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Comparisons of countermovement jump force profiles in youth athletes

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Abstract

The purposes of this study were to determine whether countermovement jump (CMJ) force profiles differ for jumps in which peak force occurred at the low position of the countermovement (LP) compared to jumps in which peak force did not occur at the low position of the countermovement (NLP), and compare relationships among CMJ and isokinetic metrics between groups. Thirty-nine male and female youth athletes between 9- and 17-year-old participated. Participants completed CMJs and isokinetic knee extensions from 60 to 300°·s^{-1}. Ground reaction forces were collected during CMJs to quantify unweighting, braking, propulsive, and performance metrics. Torque and power were quantified during all isokinetic knee extensions. Forty-one percent of participants had LP force profiles, while 59% of participants had NLP force profiles. The LP group had more efficient unweighting and braking phase metrics than the NLP group, while the NLP group had greater isokinetic torque and power, and greater relationships between CMJ and isokinetic metrics, than the LP group. CMJs from the LP group represent more biomechanically efficient jumps than CMJs from the NLP group. Additionally, the NLP group may be more reliant on concentric force production during the CMJ, while the LP group may have more efficient storage and utilization of elastic energy.

KEYWORDS

exercise, joint, musculoskeletal system

1 | INTRODUCTION

Vertical jump tests are popular assessments of athletic performance for children and adolescents.[1,2] Arguably, the most popular vertical jump test is the countermovement jump (CMJ), which involves a downward countermovement followed by a maximal vertical jump. Recently, it has become more common to assess vertical ground reaction forces (GRFs) during CMJs, typically performed with the hands on the hips, to observe acute changes or differences in vertical jump performance in adults and youth.[1-4] Previous studies utilizing this technique often report peak braking (eccentric) and peak propulsive (concentric) force, among several other metrics across the phases of the CMJ.[5-9] In these types of analyses, the low position of the center of mass (bottom of the countermovement) represents the end of the braking phase and start of the propulsive phase. However, McHugh et al[4] recently suggested this may not accurately reflect the GRFs obtained during the different phases of the CMJ. It is possible that the peak GRF may occur at the low position of the countermovement, suggesting that peak braking and propulsive phase forces occur at the same point.

There is much debate in previous literature regarding the examination of peak force relative to the low position during

CMJs. Several studies have reported values for force at the low position as well as peak propulsive force.[3,5,7,10] These studies reported peak force at the low position to be approximately 65%-110% of peak propulsive force. Several other studies have reported peak force relative to the low position of the countermovement, which showed peak force occurring before, at, and/or after the low position of the countermovement,[4,9-14] or even different values for peak eccentric force, force at the low position, and peak propulsive force.[3,7] Most recently, McHugh et al[4] examined the force profiles of NCAA Division I athletes during CMJs. The study reported that 52% of subjects achieved peak force at the low position of the countermovement, while 48% of the subjects did not. Furthermore, when peak force occurred at the low position, the authors reported more efficient CMJ metrics during the unweighting and braking phases, as well as superior performance (jump height and reactive strength index (RSI)) compared to athletes in which peak force did not occur at the low position. McHugh et al[4] concluded that examining peak force relative to the low position of the countermovement may provide unique insights for practitioners who train athletes to improve biomechanical efficiency during jumping tasks. Similarly, in pre-pubertal female children, Floría et al[15] reported that the high-performing jumpers exhibited force profiles in which peak force tended to coincide with the low position of the countermovement, though this study did not specifically examine CMJ metrics during the unweighting, braking, and propulsive phases. Thus, if the CMJ is to be used as an assessment of athletic performance in youth, perhaps examining peak force relative to countermovement depth would be helpful for assessing biomechanical efficiency, or inefficiency, of CMJ force profiles in youth.

