ORIGINAL ARTICLE

Effects of Eccentric Pre-loading on Concentric Vertical Jump Performance in Young Female Athletes

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Abstract

Purpose This study examined changes in vertical jump performance with progressively greater eccentric pre-loading in relation to growth and development in young female athletes.

Methods Twenty young female athletes ranging from 9 to 17 years old performed the following vertical jumps in random order: static jumps (SJs), counter-movement jumps (CMJs), and drop jumps (DJs) from drop heights of 20, 30, and 40 cm (DJ20, DJ30, and DJ40, respectively). Measurements included peak force (PF), peak rate of force development (RFD), peak power (PP), eccentric impulse (ECC), and concentric impulse (CON). Measurements of growth included age, maturity offset, height, body mass, fat-free mass, and thigh muscle cross-sectional area (CSA).

Results PF increased from the SJ-DJ20 ($P \leq 0.009$), then plateaued from DJ20-DJ40 ($P = 1.000$). RFD remained the same from SJ-CMJ ($P = 1.000$), increased from CMJ-DJ20 ($P < 0.001$), and plateaued from DJ20-DJ40 ($P = 0.874$). PP increased from the SJ-CMJ ($P < 0.001$), then plateaued from the CMJ-DJ40 ($P \geq 0.486$). CON remained the same across all vertical jumps ($P = 1.000$), while ECC increased from the SJ-DJ40 ($P \leq 0.038$). Jump height (JH) increased from the SJ-CMJ ($P < 0.001$), decreased from CMJ-DJ20 ($P < 0.001$), and plateaued from DJ20-DJ40 ($P = 1.000$). The change in PP from the SJ-CMJ (ΔCMJ-SJ) was related to all measurements of growth except CSA ($r = 0.558$–0.815).

Conclusion Young females produced greater power during the CMJ than SJ, but equivalent power from the CMJ-DJ40, despite increases in ECC. Additionally, ΔCMJ-SJ was not related to CSA, which suggests other underlying mechanisms affect stretch–shortening cycle utilization in young female athletes.

Keywords Stretch–shortening cycle · Youth · Ground reaction force · Kinetics

Introduction

Vertical jump tests are among the most popular assessments of lower-body power for children and adolescents [2, 7, 12, 13, 21, 34]. One of the most common vertical jump techniques is the counter-movement jump (CMJ), which involves a downward, eccentric movement followed by a maximal concentric vertical jump. Previous studies have suggested that the eccentric component of the CMJ improves utilization of the stretch–shortening cycle, leading to subsequent increases in concentric power output [2, 4–7, 12, 34]. Specifically, Bobbert et al. [5] proposed that the eccentric movement may augment the shortening velocity of the series elastic elements, leading to greater stretch–shortening cycle utilization and concentric power production. Furthermore, previous studies in adults have suggested that accentuating the eccentric phase by incorporating a drop jump (DJ) may improve power output to a greater degree than the CMJ [1, 5, 6, 8, 24, 25]. However, previous studies have suggested that children may be unable to utilize the greater eccentric pre-loading forces of a DJ [2, 12, 18, 26, 34, 35].

In fact, previous studies have demonstrated equivocal or decreased vertical jump performance from the CMJ to DJs of various drop heights in children [2, 3, 12, 18,

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26, 34, 35]. However, we are aware of only one previous study to quantify power output across vertical jumps with progressively increased eccentric pre-loading in children [12]. Gillen et al. [12] reported systematic increases in eccentric pre-loading from the static jump (SJ) to CMJ to DJs of varying drop heights (20, 30, and 40 cm). Although power output increased from the SJ to CMJ, there were no subsequent improvements in power across DJs. To address stretch–shortening cycle utilization, the authors reported significant positive relationships between the change in power from the SJ to CMJ (ΔCMJ-SJ) and measurements of growth, particularly thigh muscle cross-sectional area (CSA) [12]. It was concluded that the ability to utilize the stretch–shortening cycle may be related to increases in muscle size across growth and development. In other words, the lack of increase in power from the CMJ to DJs may be due to the fact that young children do not have the skeletal musculature necessary to absorb and reapply large eccentric pre-loading forces. However, Gillen et al. [12] only examined young males, and previous studies have suggested that muscle mass may influence skeletal muscle function to a greater degree in males than females across growth and development [29, 30].

