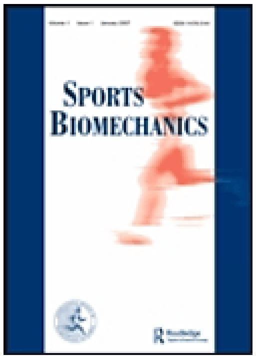

Relationships among Countermovement Vertical Jump Performance Metrics, Strategy Variables, and Inter-limb Asymmetry in Females

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Sports Biomechanics

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Associate Editor's Comments to Author:

Associate Editor: Hughes, Gerwyn
Comments to Author:
While the reviewers are satisfied with the changes that were made, my very minor comments from the previous review were not included in the response document and have not been addressed. Please consider and address the following:
Dear Editor:
Thank you for identifying these issues with our manuscript. Each comment has been addressed in the paper. Changes and additions are highlighted in the revised submission.

Line 33-34: I don't feel you need the descriptive statistics for the participant characteristics in the abstract.
The descriptive statistics have been deleted as requested.

Line 54: rather than just saying 'etc', specifically refer to all the relevant variables.
Thanks for this comment. We have removed the 'etc' and added takeoff momentum and power to this list.

Line 136: change 'subjects' to 'participants'. This should be corrected throughout the manuscript.
"Subjects" has been replaced with "Participants" throughout the manuscript as requested.

Line 138: be clear that these numbers are descriptive statistics for age, height and mass.
As requested, we have specified "age", "height", and "body mass" for these descriptive statistics.

Reviewer(s)' Comments to Author:

Reviewer: 1

Comments to the Author
Many thanks to the authors for their resubmission to SB and responses to my initial review. Some solid work here that warrants publication now, IMO. Congratulations team!
The authors thank the reviewer for their positive comments regarding our revised submission. We are appreciate of the reviewer's feedback to best prepare our paper for publication.

Relationships among Countermovement Vertical Jump Performance Metrics, Strategy Variables, and Inter-limb Asymmetry in Females

Running Head:

Relationships between Vertical Jump Performance, Total Body Strategy, and Asymmetry

ABSTRACT

Dependent variables commonly studied during countermovement vertical jump (CMVJ) tests largely stem from male-only studies despite females' distinct energy storage and reutilization strategies. This could limit progress among females seeking increased CMVJ performance through targeted changes in certain variables. We explored relationships between CMVJ performance metrics (jump height, modified reactive strength index, jump power, and takeoff momentum) and a) temporal and force application variables and b) inter-limb force and yank (i.e., rate of force development) asymmetry in 31 recreationally active females. Participants performed 8 CMVJs while ground reaction force (GRF) data were obtained. Pearson product-moment correlation coefficients assessed the strength and direction of the associations. Twenty-six significant relationships ($r \geq \pm 0.357$; $p < 0.05$) were detected across the CMVJ performance variables. The significantly correlated variables were generally isolated to only one of the four performance metrics. Only the percentage of concentric phase inter-limb force asymmetry was significantly associated with CMVJ performance, specifically jump power and takeoff momentum. Coaches and physical performance professionals should be aware of popular strategy variables' association or lack of association with commonly studied performance metrics when seeking to understand or improve specific CMVJ jumping abilities in females.

Key words: Asymmetry; countermovement jump, females, performance, strategy.

INTRODUCTION

The countermovement vertical jump (CMVJ) requires refined coordination patterns and mechanical outputs to propel the body upward with as much velocity as possible (14). As a result, the CMVJ is strongly related to sport-specific demands such as sprinting and agility (35, 46). Total body (i.e., center of mass [COM]) CMVJ strategy variables, notably rapid unloading of body weight, overall CMVJ and phase-specific quickness, and rapid force production during eccentric braking (3, 28, 29), are commonly reported as key variables to focus on in training or testing to maximize one or more common metrics of CMVJ performance (e.g., jump height, modified reactive strength index [$\mathrm{RSI_{MOD}}$], takeoff momentum, power). These and other recommended variables largely stem from investigations with male-only samples (3, 15, 29), leading to a lack of clarity for whether the variables can or should be generalized to both sexes. Despite modern-day female athletes demonstrating much greater CMVJ abilities compared to female athletes from ~15 years prior (48), it has long-been known that females reutilize more stored eccentric energy than males during CMVJs despite achieving ~17-20 cm lower jump heights (27). Thus, focused efforts to improve the aforementioned variables that are based on male-only studies could be limiting females' performance progress. To the authors' knowledge, the only study directly exploring correlates to CMVJ performance in females focused on propulsive (i.e., concentric) variables (44). Unfortunately, concentric propulsion variables do not adequately reflect a jumper's strategy or overall jump explosiveness (3). Consequently, it is unclear as to which COM strategy variables are strongly associated with CMVJ performance in female samples. Such relationships should be explored further in female-only samples to maximize potential effects of targeted interventions and establish the effects of training prescription differences within female cohorts.

In addition to COM strategy variables, inter-limb asymmetry is a commonly studied CMVJ strategy variable. Asymmetry analyses tend to focus on male-only or pooled-sex samples (1, 2, 5, 25, 34, 38), although some female-only analyses are available (8, 12, 13, 36). In pooled-sex samples, weaker athletes tend to exhibit more asymmetry in some performance variables than stronger athletes during the CMVJ and other tasks (2). Further, females typically display less muscular strength relative to fat free mass (48) and lesser relative force application abilities during CMVJs (23) than males. Females tend to exhibit greater asymmetries than males do during dynamic movements with rapid eccentric decelerations (41). Eccentric deceleration and the rapid application of net eccentric forces can be quite demanding during CMVJs (3, 20). Thus, consequences of inter-limb asymmetry during bilateral CMVJs may be more severe for females as lesser relative strength and increased eccentric force application asymmetry might alter intended CMVJ techniques and lead to requisite compromises in performance.