Several recent studies have also suggested that CMJ performance may be related to the isokinetic torque and power-producing capabilities of skeletal muscle in young males and females. In adolescent females, Rouis et al[16] reported that isokinetic strength at high angular velocities was related to CMJ jump height. Furthermore, in adolescent males, McKinlay et al[17] found that isokinetic strength and body mass were related to, and contributed to predictions of, CMJ jump height. Most recently, Gillen et al[18] found that normalized isokinetic strength consistently predicted, with moderate to strong relationships, CMJ power and jump height. Therefore, it is possible that stronger relationships between isokinetic strength and CMJ force profile metrics may reflect individuals who are more reliant on concentric force production than elastic energy storage/utilization for CMJ propulsion. However, we are unaware of any studies to examine the relationships between isokinetic strength and power between youth athletes for which peak force coincides with the low position of the countermovement versus youth athletes for which peak force does not coincide with the low position of the countermovement. Therefore, the purposes of this study were to (1) determine whether CMJ force profiles differ for jumps in which peak force occurred at the low position (LP) compared to jumps in which peak force did not occur at the low position (NLP), and (2) compare the relationships between CMJ metrics and concentric isokinetic strength and power between groups (LP vs. NLP). We hypothesized that the LP group would have superior CMJ metrics and performance, and that concentric isokinetic strength and power would be less related to CMJ metrics in the LP group.

2 | MATERIALS AND METHODS

2.1 | Subjects

Thirty-nine male and female youth athletes (n = 20 females, n = 19 males, mean ± 95% confidence interval (CI), age = 12.6 ± 0.6 y, height = 156.3 ± 3.9 cm, body mass = 52.6 ± 5.2 kg) participated in this study. All subjects reported participating in one or more sports for one to five hours 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. The subjects and their parent or legal guardian completed the PAR-Q + 2015[19] and were allowed to participate if questions 1-7 were answered “no” or all of the follow-up questions were answered “no.” The present study was approved by the University of Nebraska-Lincoln Institutional Review Board for the protection of human subjects (IRB # 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 subject signed the approved assent form. One parent or legal guardian signed the approved consent form.

2.2 | Research design

A cross-sectional design was used for this study. Subjects visited the laboratory twice, once for familiarization and once for the experimental trial. Anthropometric and body composition assessments were performed at each trial. During each visit, subjects completed three countermovement jumps (CMJs), as well as three maximal voluntary isokinetic knee extension muscle actions at 60, 120, 180, 240, and 300°·s^{-1} in random order. Two to 7 days after the familiarization trial, subjects completed the experimental trial at approximately the same time of day (± 2 hours). The familiarization trial allowed subjects to experience and practice interacting with the testing equipment and procedures. Data from the experimental trial are reported herein. Variables calculated during the different phases of the CMJs are presented in Table 1. Variables calculated during all isokinetic knee extension muscle actions were peak torque (PT) and mean power (MP).

2.3 | Anthropometrics and body composition

Height (cm), seated height (cm), and body mass (kg) were measured using a digital scale and stadiometer (Seca 769, Hamburg, Germany). These variables were used to calculate estimated maturity offset using the Mirwald equation [20] 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.[21] Equations established by Housh et al[22] and Brozek et al[23] were used to estimate body density and percent body fat, respectively. Fat-free mass (FFM) was calculated as the difference between body mass and fat mass as determined by percent body fat.

2.4 | Countermovement jumps

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. To perform the CMJ, subjects 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 all CMJ attempts, subjects were required to keep their hands on their hips. Subjects completed three attempts of the CMJ, with 1-min of rest between attempts. The attempt with the highest jump height (JH) was used for all subsequent analyses. Recent data from our laboratory,[24] in conjunction with analyses of the present data set, have determined CMJs in youth ranging from 6 to 17 years old may be considered reliable assessments (intraclass correlation coefficients = 0.91, coefficient of variation = 8.54% in