Two studies by O'Brien et al. [29, 30] have suggested sex-specific adaptations in skeletal muscle across growth and development for males and females. O'Brien et al. [30] found that power production from the SJ was related to quadriceps femoris muscle volume for both child and adult males and females. However, the greater discrepancy in muscle volume between the males and females indicated that muscular hypertrophy affected SJ power production to a greater extent in males. Similarly, O'Brien et al. [29] showed that quadriceps femoris muscle CSA accounted for a greater proportion of the differences in maximal leg extension strength between child and adult males than child and adult females. In other words, increases in muscle strength may be mostly accounted for by increases in muscle size for males, but not females. Although previous studies [12, 33] have suggested that utilization of the energy absorbed during the eccentric phase (i.e., stretch–shortening cycle utilization) may be related to muscle mass in child and adults males, based on the conclusions of O'Brien et al. [29, 30], this may not be true in females. Therefore, the purpose of this study was to examine changes in vertical jump power with progressively greater eccentric pre-loading in relation to measurements of growth and muscle size in young female athletes. We hypothesize that, similar to males, power production will increase from SJ to CMJ, with no further increases across DJs. Additionally, we hypothesize that ΔCMJ-SJ will be related to measurements of growth but will have a lower magnitude of relationship with thigh muscle CSA compared to males.

Methods

Twenty young female athletes (mean ± 95% confidence interval, age = 12.43 ± 0.96 years) participated in this study. An a priori power analysis using G*Power software determined the minimum sample size needed to detect changes in outcome measurements across vertical jump conditions was $n = 13$. All participants reported participating in one or more sports for 1–5 h per week during the year prior to this study. Sports included baseball, basketball, cheerleading, cross-country, football, gymnastics, lacrosse, rugby, soccer, softball, speed/power/agility training, swimming/diving, tennis, track and field, trap shooting, volleyball, weightlifting, and wrestling. Each participant and their parent or legal guardian completed the PAR-Q+ (2015) [37] prior to testing. Participants were allowed to participate in the study if questions 1–7 were answered "no" or all follow-up questions of the PAR-Q+ (2015) were answered "no." This study was approved by the University of Nebraska-Lincoln Institutional Review Board for the protection of human subjects (Institutional Review Board # 20171017495EP, title: *Changes in noninvasive, applied physiological laboratory measurements and field measurements of athletic performance in children and youth: Influences of growth and development*). Each participant signed the approved assent form, while one parent or legal guardian signed the approved consent form.

The experimental design and all procedures for the present study were identical to a previous report on young males from our lab [12]. The only difference being that young females were studied in the present report. Each participant visited the laboratory twice separated by 2–7 days at approximately the same time of day (± 2 h), once for familiarization and once for the experimental trial. Participants completed the SJ, CMJ, and DJs of three different heights [20.32 (DJ20), 30.48 (DJ30), and 40.64 (DJ40) cm] in a random order during each visit. Outcome variables were peak force (PF, N), peak rate of force development (RFD, N/s), peak power (PP, W), eccentric impulse (ECC, N·s), concentric impulse (CON, N·s), and jump height (JH, cm). Measurements of growth included age (years), maturity offset (years), height (cm), body mass (kg), fat-free mass (FFM, kg), and thigh CSA (cm²).

Height (cm), seated height (cm), and body mass (kg) were measured using a digital scale and stadiometer (Seca 769, Hamburg, Germany). Maturity offset from peak height velocity was calculated using the Mirwald equation [27]. Percent body fat was calculated from skinfold measurements taken with a Lange caliper (Model 68902, Cambridge Scientific Industries, Inc., Cambridge, MD, USA). All skinfolds were taken on the right side of the

body at the subscapular (diagonal fold immediately inferior to the interior angle of the scapula), triceps (vertical fold in the middle of the arm, midway between the acromion and olecranon process), and suprailiac (diagonal fold immediately superior to the anterior superior iliac spine) sites and were recorded to the nearest 0.5 mm [17]. Equations established by Housh et al. [15] and Brozek et al. [9] estimated body density and percent body fat, respectively. FFM was calculated as the difference between body mass and fat mass as determined by percent body fat.

Ground reaction forces during each vertical jump test were collected using two force plates (PASCO PS 2142, PASCO Scientific, Roseville, CA) seated in a custom platform. Figure 1 provides a depiction of the experimental setup. To perform the SJ, participants began with their feet in the middle of each force plate and their knees and hips flexed into a static squat position with a knee angle of 90°,

using the Original Step (F1005, Marietta, GA) as a guide. Participants then performed a maximal vertical jump without the use of a countermovement. For the CMJ, participants began standing in an upright position with their feet in the middle of the force plates and their knees and hips extended. A rapid countermovement of self-selected depth followed by a maximal vertical jump was performed. For the DJ, the Original Step was used to achieve each drop height (20, 30, and 40 cm). Participants began by standing on top of the step and were then instructed to drop off the step, land with their feet in the middle of each force plate and perform a maximal vertical jump as fast as possible upon landing. For all vertical jump conditions, participants were required to keep their hands on their hips.