The prominent techniques used to assess inter-limb asymmetry are the bilateral asymmetry index and the symmetry index (11), with the former suggested as the most appropriate technique (10). However, there are two main issues with symmetry indices. First, asymmetry is a 'noisy' concept in that data sources from two limbs are combined into a single source. Second, the metrics examined to create the index are typically discrete variables (e.g., peak force, peak power) that only represent what is occurring at a single instant in time. Because contemporary force platforms record data at sampling frequencies of 1000 Hz (22, 30, 33), the resulting asymmetry index only represents the inter-limb difference over a 0.001 s (i.e., 1 millisecond) interval. This is problematic because a typical CMVJ lasts ~0.7 s to 1.0 s (21, 26) and an inter-limb difference over 1 millisecond reveals a trivial amount of information relative to the overall CMVJ. Even if variables used in symmetry index calculations are obtained over a specific interval or CMVJ phase (e.g., impulse, average force production) before being reduced to a single value, hundreds of data points are disregarded. Thus, current symmetry processes potentially masks a wealth of information that could be explored throughout a time period of interest (19). Finally, symmetry indices are most often interpreted using subjective meaningfulness thresholds based on discrete variables, such as the 15% threshold (6, 17, 25), which are unlikely to indicate worthwhile asymmetry through the entire CMVJ.

A procedure that could be used to more deeply explore inter-limb asymmetry throughout the entire CMVJ while also addressing issues related to combining two sources of data into one is the point-to-point statistical analysis, which is primarily used to explore inter-limb asymmetry during gait (18). This procedure uses the Model Statistic technique (4), which is similar to a t-test but it accounts for variability associated with each comparative mean as well as the number of trials recorded. Comparisons between limbs are conducted across all recorded data points at the single-subject level (i.e., for each individual participant), providing the option to explore the presence of asymmetry as well as the magnitudes and directions of the asymmetries throughout a complete movement. Complete movement trials, phases, or both are time-normalized to a user-selected number of data points before comparisons (usually 101 to reveal differences from 0-100% of a movement or movement phase duration), which retains much more information than typical symmetry indices based on discrete variables. Thus, it may be more advantageous to use point-to-point statistical tests to understand the patterns and magnitudes of asymmetry across phases of the CMVJ compared to discrete time points.

The purpose of this preliminary study was two-fold. First, we sought to explore the relationships between COM strategy variables associated with key metrics of CMVJ performance in females to strengthen the body of literature on important jumping characteristics in this population. We focused on four CMVJ performance metrics (jump height, RSI_{MOD}, jump power, and takeoff momentum) to obtain correlates to performance that could be associated with task- or athlete-specific jumping demands of various sports or playing positions, which cannot be revealed when studying one CMVJ performance metric alone. The second purpose was to explore the relationships between point-to-point asymmetry in vertical force application and yank, sometimes called rate of force development (32), throughout the CMVJ phases to determine whether greater proportions of asymmetry within a specific CMVJ phase are associated with reduced outcomes for the CMVJ performance metrics. It was hypothesized that COM strategy variables and inter-limb asymmetry will be uniquely associated with specific CMVJ performance metrics.

METHODS

Participants

A convenience sample of 31 females (mean ± standard deviation [95% confidence interval]; age: 22.10 ± 2.51 [21.18-23.02] y; height: 1.65 ± 0.64 [1.42-1.89] m; body mass: 63.31 ± 7.63 [60.51-66.10] kg) participated in this study. Participants were defined as recreationally active athletes due to their ≥ 1 y of upper and lower body resistance training experience at a frequency of 2-4 weekly sessions. Participants were excluded if they did not meet this training criteria or if they were pregnant, thought they were pregnant, or trying to become pregnant, currently breastfeeding, or had any musculoskeletal or physiological ailments that could affect their ability to perform maximum effort jumps or continue with resistance training. We did not consider use of hormonal contraceptives nor control for phase of the menstrual cycle. Prior to completing any experimental tasks, participants provided written informed consent as approved by the Institutional Review Board at XXX University in accordance with the Declaration of Helsinki.

Procedures

Participants completed all tasks while wearing their own athletic footwear (i.e., no dress shoes, casual shoes, or boots). First, a standardized warm-up was completed consisting of 5-minutes of stationary cycling at a self-selected pace. This was followed by a 1-minute break, after which approximately five CMVJ practice trials were performed at a self-selected intensity, working up from low-intensity to maximum-intensity, to become familiarized with performing CMVJs within the laboratory environment while adhering to the technical instructions/requirements described later in this section. Participants were allotted up to 1-minute between CMVJ familiarization trials. Participants then completed eight maximum effort CMVJ trials while ground reaction force (GRF) data were recorded using two three-dimensional force platforms (OPT464508; Advanced Mechanical Technology, Inc., Watertown, MA) sampling at 1000 Hz and mounted both side-by-side and flush with the laboratory floor. The force platforms were zeroed prior to each trial and synchronously interfaced to a PC running NetForce acquisition software (Advanced Mechanical Technology, Inc., Watertown, MA). To begin each trial, participants were instructed to stand in a motionless position for ~1 second with their arms akimbo (i.e., hands on hips with elbows pointed laterally). Upon a “go” command, participants initiated the CMVJ using their preferred countermovement depth, followed by a vertical jumping action. Participants were instructed to achieve maximum jump height in the shortest possible time. No instructions were provided for the landing, except to land with each foot contacting a force platform before terminating downward motion and returning to a standing still position. Approximately 30 seconds of rest separated each trial. If participants did not adhere to these instructions, the trial was discarded and repeated. Trials were also discarded and repeated if the researchers, participants, or both observed or determined that a trial was less than maximal effort.

Data Analysis

The raw GRF data from each force platform were exported to MATLAB® (R2020a; The Mathworks, Inc., Natick, MA). The vertical GRF from each platform were smoothed using a 4th-order, bi-directional, low pass, Butterworth digital filter with a 50 Hz cutoff frequency, where the order of the filter and the cutoff were set before the bi-directional passes (21). To extract CMVJ performance and total body strategy metrics, the vertical GRF from the two force platforms were summed to create a vertical GRF profile representing the force acting on the COM. Time data were calculated from the vertical GRF by creating a new array (i.e., column of data points), starting at zero and ending with the penultimate data point, and multiplying each data point by the inverse of the sampling frequency (i.e., 1/1000). Instantaneous vertical yank was calculated as the time-derivative of the vertical GRF.