TABLE 1 Countermovement jump metrics

Metric	Definition
Unweighting phase	
Duration (s)	Time from initiation of unweighting to low velocity.
Low Force (%BW)	Nadir of the force signal, expressed relative to body weight.
Braking phase	
Duration (s)	Time from low velocity to low position.
Countermovement Depth (m)	Nadir of the position signal.
Peak Braking Power ($W{\cdot}kg^{-1}$)	Peak value of the product of the force and velocity signals from low velocity to the low position, expressed relative to body mass.
Force at Low Position (%BW)	Force at the nadir of the position signal, expressed relative to body weight.
Braking RFD ($\%BW{\cdot}s^{-1}$)	The change in force from low velocity to the low position divided by duration, expressed relative to body weight.
Eccentric Force (%BW)	The change in force from low force to low position, expressed relative to body weight.
Eccentric Stiffness ($N{\cdot}m^{-1}$)	Absolute eccentric force divided by countermovement depth.
Propulsive phase	
Duration (s)	Time from low position to take-off.
Peak Propulsive Power ($W{\cdot}kg^{-1}$)	Peak value of the product of the force and velocity signals from the low position to take-off, expressed relative to body mass.
Mean Propulsive Force (%BW)	The average of the force signal from the low position to take-off, expressed relative to body weight.
Performance metrics	
Jump Height (m)	Calculated using the impulse-momentum method, where jump height equals the velocity at take-off (calculated as net propulsive impulse divided by body mass) squared, divided by the constant acceleration of gravity multiplied by 2.
RSI	Flight time divided by the duration from initiation of unweighting to take-off.

Abbreviations: BW, body weight (N); RFD, rate of force development; RSI, reactive strength index.

the present study). We also assessed reliability split by LP and NLP groups, which provided intraclass correlation coefficients ≥0.89 and coefficients of variation ≤9.01%. Thus, regardless of CMJ force profile, we are confident in the reliability of the CMJs in the present study.

2.5 | Isokinetic knee extensions

All isokinetic knee extension muscle actions were completed on a calibrated isokinetic dynamometer (Biodex System 3, Biodex Medical Systems, Inc, Shirley, NY, USA) that was custom fitted with a load cell (Omegadyne, model LCHD-500, 0-500 lbs, Stamford, CT, USA) located between the shin pad and the lever arm. Recorded force (N) was taken during each isokinetic muscle action. Subjects were seated with restraining straps over the pelvis, trunk, and contralateral thigh. The lateral condyle of the femur was aligned with the axis of rotation of the dynamometer head. The range of motion for the isokinetic muscle actions was set from 0° to 90°, with 0° representing full knee extension. Subjects completed three repetitions of maximal voluntary isokinetic knee extension muscle actions at 60, 120, 180, 240, and 300°·s^{-1}, with 1-min of rest between each angular velocity. Each subject was instructed to extend their leg as hard and fast as possible, while strong verbal encouragement was provided. The order of the angular velocities was randomized separately for the familiarization and experimental trials. The repetition with the highest PT for each angular velocity was used for all subsequent analyses.

2.6 | Signal processing

During all CMJs, the y-axis, vertical ground reaction forces were sampled at 1 kHz using PASCO Capstone software (PASCO Scientific, Roseville, CA). During the isokinetic muscle actions, the position (°) and velocity (°·s^{-1}) signals were sampled from the isokinetic dynamometer, while force (N) was recorded simultaneously from the load cell at 1 kHz with a Biopac data acquisition system (MP150, Biopac Systems, Inc, Santa Barbara, CA). All signals were stored on a personal computer and processed off-line with custom written software (LabVIEW v. 18.0, National Instruments, Austin, TX).