For the SJ and CMJ, the investigator manually identified (a) the initial onset of movement (always downward, negative force), (b) the point at which the velocity signal
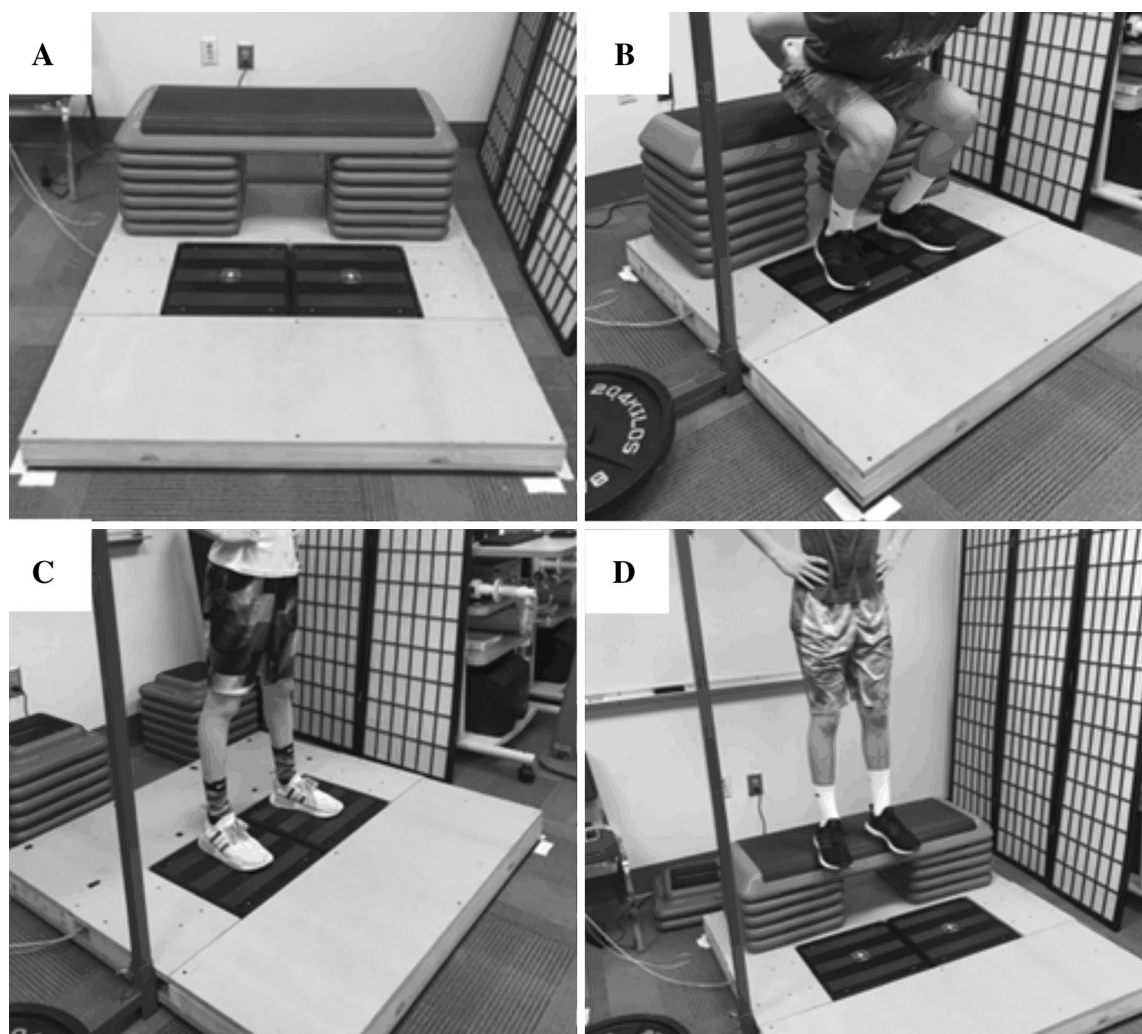
Fig. 1 Examples of the experimental setup for **a** the force plates seated in a custom platform, **b** the starting position for the static jump, **c** the starting position for the countermovement jump, and **d** the starting position for a drop jump (30-cm drop jump depicted)

was equal to zero, and (c) the point at which the feet left the force plates (toe off, zero force). Based on the description of previous authors [5, 12, 20] the epoch of the force signal from (a) to (b) was considered the eccentric phase, while the epoch of the force signal from (b) to (c) was considered the concentric phase. Additionally, during the analysis of each DJ, the investigator identified (a) the initial positive force deflection after the participant's free fall and the point at which the feet left the force plates ((c) above). The following equation was used to calculate the end of the eccentric phase for each DJ [6].

$$p_{downward} = \sqrt{\frac{m \cdot g \cdot h}{1/2 \cdot m}} \cdot m$$

where $p_{downward}$ is the vertical force at the end of the eccentric phase, m is body mass (kg), g is the acceleration due to gravity (m/s^2), and h is drop height (m). The point at which the force signal crossed $p_{downward}$, after the initial peak eccentric impact force, was considered the start of the concentric phase ((b) above) [6].