Body weight was calculated as the average vertical GRF during the first 0.5 s of the ~1 s quiet standing period prior to initiation of the jump. Five standard deviations of the vertical GRF and the maximum vertical GRF during this period was also calculated. Due to the possibility that the maximum vertical GRF recorded during the quiet standing period can be greater than the calculated body weight + five standard deviations, we used an adaptation of the process outlined by Owen and colleagues (40) to detect the start of the CMVJ. Specifically, if the maximum vertical GRF during the quiet standing period was greater than the calculated body weight + 5 standard deviations, the maximum vertical GRF ± five standard deviations was used for the start threshold, otherwise body weight ± five standard deviations was used. This allowed the start of the CMVJ to be defined by a meaningful increase or decrease in vertical GRF, whichever occurred first. Using, the time 200 ms prior to the start of the CMVJ was used to start calculations of vertical COM acceleration, velocity, and position. This ensured there was zero acceleration (i.e., vertical GRF as close as possible to the calculated body weight) at the start of the COM velocity and position integration calculations. This process was also used to minimize potential error-related drift in the COM velocity and position results that might have occurred if starting integrations from the first recorded data point even if the requirement of ~0 acceleration was met. Thus, from the start-200 ms time point, vertical COM acceleration was calculated from the vertical GRF data using Newton's law of acceleration ($a = \Sigma F/m$) where, 'ΣF' represents the difference between the vertical GRF and the calculated body weight, and 'm' represents body mass (i.e., body weight divided by the absolute value of gravitational acceleration). Vertical COM velocity was then calculated as the cumulative time-integral of the vertical COM acceleration, using the trapezoidal method. Vertical COM position was then calculated as the cumulative time-integral of the vertical COM velocity, again using the trapezoidal method. The vertical GRF, yank, and COM acceleration, velocity, and position time-histories were then trimmed to the time between the start of the CMVJ and takeoff, with takeoff defined as the time when the vertical GRF decreased below a threshold equal to the mean + five standard deviations of the flight phase vertical GRF, similar to the procedure outlined by Lake and colleagues (31). Specifically, surrogate takeoff and ground contact times were first identified as the times when the vertical GRF decreased below and then increased above 30 N, specifying the start of the search after the minimum COM velocity to account for participants who may have reduced the vertical GRF below 30 N immediately after the start of the CMVJ. The first and last 25% of this surrogate flight phase was disregarded, and the middle 50% of flight was used to calculate the mean + five standard deviations of the flight phase vertical GRF. The first time the vertical GRF decreased below that threshold defined the true time of takeoff.

The CMVJ was deconstructed into the phases recommended by Harry, Barker and Paquette (20), as shown in Figure 1. Specifically, the unloading phase was defined as the time between the start of the CMVJ and the local minimum vertical GRF. The eccentric yielding phase was defined as the time between the end of unloading and the minimum COM velocity. The eccentric braking phase was defined as the time between the end of eccentric yielding and the time when vertical COM velocity crossed zero (i.e., time of the minimum COM position). Finally, the concentric propulsion phase was defined as the time between the end of eccentric braking and takeoff. Jump height (i.e., COM flight height) was calculated as the square of vertical COM velocity at takeoff divided by two-times the absolute value of gravitational acceleration. RSI_{MOD} was calculated as the ratio of jump height and jump time (i.e., time between CMVJ start and takeoff). Takeoff momentum was calculated as the product of velocity at takeoff and body mass. This metric was included because of its strong association with sprint ability (37), suggesting takeoff momentum can be a key metric to explore during CMVJ tests in athletes of various body masses playing contact sports or sports where jumping and sprinting abilities are emphasized (e.g., rugby, basketball, etc.). Jump power (i.e., average power during the concentric phase) was calculated using the equation described by Samozino and colleagues (45) to account for issues related to the misuse of mechanical power in previous research (47). Countermovement depth was calculated as the difference in vertical COM position between CMVJ start and the end of eccentric braking. Push-off distance was calculated as the difference in vertical COM position between the end of eccentric braking and takeoff. The magnitude of body weight unloading was calculated as the percentage of body weight reduced by the end of the unloading phase. The magnitude of vertical GRF at the end of eccentric braking (i.e., eccentric braking force, sometimes called ‘amortization force’ or ‘force at zero velocity’) was extracted to reflect the amount of stored mechanical energy in the system. The average vertical GRF during the concentric propulsion phase was calculated. The average yank (i.e., change of vertical GRF divided by the change of time) was calculated during each phase. These force and yank values were normalized to body weight to allow the magnitudes to be compared with other studies. For each variable, the average across the eight recorded trials was used for analysis.

< Figure 1 About Here >

For the point-to-point asymmetry analysis, the vertical GRF time-histories from each force platform were used, and vertical yank was calculated for each time-history as the time-derivative of each platform’s force curve. The bilateral vertical GRF and yank time-histories were then time-normalized to 101 data points (i.e., 0-100% of the phases) for each phase via linear interpolation. Mean and standard deviation values were then calculated across the eight trials for all 101 data points within the phases to create mean and standard deviation ensemble curves bilaterally.

Statistical Analysis

Processed data were exported to SPSS (version 26; IBM Corp., Armonk, NY), where Pearson product-moment correlation coefficients were calculated to report the measure of strength and direction of association existing between the CMVJ performance and COM strategy variables. Data normality was assessed using the Shapiro-Wilk test, and linearity was inspected using scatterplots. The threshold for statistical significance of the correlation coefficients was based on a 5% alpha level ($\alpha = 0.05$). We elected not to include an alpha adjustment for the significance tests because alpha adjustments reduce statistical power and there is no justifiable way to localize results that capitalize on chance (39). In addition, we did not boot-strap the data in the event that normality was violated after weighing the effects of non-normal distributions (4, 42) in consideration of our combined use of single-subject and group statistical tests. Instead, the magnitudes of the correlations were interpreted alongside Hopkins' (24) scale (0 < trivial ≤ 0.1 < small ≤ 0.3 < moderate ≤ 0.5 < large ≤ 0.7 < very large 0.9) to identify potentially concerning results (i.e., a significant correlation of trivial-to-small strength).

