jump height; CMD = countermovement depth; TTTo = time to takeoff; PBP = peak braking power; PPP = peak propulsive power; PBF Asym = peak braking force asymmetry; L left; R = right peak; PPF Asym = peak propulsive force asymmetry; Ave BRFD Asym = average braking rate of force development asymmetry; PLF Asym = peak landing force asymmetry; RSI mod = the modified reactive strength index; * = p<0.05; ** = p<0.01; *** = p<0.001.

Supplementary Table 2. Summary of principal component analysis loading coefficients. The magnitude and direction of the loading coefficients found are indicated using a colour coded scale, such that the loading coefficients become increasingly more negative with darker shades of yellow, while the loading coefficients become increasingly more positive with deeper shades of blue.

CMJ Metrics Included	**PC1**	**PC2**	**PC3**	**PC4**	**PC5**	**PC6**
Jump Height	-0.2	0.28	0.39	0.02	-0.14	0.24
CMD	0.2	-0.13	-0.36	0.03	0.47	0.46
Time to Takeoff	-0.17	-0.27	0.3	0.24	0.02	-0.32
Peak Braking Power	-0.26	-0.23	0	0.1	0.34	0.12
Peak Propulsive Power	0.22	0.17	0.4	0.25	0.05	0.09
Peak Braking Force Asymmetry	0.16	-0.33	0.19	-0.35	-0.17	0.18
Left Peak Braking Force	0.35	-0.02	0.06	-0.09	-0.18	-0.13
Right Peak Braking Force	0.29	0.23	-0.1	0.15	-0.05	-0.3
Peak Propulsive Force Asymmetry	0.2	-0.26	0.28	-0.31	-0.17	0.01
Left Peak Propulsive Force	0.35	-0.05	0.07	0.03	-0.02	-0.13
Right Peak Propulsive Force	0.32	0.09	-0.09	0.21	0.11	-0.18
Ave Braking RFD Asymmetry	0.14	-0.38	0.02	-0.23	0.01	0.12
Left Ave Braking RFD	0.32	0.08	-0.13	-0.2	-0.05	0.08
Right Ave Braking RFD	0.21	0.33	-0.18	-0.12	-0.03	0.07
Peak Landing Force Asymmetry	0.21	-0.19	0.09	0.5	-0.16	0.33
Left Peak Landing Force	0.26	-0.05	0.33	0.26	0.26	0.17
Right Peak Landing Force	0.06	0.2	0.36	-0.36	0.64	-0.22
RSI mod	-0.08	0.41	0.16	-0.15	-0.13	0.45
% Var. Exp. Individually	43	23	9	8	5	4
Total Cumulative % Var. Exp.	43	66	75	83	88	92

CMJ = countermovement jump; PC = principal component; CMD = countermovement depth; Ave = average; RFD = rate of force development; RSI mod = the modified reactive strength index; Var. Exp. = percent variance explained.