For the SJ and CMJ force signals, a stable, static epoch of force representing the participants' body weight was averaged, and this baseline average force was subtracted. For the DJs, the body mass measured by the scale was converted to N and subtracted from each DJ force signal. The

bodyweight corrected force signals from all attempts were used to calculate the variables of interest. PF was taken as the highest force value during the concentric phase of the force–time tracing. RFD was taken as the peak of the first derivative of the force–time tracing during the concentric phase. Velocity–time tracings were calculated by taking the integral of the force–time curve divided by body mass. Power-time tracings were then calculated by multiplying the force–time curve by the velocity–time curve. PP was taken as the highest value during the concentric phase of the power-time tracing. ECC and CON were calculated as integrated areas under the eccentric and concentric force–time curves, respectively. JH was calculated using the impulse-momentum method [20]. Previous data from our laboratory has determined PF, RFD, PP, ECC, CON, and JH in youth may be considered reliable measurements (intraclass correlation coefficients ≥ 0.81, coefficients of variation ≤ 11.07%). Figure 2 provides an example of one participant's force–time tracing for each jump.

During each visit, panoramic cross-sectional images of the quadriceps and hamstrings were taken to quantify thigh CSA. Ultrasound images were obtained using a portable brightness mode (B-mode) ultrasound-imaging device (GE Logiq e, USA) and a multi-frequency linear-array probe (12L-RS; 5–13 MHz; 38.4 mm field-of-view). Participants were positioned on a plinth in the supine position for the
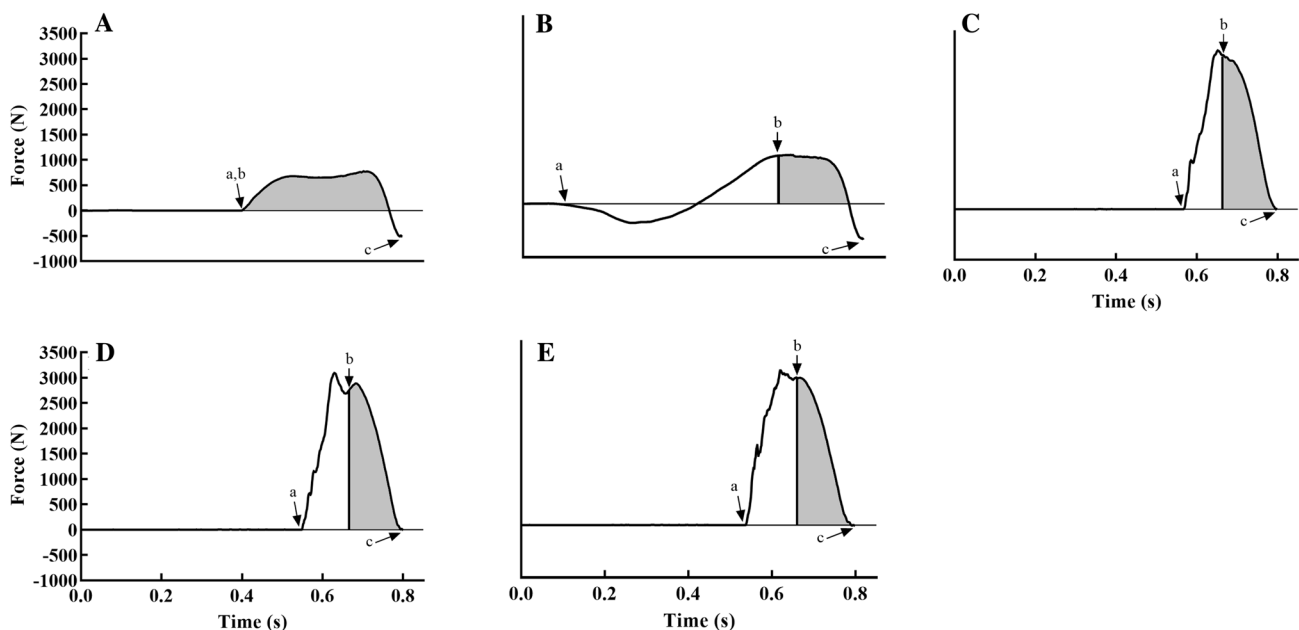
Fig. 2 Examples of one participant's force–time tracing for **a** a static jump (SJ), **b** a countermovement jump (CMJ), **c** a 20-cm drop jump (DJ), **d** a 30-cm DJ, and **e** a 40-cm DJ. The letters and arrows denote important time points that were determined to represent a) the initial onset of movement for the SJ and CMJ and the initial positive force deflection after the participant's free fall for the DJs, b) the point at which the velocity signal was equal to zero (for SJ and CMJ), indicating the end of the eccentric phase and start of the concentric phase, and c) point at which the feet left the force plates, which was used as a common point to align all jumps. The unshaded area represents the eccentric phase and the light gray shaded area represents the concentric phase