To determine the strength and direction of the associations between the CMVJ performance metrics and phase-specific inter-limb asymmetries, the Model Statistic technique (4) was first used to determine the number of statistically significant ($\alpha = 0.05$) inter-limb differences in vertical GRF and vertical yank throughout each phase for each individual participant. In addition, Cohen's *d* effect sizes were calculated to supplement the Model Statistic tests and determine the number of large-magnitude inter-limb differences, as defined by Hopkins' (24) scale (large: $d \geq 1.2$). The numbers of statistically significant and large-magnitude differences within the phases were then converted to a percentage of the phase durations and averaged across participants. Finally, the strengths and directions of the associations between CMVJ performance and phase-specific inter-limb vertical GRF and yank asymmetry were examined using Pearson product-moment correlation coefficients. As mentioned previously, we used a 5% threshold for statistical significance ($\alpha = 0.05$) and Hopkins' scale for the magnitude of the associations (24).

RESULTS

Descriptive statistics, presented using the mean and standard deviation across trials along with 95% confidence intervals for all variables are presented in Table 1. Individual results for the CMVJ performance metrics are provided in Figure 2. The percentages of significant and large-magnitude inter-limb force production and yank asymmetries are provided in Figures 3 and 4, respectively. The relationships between CMVJ performance metrics and both total body strategy and vertical GRF and yank asymmetry are presented in Table 2. Absolute and relative reliability statistics were calculated across trials per participant and averaged across the group (Table 3). An exemplar, representation of the number of statistically significant and large-magnitude inter-limb asymmetries is provided in Figure 5.

< Insert Table 1 and Figures 2-5 About Here >

Jump Height

Significant, large associations were detected between jump height and countermovement depth (r = -0.572; p = 0.001), push-off distance (r = 0.597; $p < 0.001$), average concentric force (r = 0.548; p = 0.001), and unloading yank (r = 0.408; p =0.023). No other significant associations were detected for the remaining variables (Table 2).

Modified Reactive Strength Index (RSI$_{MOD}$)

Significant, very-large associations were observed between RSI$_{MOD}$ and eccentric braking force (r = 0.786; $p < 0.001$) and concentric average force (r = 0.870; $p < 0.001$). A significant, large association was also observed between RSI$_{MOD}$ and eccentric braking yank (r = 0.703; $p < 0.001$). Significant, moderate associations were observed with jump time (r = -0.406; p = 0.023), the durations of the eccentric yielding (r = -0.361; p = 0.046), eccentric braking (r = -0.539; p = 0.002) and concentric phases (r = -0.444; p = 0.012), the amount of body weight unloading ($r = -0.456$; $p = 0.011$), and concentric yank ($r = -0.517$; $p = 0.003$). No other significant associations were detected for the remaining variables (Table 2).

Jump Power

Significant, moderate associations were detected between jump power and countermovement depth ($r = -0.357$; $p = 0.049$), push-off distance ($r = 0.385$; $p = 0.033$), and average concentric force ($r = 0.730$; $p < 0.001$), and eccentric braking yank ($r = 0.388$; $p = 0.031$).No other significant associations were detected for the remaining variables (Table 2).

Takeoff Momentum

Significant, large associations were observed between takeoff momentum and countermovement depth ($r = -0.550$; $p = 0.001$), push-off distance ($r = 0.621$; $p < 0.001$), unload yank ($r = 0.598$; $p < 0.001$), and eccentric yielding yank ($r = -0.558$; $p = 0.001$). Significant, moderate associations were also detected with jump time ($r = 0.416$; $p = 0.020$), concentric yank ($r = 0.367$; $p = 0.042$), the percentage of significant inter-limb force production asymmetries during the concentric phase ($r = -0.385$; $p = 0.033$), and the percentage of large-magnitude inter-limb force production asymmetries during the concentric phase ($r = -0.428$; $p = 0.016$). No other significant associations were detected for the remaining strategy or inter-limb asymmetry variables (Table 2).

< Insert Tables 2 & 3 About Here >

DISCUSSION AND IMPLICATIONS

This preliminary analysis identified multiple significant associations between the CMVJ performance metrics and the COM strategy metrics, with the most significant associations connected to RSI_{MOD} (n = 9) and takeoff momentum (n = 9), followed by jump power (n = 4) and jump height (n = 4). Only two significant associations were observed among all CMVJ performance metrics and inter-limb asymmetry. As such, our hypothesis that significant associations would be detected between the CMVJ performance metrics and both COM strategy variables and inter-limb asymmetry variables was partially accepted.

The strongest COM strategy correlates to jump height were countermovement depth and, consequently, push-off distance, in addition to average concentric force. Interestingly, only concentric displacement (i.e., push-off distance) and concentric work were significantly correlated to jump height in previous work on male athletes (3). Although we did not study concentric work directly, our results for average concentric force and push-off distance indicate concentric work would also correlate strongly to females' jump height. Interestingly, there was a significant correlations between jump height and yank only in the unloading phase, which contrasts previous evidence from male team sport athletes that eccentric yank (throughout the eccentric yielding and braking phases combined) was the strongest correlation to jump height (29). Finally, our observation that average concentric force was a significant, large-magnitude correlate to jump height contrasts previous results in female volleyball athletes (44), which calls for further study on its importance in determining jump height in females, particularly when training status and strength and power capabilities are unique.