Based on the methods used in previous studies,[1,2,18,25] for all CMJs, the investigator (ZMG) manually identified (a) the initial onset of movement (always downward and negative force), (b) the point at which the velocity signal was equal to zero (low position), (c) the point at which the feet left the force plates (toe off, zero force), and (d) the point at which the feet contacted the force plates after the jump. Velocity-time tracings were calculated by taking the integral of the force-time curve divided by mass. Power-time tracings were calculated by multiplying the force-time tracing by the velocity-time tracing. Position-time tracings were calculated by taking the integral of the velocity-time tracing. Based on previous studies,[25-28] the epoch of the force signal from (a) to low velocity was considered the unweighting phase, the epoch of the force signal from low velocity to (b) was considered the braking phase, the epoch of the force signal from (b) to (c) was considered the propulsive phase, and the epoch of the force signal from (c) to (d) was considered flight time. Metrics taken during each phase of the CMJ are presented in Table 1, while JH was calculated using the impulse-momentum method.[27] Based on previous methods,[4] jumps were categorized as either (1) peak force occurring at the low position (LP) or (2) peak force not occurring at the low position (NLP). If force at the low position was within 1% of peak force, then it was categorized as occurring at the low position. Sample force-time tracings for an LP and NLP jump are presented in Figure 1.

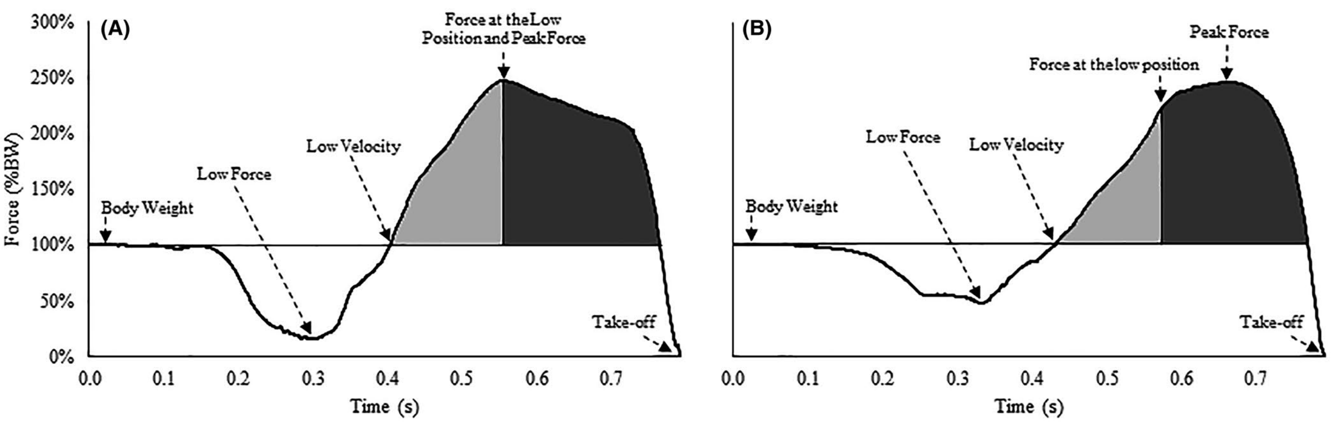

FIGURE 1 A sample force-time tracing for (A) a countermovement jump (CMJ) in which peak force occurred at the low position and (B) a CMJ in which peak force did not occur at the low position. The unshaded area where force is below body weight represents the unweighting phase, the light gray shaded area represents the braking phase, and the dark gray shaded area represents the propulsive phase

Prior to all analyses for isokinetic muscle actions, a correction for leg weight was performed and raw recorded force (N) was multiplied by lever arm length (m) to provide torque (Nm) in the custom written software. During all isokinetic muscle actions, the load range was automatically determined from the onset to the end of the constant-velocity phase.[29-31] The onset of the isokinetic load range was automatically detected as the joint angle (°) at which the velocity signal had reached the pre-determined velocity.[29-31] The end of the isokinetic load range was the joint angle (°) at which the velocity signal dropped below the pre-determined angular velocity.[29-31] These start and end positions were used as the ranges of motion during which PT (Nm) and MP (W) were taken during all angular velocities. During the automatic detections of each subject's isokinetic load range, the investigator visually inspected the velocity- and position-time signals to ensure that an onset had not been falsely triggered and that the range of motion for all angular velocities was within the load range. Isokinetic PT was taken as the highest torque value from the torque-time signal during the selected epoch of each angular velocity. Power-time tracings were calculated by multiplying the torque-time tracings by the velocity-time tracings. The same epoch was taken from the power-time signal during each angular velocity to calculate MP, expressed as the average power during the selected epoch. Both PT and MP were expressed relative to body mass ($Nm \cdot kg^{-1}$ and $W \cdot kg^{-1}$, respectively) for each subject.