quadriceps imaging and prone position for the hamstrings imaging while lying fully relaxed with their legs extended and supported on the plinth with feet braced. The panoramic images of the quadriceps were taken at two-thirds the distance from the anterior superior iliac spine to the lateral border of the patella from the most lateral aspect to the most medial aspect of the quadriceps. The panoramic images of the hamstrings were taken at one-half the distance from the ischial tuberosity to the lateral epicondyle of the tibia from the most lateral aspect to the most medial aspect of the hamstrings. A generous amount of water-soluble transmission gel was applied to the skin to enhance acoustic coupling and reduce near field artifacts.

The equipment settings were optimized for image quality with a gain of 58 dB and a frequency of 12 MHz. These settings were held constant across participants. The image depth, however, was adjusted based on each participant's leg size and was then held constant for each participant. All images were taken by the same investigator (ZMG) prior to any exercise assessments. Images were taken until three images of acceptable image quality were acquired. Images with the highest visual contrast were used for analysis. All images were analyzed using Image-J Software (National Institutes of Health, USA, version 1.47v). Prior to analysis, images were scaled from pixels to cm using the Image-J straight-line function. To quantify CSA of the quadriceps and hamstrings, the polygon function in Image-J was used to select the maximal region of interest that included as much of the muscle group of interest as possible while excluding the surrounding fascia. Quadriceps and hamstrings CSA were summed as thigh CSA. Previous data from our laboratory and the investigator (ZMG) has determined that quadriceps and hamstrings CSA measurements from ultrasound images may be considered reliable measurements (intraclass correlation coefficients ≥ 0.90, coefficients of variation $\leq 2.97\%$).

Means and 95% confidence intervals were calculated for all participant demographics, measurements of growth, and vertical jump outcomes (Table 1). Five separate one-way repeated measures analyses of variance (ANOVAs) were used to compare PF, RFD, PP, ECC, CON, and JH across all vertical jump conditions (SJ vs. CMJ vs. DJ20 vs. DJ30 vs. DJ40). Delta scores of the PP values of successive

Table 1 Means $\pm 95\%$ confidence interval for measurements of growth

Age (years)	12.43 ± 0.96
Maturity offset (years)	0.29 ± 0.76
Height (cm)	155.08 ± 4.75
Body mass (kg)	49.89 ± 6.83
Fat-free mass (kg)	37.86 ± 3.57
Thigh muscle cross-sectional area (cm^2)	62.14 ± 7.97