With respect to $\mathrm{RSI}_{\mathrm{MOD}}$, which has been shown to be a valid measure of CMVJ explosiveness (26), jump time should always be a significant correlate for both males and females because $\mathrm{RSI}_{\mathrm{MOD}}$ is the ratio of jump height and jump time. However, and more importantly, the amount of body weight unloading appears to be a moderately strong correlate to CMVJ explosiveness via $\mathrm{RSI}_{\mathrm{MOD}}$ (i.e., unload more body weight to jump more explosively) in both females and males (3), although the rate of body weight unloading (i.e., unloading yank) may not be. This is not to say that unloading yank is not an important COM strategy metric to explore, as there is evidence to suggest it is a distinguishing feature of male basketball athletes exhibiting high versus low RSI_{MOD} outputs (28) and therefore might also separate female athletes, notably basketball, with high versus low RSI_{MOD} output. The very large and large magnitude correlations between RSI_{MOD} and eccentric braking force and eccentric braking yank, respectively, indicate these variables are key determinants of explosive jump ability in females and supports similar results in males (3, 28). Eccentric braking yank may be particularly valuable for subsequent work in females, as it is also a distinguishing feature of male basketball athletes with high versus low RSI_{MOD} outputs (28). However, females and males can generate similar relative yanks during the overall eccentric phase (eccentric yielding and braking phases combined) and similar relative eccentric braking forces at zero velocity (43) despite females producing lower jump height and RSI_{MOD} outputs (43). Therefore, it is not recommended that these variables be studied in pooled-sex samples or in comparisons between sexes when RSI_{MOD} (or jump height) is the central outcome. Finally, the significant, moderate magnitude correlations between RSI_{MOD} and the eccentric braking and concentric phase durations suggest that cues for rapid deceleration and change of direction could be simple non-invasive strategies to augment CMVJ explosiveness in female athletes. This may be a promising topic to study for future work.

Relative to jump power, we first must clarify that the jump power equation from Samozino and colleagues (45) accounts for push-off distance and is not simply the product of the vertical GRF and vertical COM velocity. The value to this equation is that starting the concentric phase from inconsistent countermovement depths, finishing the concentric phase with inconsistent body postures (i.e., joint extensions), or both, can lead to equal jump heights achieved via different power outputs because greater push-off distances would indicate lower power output (45). Thus, the fact that countermovement depths and push-off distances were significant, moderate-magnitude correlates with jump power is not surprising, and they should be independent of sex. Interestingly, eccentric braking yank was significantly associated with jump power. This suggests that exercises aiming to develop or refine rapid eccentric force application strategies (e.g., snatch balance [i.e., drop snatch] or rapid eccentric-to-isometric squats) should yield increased CMVJ power output in females (or speculatively weaker males) by adapting to the augmented downward kinetic energy developed by gravity's downward pull on the system. Jump power does not appear to be associated with asymmetrical inter-limb force production during any phase. However, Bell and colleagues reported that asymmetrical concentric mechanical output, specifically peak power and force, can reduce jump height by ~9 cm (5). Thus, focused efforts on symmetrical concentric force production could be valuable during training for maintaining or increasing females' jump power despite the current lack of any significant association. Such efforts can be accomplished through use of practitioner-targeted dual force platform systems (e.g., Hawkin Dynamics, ForceDecks, etc.) during that have the capacity to both permit thorough asymmetry assessments similar to the current study and provide immediate feedback to the practitioner and athlete to make real-time adjustments to an athlete's force application strategy during jumping tests, strength exercises, or both.

The significant, large-magnitude correlations between takeoff momentum and countermovement depth and push-off distance indicate both greater countermovement depths (i.e., larger negative displacements) and greater push-off distances should result in greater takeoff momentum. While the result is not surprising, it is important because starting the concentric phase from greater depths typically coincides to greater jump height and therefore greater takeoff velocity and momentum for a given athlete (16). Given the time-constrained nature of movement performance in recreational and competitive sports, seeking to maximize the ability to jump quickly while also using greater countermovement depths, greater extension at takeoff, or both may be a useful training goal for female athletes seeking to increase takeoff momentum in females. Particularly unique associations to takeoff momentum were detected with unloading and eccentric yielding yank, as greater yank in these phases appear associated with lesser takeoff momentum. This suggests that rapid unloading and yielding qualities should not be key targets for increasing takeoff momentum alone in females. This might not be surprising since the quantity of motion upon takeoff is largely dictated by concentric (i.e., upward) force application while unloading and yielding characteristics describe the conversion of gravitational potential energy to downward kinetic energy (3) and the neuromuscular system's attempt to initiate COM braking (20), respectively. The significant associations between takeoff momentum and both concentric yank and the percentage of both significant and large-magnitude inter-limb force production asymmetries can be bridged with takeoff momentum's relationship with countermovement depth and push-off distance. Takeoff momentum is a valuable metric in sports where athletes can have markedly different body masses (37). For situations where athletes of different body masses need to maximize short sprint abilities, recent evidence suggests takeoff momentum can be a useful metric to monitor when predicting sprint performance changes (37). In addition, it could be especially useful to target increased takeoff momentum in training of female athletes with lesser mass who need to match the impetus of more massive opponents or in females of greater mass who need to maximize their own impetus by moving more quickly (e.g., post positions in basketball, blockers in volleyball). Collectively, these associations indicate maintaining as much concentric force production while using symmetrical inter-limb force application throughout the entire push-off distance, or greater distances should be considerations for increasing takeoff momentum in females.

A possible limitation of this study relates to the very few significant associations detected between the CMVJ performance metrics and the percentages of phase-specific inter-limb asymmetries. An explanation for those results may be the variation across participants for inter-limb asymmetry in each phase, as shown in Table 1 and Figures 3 & 4. The few significant associations between performance metrics and inter-limb asymmetry supports prior work demonstrating the "noisiness" of asymmetry (i.e., large inter-subject variability) across a sample of individuals (7, 9). This may be a positive characteristic because it suggests inter-limb asymmetry assessments similar to the one used herein should not include group generalization prior to exploring associations between or among variables unless only using asymmetry results from the concentric phase. Instead associations between CMVJ performance metrics and point-to-point inter-limb asymmetries may need to be treated as a participant-specific approach after which generalizations can be made. Finally, our reliance on recreationally active females was a limitation, and so our interpretations should be considered with caution when generalizing to different female populations.

In summary, this study revealed unique correlates to various CMVJ performance metrics (e.g., jump height, RSI_{MOD}, power, takeoff momentum) in females, some of which were inconsistent to those observed in male participants. Thus, some variables often thought to be critical to CMVJ performance according male participant studies might not be critical in female samples. As no COM strategy (e.g., phase durations, discrete force and rapid force production) or inter-limb asymmetry variables were significantly associated with all CMVJ performance metrics, these results revealed specific COM strategy and inter-limb asymmetry variables that should be considered when seeking improvement in a specific CMVJ performance metric. Ultimately, these results provide direct information regarding specific COM variables and inter-limb asymmetry qualities that could benefit female athletes, human performance professionals, or both when seeking to understand or improve their CMVJ jumping abilities.

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Figure Captions

Figure 1. Visualization of the CMVJ phases defined using vertical GRF and vertical COM velocity.

Notes – CMVJ: countermovement vertical jump; GRF: ground reaction force; COM: center of mass.

Figure 2. Individual participant averages across trials for jump height and $\mathrm{RSI}_{\mathrm{MOD}}$ (top), jump power (middle), and takeoff momentum (bottom) metrics.

Figure 3. Percentages of significant and large-magnitude inter-limb force production asymmetries during the unloading, eccentric yielding, eccentric braking, and concentric phases for each participant.

Figure 4. Percentages of significant and large-magnitude inter-limb yank asymmetries during the unloading, eccentric yielding, eccentric braking, and concentric phases for each participant.

Figure 5. Exemplar representation from one participant to visualize the numbers of statistically significant inter-limb force production asymmetries (A) and the numbers of large-magnitude inter-limb yank asymmetries (B) during the CMVJ phases.

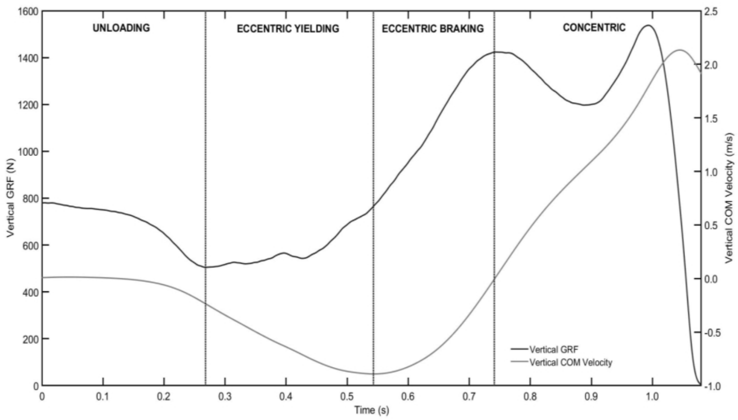

Figure 1

210x297mm (600 x 600 DPI)

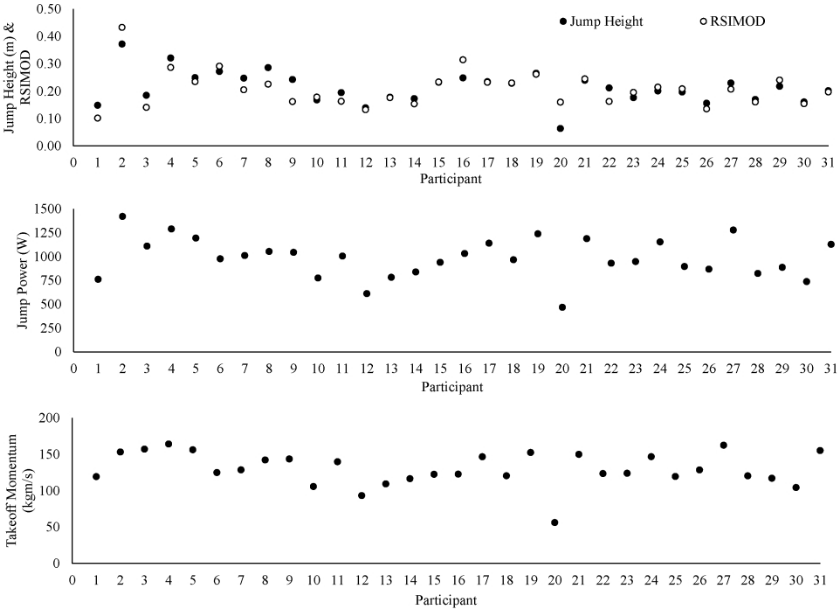

Figure 2

297x210mm (300 x 300 DPI)

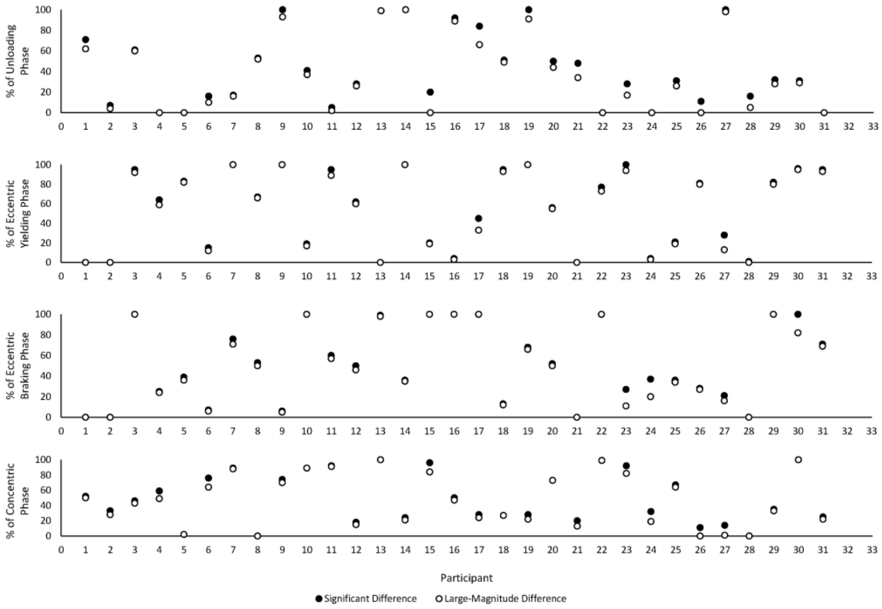

Figure 3

297x210mm (300 x 300 DPI)