vertical jump conditions were calculated from SJ to CMJ (ΔCMJ-SJ), CMJ to DJ20 (ΔDJ20-CMJ), DJ20 to DJ30 (ΔDJ30-DJ20), and DJ30 to DJ40 (ΔDJ40-DJ30). Pearson product moment correlation coefficients were calculated to determine the relationships among measurements of growth and delta scores. First-order partial correlations were performed to examine the unique relationships among delta scores and measurements of growth. The following qualitative evaluations of the strength of association were made according to Mukaka [28] based on the absolute values of correlation coefficients: 0.90 to 1.00 = very high, 0.70 to 0.89 = high, 0.50 to 0.69 = moderate, 0.30 to 0.49 = low, and 0.00 to 0.29 = negligible. All statistical analyses were performed in IBM SPSS v. 26 (Chicago, IL, USA). An alpha level of $P < 0.05$ was considered statistically significant for all analyses.
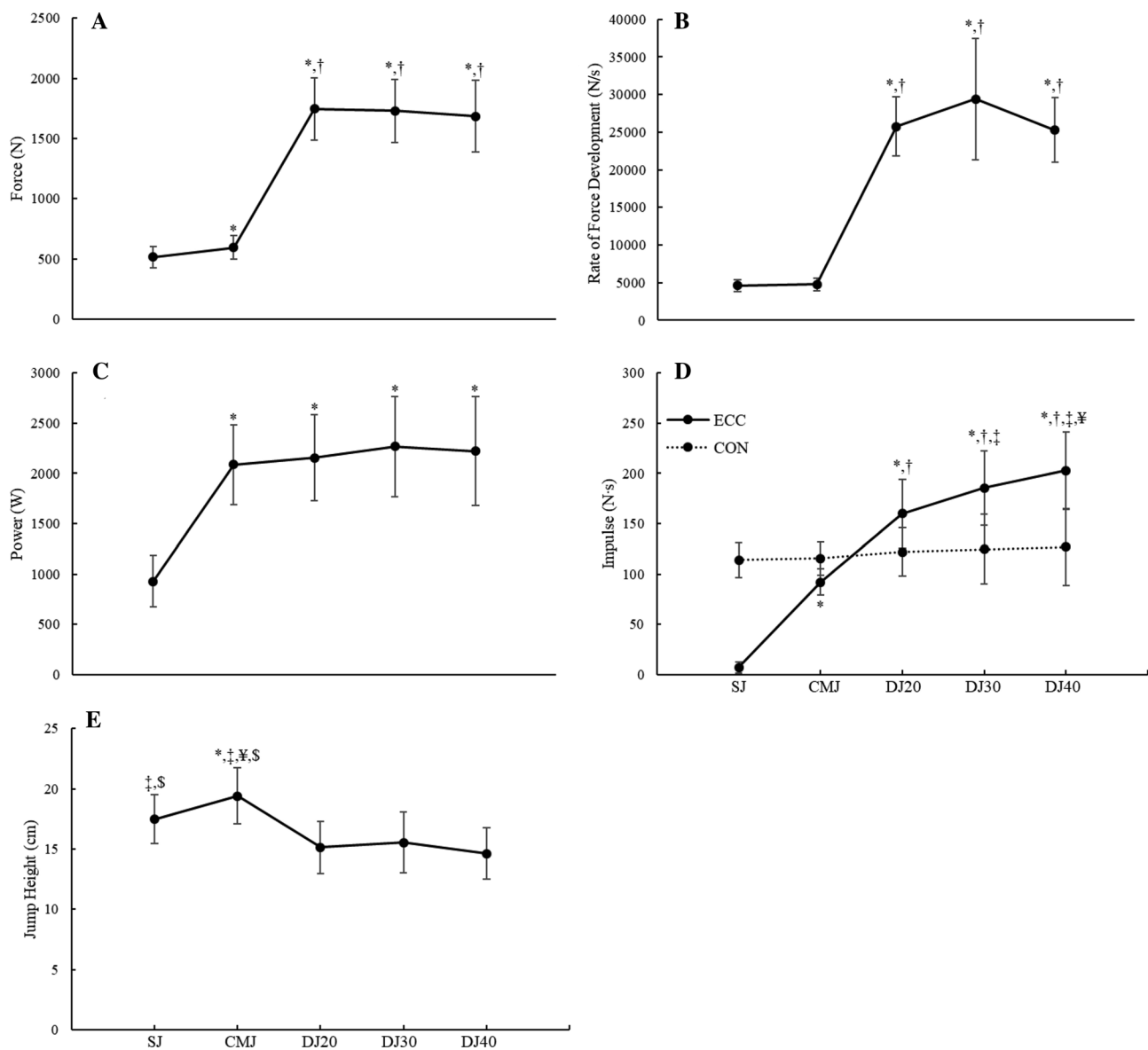
Results

The results of this study showed that, for PF, there was an increase from SJ to CMJ ($P = 0.009$), an increase from CMJ to DJ20 ($P < 0.001$), and no changes across DJs ($P = 1.000$, Fig. 3a). For RFD, there was no change from SJ to CMJ ($P = 1.000$), an increase from CMJ to DJ20 ($P < 0.001$), and no changes across DJs ($P = 0.874$, Fig. 3b). PP increased from SJ to CMJ ($P < 0.001$), with no further changes from CMJ to DJ20 to DJ30 to DJ40 ($P \geq 0.486$, Fig. 3c). CON remained the same across all vertical jump conditions ($P = 1.000$, Fig. 3d), while ECC increased systematically from SJ to DJ40 ($P \leq 0.038$, Fig. 3d). JH increased from the SJ to CMJ ($P < 0.001$, Fig. 3e), decreased from CMJ to DJ20 ($P < 0.001$, Fig. 3e), and plateaued from DJ20-DJ40 ($P = 1.000$, Fig. 3e). JH from the SJ was greater than JH from DJ20 and DJ30 ($P \leq 0.037$, Fig. 3e).

There were significant, moderate to high relationships between all measurements of growth (except for thigh CSA) and ΔCMJ-SJ ($r = 0.558-0.815$, Table 2). ΔDJ20-CMJ exhibited a low relationship with CSA ($r = 0.446$, Table 2), while ΔDJ30-DJ20 exhibited low to moderate relationships with measurements of growth ($r = 0.454-0.682$, Table 2). Partialing out age and maturity offset eliminated the significant relationships between ΔCMJ-SJ and all measurements of growth ($|r_{\Delta\text{CMJ-SJ,y.age}}| = 0.002-0.278$, $|r_{\Delta\text{CMJ-SJ,y.maturity offset}}| = 0.023-0.268$). Partialing out height eliminated the significant relationships between ΔCMJ-SJ and body mass and FFM ($r_{\Delta\text{CMJ-SJ,y.height}} = 0.044-0.197$), but not age and maturity offset ($r_{\Delta\text{CMJ-SJ,y.height}} = 0.506-0.507$). When body mass was partialed out, ΔCMJ-SJ was still significantly related to all other measurements of growth ($r_{\Delta\text{CMJ-SJ,y.body mass}} = 0.589-0.738$). Partialing out FFM eliminated the relationships between ΔCMJ-SJ and height and