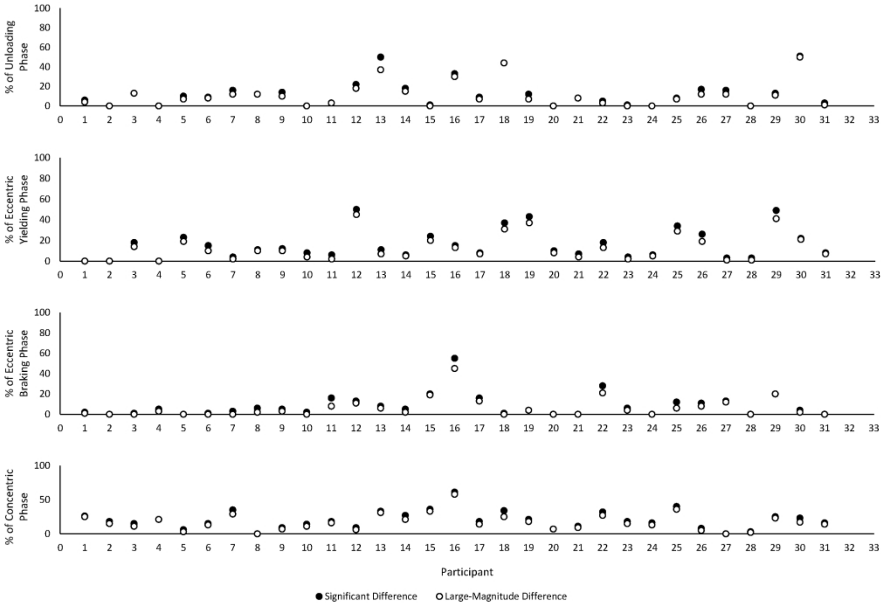

Figure 4

297x210mm (300 x 300 DPI)

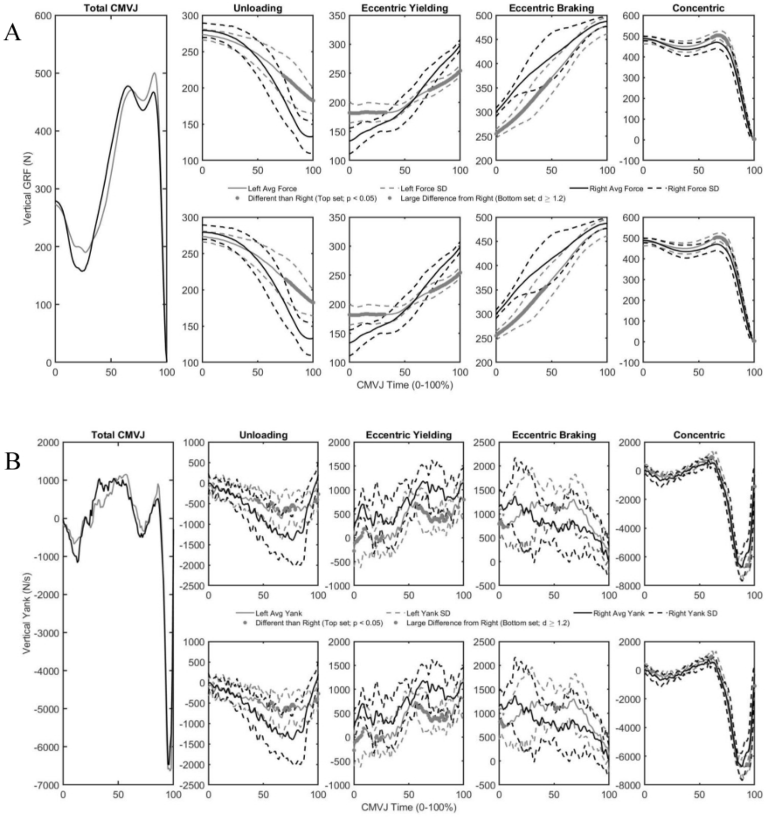

Figure 5

210x297mm (600 x 600 DPI)

Table 1. Descriptive statistics for demographic and anthropometric and CMVJ performance, temporal, and force application variables across the entire sample.

			95% CI	
Variable	**Mean**	**SD**	**Lower**	**Upper**
Age (y)	22.10	2.51	21.18	23.02
Height (m)	1.65	0.64	1.42	1.89
Mass (kg)	63.31	7.63	60.51	66.10
Jump Height (m)	0.221	0.060	0.199	0.243
RSI_{MOD}	0.230	0.071	0.204	0.256
Jump Power (W/BW)	1.627	0.330	1.506	1.748
Jump Momentum (kgm/s)	132.339	23.645	123.667	141.001
Jump Time (s)	1.011	0.221	0.930	1.092
Unload Time (s)	0.263	0.091	0.229	0.296
Yielding Time (s)	0.201	0.067	0.177	0.226
Braking Time (s)	0.235	0.080	0.206	0.264
Concentric Time (s)	0.312	0.059	0.290	0.333
CM Depth (m)	-0.301	0.069	-0.330	-0.280
Push-off Distance (m)	0.393	0.079	0.365	0.422
Unload Amount (% BW)	0.787	0.077	0.759	0.815
Braking Force (xBW)	1.464	0.215	1.385	1.542
Concentric Avg Force (xBW)	1.691	0.152	1.635	1.746
Unload Yank (BW/s)	-2.282	1.828	-2.95	-1.610
Yielding Yank (BW/s)	2.980	2.495	2.065	3.895
Braking Yank (BW/s)	4.887	3.063	3.764	6.010
Concentric Yank (BW/s)	-6.578	2.489	-7.490	-5.670
Unload Force Asym. *p*	41.677	35.609	28.618	54.737
Yielding Force Asym. *p*	55.000	39.782	40.410	69.590
Braking Force Asym. *p*	51.742	37.495	37.991	65.493
Concentric Force Asym. *p*	50.032	33.635	37.697	62.368
Unload Force Asym. *d*	36.677	35.396	23.696	49.659
Yielding Force Asym. *d*	52.581	39.826	37.974	67.187
Braking Force Asym. *d*	48.871	37.760	35.022	62.720
Concentric Force Asym. *d*	45.806	34.258	33.242	58.371
Unload Yank Asym. *p*	12.710	14.166	7.514	17.905
Yielding Yank Asym. *p*	15.516	14.212	10.304	20.729
Braking Yank Asym. *p*	8.290	11.338	4.132	12.449
Concentric Yank Asym. *p*	19.839	13.224	14.989	24.689
Unload Yank Asym. *d*	10.677	12.968	5.921	15.433
Yielding Yank Asym. *d*	12.484	12.583	7.869	17.099
Braking Yank Asym. *d*	6.129	9.591	2.612	9.646
Concentric Yank Asym. *d*	16.935	12.375	12.397	21.474