Fig. 3 Means ± 95% confidence intervals for **a** peak force, **b** peak rate of force development, **c** peak power, **d** eccentric and concentric impulse, and **e** jump height for all vertical jump conditions. * Indicates greater than static jump ($P < 0.05$), † indicates greater than counter-movement jump ($P < 0.05$), ‡ indicates greater than 20-cm drop jump ($P < 0.05$), ¥ indicates greater than 30-cm drop jump ($P < 0.05$), $ indicates greater than 40-cm drop jump ($P < 0.05$)

body mass ($|r_{\Delta CMJ-SJ,y.FFM}| = 0.305$–$0.336$), but not age and maturity offset ($r_{\Delta CMJ-SJ,y.FFM} = 0.506$–$0.568$).

Discussion

Our previous study quantified PF, RFD, PP, ECC, and CON during the SJ, CMJ, DJ20, DJ30, and DJ40 vertical jumps with progressively increased eccentric preloading in young males [12]. To our knowledge, the present study is the first to quantify the same vertical jump performance assessments

in young females. As with the males [12], the young females in the present study showed increases in PP from the SJ to CMJ with no further improvements in PP beyond the CMJ, despite a linear increase in ECC (Fig. 3). In males [12], there was a 52% increase in PP from SJ to CMJ. Similarly, the females in the present study showed a 56% increase in PP from SJ to CMJ. Our previous study in males did not report JH, however, in the present study there was an 11% increase in JH from SJ to CMJ, followed by a 22% decrease from CMJ to DJ20, which remained the same across DJs. Perhaps the most unique finding in the present study was that the

Table 2 Pearson product moment correlation coefficients for the relationships between the changes in power from static jump to countermovement jump (ΔCMJ-SJ), CMJ to the 20-cm drop jump (ΔDJ20-CMJ), DJ20 to the 30-cm drop jump (ΔDJ30-DJ20), and DJ30 to the 40-cm drop jump (ΔDJ40-DJ30) and measurements of growth

	ΔCMJ-SJ	ΔDJ20-CMJ	ΔDJ30-DJ20	ΔDJ40-DJ30
Age (years)	0.798*	0.312	0.473*	0.278
Maturity offset (years)	0.815*	0.298	0.526*	0.279
Height (cm)	0.741*	0.172	0.504*	0.200
Body mass (kg)	0.558*	0.207	0.682*	0.046
Fat-free mass (kg)	0.723*	0.328	0.555*	0.210
Thigh muscle cross-sectional area (cm^2)	0.416	0.406	0.415	0.126

*Indicates significant correlation ($P < 0.05$)

increase in PP from SJ to CMJ (ΔCMJ-SJ) exhibited by the females was unrelated to thigh muscle CSA (Table 2). The males [12] exhibited moderate to high relationships between ΔCMJ-SJ and measurements of growth, including a moderate relationship with thigh CSA ($r = 0.55$). Compared to the males [12], the females in the present study exhibited similar moderate to high relationships between ΔCMJ-SJ and all other measurements of growth, including age, maturity offset, height, body mass, and FFM (Table 2). Thus, despite similar magnitudes of increase for PP and ECC from the SJ to CMJ, the correlations in the present study suggest that utilization of the stretch–shortening cycle to increase vertical jump power production in young females may be less related to thigh muscle CSA.

Previous studies in adults have reported increases in vertical jump performance with progressive increases in eccentric pre-loading from SJs to CMJs to DJs [5, 6, 10, 11, 23, 24, 36]. Specifically, 5%–42% increases in jump performance from SJ to CMJ, and 3%–32% increases from CMJ to DJ. Similar studies in children have reported greater CMJ performance compared to the SJ, and equivalent jump performance between the CMJ and DJ [2, 3, 12, 18, 21, 26, 34]. For example, 15%–110% increases in performance have been reported [2, 3, 12, 18, 21, 34] from the SJ to CMJ, but only 5%–10% increases have been reported [2, 3, 12, 26, 34] from CMJ to DJ. Therefore, it seems that children, unlike adults, are unable to utilize the greater eccentric pre-loading forces to increase vertical jump performance beyond that of the CMJ. The present study, as well as our previous study [12], reported that PP increased from the SJ to CMJ, with no subsequent changes from the CMJ to DJs, despite systematic increases in ECC (Fig. 3). Furthermore, in the present study, JH increased from SJ to CMJ, but decreased from CMJ to DJ20 (Fig. 3). It has been proposed that the mechanisms leading to greater concentric power output and vertical jump performance following the eccentric phase may be inhibited in children due to lower muscle mass and limited force-producing capabilities [6, 12, 16]. A previous study from our laboratory demonstrated strong relationships