Notes – Mean: mean calculated across all participants; SD: ± one standard deviation across all participants; 95% CI: lower and upper bounds of the 95% confidence interval; Force/Yank Asym. *p:* percentage of significant ($p < 0.05$) point-to-point differences between left and right limbs throughout the time-normalized phase; Force/Yank Asym. *d:* percentage of large-magnitude ($d \geq 1.2$) point-to-point differences between left and right limbs throughout the time-normalized phase.

Table 2. Relationships among performance, temporal, and force application variables.

Variable	Jump Height	RSI_{MOD}	Jump Power	Jump Momentum
Jump Height	1	0.785*	0.967*	0.705*
RSI_{MOD}	0.785*	1	0.883*	0.366*
Jump Power	0.967*	0.883*	1	0.634*
Jump Momentum	0.705*	0.366*	0.634*	1
Jump Time	0.206	-0.406*	0.022	0.416*
Unload Time	0.330	0.037	0.308	0.301
Yielding Time	0.155	-0.361*	0.026	0.316
Braking Time	0.003	-0.539*	-0.159	0.283
Concentric Time	0.087	-0.444*	-0.146	0.357*
CM Depth	-0.572*	-0.072	-0.357*	-0.550*
Push-off Distance	0.597*	0.075	0.385*	0.621*
Unload Amount	0.070	-0.453*	-0.025	-0.342
Braking Force	0.324	0.786*	0.465	-0.128
Concentric Avg Force	0.548*	0.870*	0.730*	0.135
Unload Yank	0.408*	-0.083	0.312	0.598*
Yielding Yank	-0.291	0.220	-0.149	-0.558*
Braking Yank	0.219	0.703*	0.388*	-0.233
Concentric Yank	-0.001	-0.517*	-0.194	0.367*
Unload Force Asym. *p*	-0.090	-0.080	-0.066	-0.047
Yielding Force Asym. *p*	-0.104	-0.318	-0.156	0.065
Braking Force Asym. *p*	-0.191	-0.050	-0.161	-0.209
Concentric Force Asym. *p*	-0.188	-0.138	-0.161	-0.385*
Unload Force Asym. *d*	-0.083	-0.090	-0.061	-0.043
Yielding Force Asym. *d*	-0.110	-0.320	-0.164	-0.038
Braking Force Asym. *d*	-0.164	-0.027	-0.140	-0.200
Concentric Force Asym. *d*	-0.219	-0.170	-0.194	-0.428*
Unload Yank Asym. *p*	-0.118	-0.095	-0.104	-0.236
Yielding Yank Asym. *p*	-0.123	-0.011	-0.115	-0.246
Braking Yank Asym. *p*	0.055	0.209	0.102	-0.102
Concentric Yank Asym. *p*	0.095	0.299	0.176	-0.184
Unload Yank Asym. *d*	-0.106	-0.076	-0.087	-0.241
Yielding Yank Asym. *d*	-0.111	0.000	-0.104	-0.244
Braking Yank Asym. *d*	0.063	0.243	0.120	-0.096
Concentric Yank Asym. *d*	0.105	0.319	0.180	-0.178

Notes - *: significant relationship ($p < 0.05$); Force/Yank Asym. *p:* percentage of significant ($p < 0.05$) point-to-point differences between left and right limbs throughout the time-normalized phase; Force/Yank Asym. *d:* percentage of large-magnitude ($d \geq 1.2$) point-to-point differences between left and right limbs throughout the time-normalized phase.

Table 3. Reliability statistics for performance, temporal, and force application variables.

	Relative Reliability			**Absolute Reliability**		
Variable	**ICC**	**Lower 95% CI**	**Upper 95% CI**	**CV**	**Lower 95% CI**	**Upper 95% CI**
Jump Height	0.994	0.991	0.997	5.5%	4.6%	6.3%
RSI_{MOD}	0.966	0.944	0.981	14.2%	12.2%	16.1%
Jump Power	0.993	0.989	0.996	4.5%	3.9%	5.1%
Takeoff Momentum	0.997	0.995	0.998	2.7%	2.3%	3.1%
Jump Time	0.911	0.854	0.951	14.9%	11.5%	18.3%
Unload Time	0.550	0.264	0.755	47.8%	38.2%	57.5%
Yielding Time	0.949	0.916	0.972	18.7%	15.9%	21.5%
Braking Time	0.96	0.934	0.978	14.5%	12.2%	16.9%
Concentric Time	0.989	0.981	0.994	5.1%	4.3%	5.8%
CM Depth	0.988	0.98	0.993	-6.4%	-7.3%	-5.6%
Pushoff Distance	0.992	0.987	0.996	4.7%	4.1%	5.3%
Unload Amount	0.893	0.824	0.941	8.9%	7.4%	10.5%
Braking Force	0.980	0.967	0.989	5.5%	4.9%	6.2%
Concentric Avg Force	0.989	0.982	0.994	2.5%	2.2%	2.8%
Unload Yank	0.973	0.955	0.985	-36.6%	-41.7%	-31.6%
Yielding Yank	0.983	0.972	0.991	29.0%	24.7%	33.2%
Braking Yank	0.984	0.975	0.992	24.7%	20.7%	28.8%
Concentric Yank	0.991	0.985	0.995	-9.7%	-11.2%	-8.2%

Notes – ICC: intra-class correlation coefficient; CV: coefficient of variation; Lower 95% CI: lower bound of the 95% confidence interval; Upper 95% CI: upper bound of the 95% confidence interval.