between muscle CSA and passive musculotendinous stiffness [33], which is thought to reflect the amount of energy a muscle can absorb during the stretching phase. Although PP did not increase beyond the CMJ in our previous study [12], the positive relationship between ΔCMJ-SJ and CSA suggested that utilization of the energy absorbed during the stretching phase of rebound vertical jumps was related to muscle mass in young males. However, in the present study, there was no significant relationship between ΔCMJ-SJ and CSA, which suggested that augmentations of power production by including an eccentric pre-load during vertical jumps is likely influenced by mechanisms other than muscle mass in young females.

In males [12], it was demonstrated that age, maturity offset, height, body mass, and CSA all similarly accounted for the relationships between measurements of growth and ΔCMJ-SJ. In the present study, there were moderate to high relationships ($r = 0.558$–0.815) between ΔCMJ-SJ and several measurements of growth. Furthermore, partial correlations revealed that age and maturity offset, which provide estimates of biological maturation, were able to fully account for the relationships between ΔCMJ-SJ and height, body mass, and FFM. In contrast, partialing out the influence of height, body mass, and FFM did not eliminate the relationship between ΔCMJ-SJ and age/maturity offset. Thus, the unique relationships between age, maturity offset, and ΔCMJ-SJ, but not body or muscle size, suggest that mechanisms other than muscular hypertrophy may influence stretch–shortening cycle utilization in young females. Previous studies in children have suggested that other mechanisms, such as elastic energy utilization, augmentations in the stretch reflex, and neural maturation, which improve as children grow, may influence stretch–shortening cycle utilization [14, 19, 22, 31, 32]. However, future studies comparing these mechanisms in young males versus females are needed to better understand the growth and development-related adaptations in stretch–shortening cycle utilization.

Several studies have suggested that both changes in muscle size and muscle activation may affect the underlying

mechanisms leading to improvements in stretch–shortening cycle utilization [14, 19, 22, 31, 32]. Based on the relationships in the present study, it is possible that muscle activation may affect these mechanisms more than muscle size in young females. Among child and adult males and females, O'Brien et al. [30] found that concentric power production (measured during the SJ) was positively related to quadriceps femoris muscle volume. However, the authors concluded that the greater discrepancy in muscle volume between child and adult males compared to females may indicate that the growth-related differences in power production were more influenced by muscular hypertrophy in males. Another study from O'Brien et al. [29] reported sex-specific differences in muscle strength, size, and activation between child and adult males and females. Specifically, O'Brien et al. [29] suggested that muscle size accounted for a majority of the difference in strength between child and adult males, while differences in strength between child and adult females was more affected by muscle activation. Therefore, the findings of O'Brien et al. [29, 30], in conjunction with the results of the present study in females and our previous study in males [12], suggest there may be sex-specific morphological and neuromuscular adaptations that influence stretch–shortening cycle utilization during growth and development.

In conclusion, the results of the present study demonstrate that young females produce greater power during the CMJ than the SJ, but equivalent power compared to the DJs despite progressive increases in eccentric pre-loading. These results are in agreement with our previous study in males [12], demonstrating the inability of young males and females to utilize the stretch–shortening cycle for increases in concentric power production beyond the CMJ. Furthermore, in contrast to males [12], the increase in PP from the SJ to CMJ was not related to muscle size in females, which suggests there may be sex-specific adaptations which affect stretch–shortening cycle utilization during growth and development. Several previous studies have suggested that the underlying mechanisms that influence stretch–shortening cycle utilization may be affected by both changes in muscle size and muscle activation [14, 19, 22, 31, 32]. Additionally, O'Brien et al. [29, 30] reported sex-specific differences in muscle strength, size, and activation between child and adult males and females. Therefore, the relationship between ΔCMJ-SJ and CSA in males [12], but not females, may indicate that stretch–shortening cycle utilization is differentially affected by changes in muscle size and muscle activation as young males and females grow and develop. Due to the popularity of vertical jump tests in assessing athletic performance in young males and females, future researchers may wish to use similar vertical jump techniques to quantify and compare kinetic (ground reaction forces) and kinematic (hip to knee to ankle sequencing) data to provide a better understanding of elastic energy storage and utilization during vertical jumps of increasing eccentric preloading during growth and development. This may provide beneficial information for coaches and practitioners designing training programs to optimize power production in young females. Furthermore, future studies should consider assessing differences in skeletal muscle hypertrophy and neuromuscular adaptations during growth and development in young males and females to determine if sex-specific morphological and neuromuscular adaptations exist.

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