2.7 | Ultrasound imaging

During each visit, panoramic cross-sectional images of the quadriceps and hamstrings were taken to quantify thigh muscle cross-sectional area (CSA, cm^2). Ultrasound images were obtained using a portable brightness mode (B-mode) ultrasound-imaging device (GE Logiq e, USA) interfaced with a multi-frequency linear-array probe (12L-RS; 5-13 MHz; 38.4 mm field-of-view). Subjects were positioned on a plinth in the supine position for the 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. 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 to the most medial aspect of the quadriceps. 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 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.

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 subjects. The image depth was adjusted based on each subject's leg size and was then held constant for each subject. Images were taken until three images with acceptable image quality, as determined by the investigator, were obtained. The image with the highest visual contrast was used for analysis. All images were measured by the same investigator (ZMG) across all subjects and prior to any exercise by the subject. 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. Quadriceps CSA and hamstrings CSA were quantified using the polygon function in Image-J to select the maximal region of interest that included as much of the quadriceps and hamstrings muscles 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) have determined that quadriceps and hamstrings CSA measurements from ultrasound images may be considered reliable measurements (intraclass correlation coefficients ≥ 0.90, coefficients of variation $\leq 2.97\%$). This methodology of assessing thigh CSA has been used in several recent studies in young males and females.[1,2,18]

2.8 | Statistical analyses

Means and 95% confidence intervals of all measurements of growth (age, maturity offset, height, body mass, FFM, CSA, Table 2), CMJ metrics (Table 2), and isokinetic metrics (Figure 2) were calculated. Independent samples *t* tests were used to compare measurements of growth and CMJ metrics between groups (LP vs. NLP). Two-way mixed factorial ANOVAs (group [LP vs. NLP] × muscle action [$60° \cdot s^{-1}$ vs. $120° \cdot s^{-1}$ vs. $180° \cdot s^{-1}$ vs. $240° \cdot s^{-1}$ vs. $300° \cdot s^{-1}$]) were used to compare PT and MP. When appropriate, follow-up analyses included low-order ANOVAs and dependent samples t tests. The following qualitative evaluations of the strength of association among CMJ metrics and isokinetic metrics were made according to Mukaka [32] based on the absolute values of correlation coefficients: 0.900 to 1.000 = very high, 0.700 to 0.899 = high, 0.500 to 0.699 = moderate, 0.300 to 0.499 = low, and 0.000 to 0.299 = negligible. All statistical analyses were performed in IBM SPSS v. 25 (Chicago, IL, USA). An alpha level of $P \leq .05$ was considered statistically significant.

3 | RESULTS

The NLP group was older, had greater maturity offset, height, body mass, and FFM than the LP group ($P \leq .020$, Table 2). During the unweighting phase, the NLP group did not unweight themselves as much as the LP group ($P = .024$,

TABLE 2 Means ± 95% confidence intervals for measurements of growth and countermovement jump metrics between jumps in which peak force occurred at the low position versus jumps in which peak force did not occur at the low position

Metric	Peak force at low position (n = 16)	Peak force not at low position (n = 23)	P value
Age (y)	***11.6 ± 0.9***	***13.2 ± 0.8***	***.010***
Maturity offset (y)	***−1.4 ± 0.8***	***0.2 ± 0.7***	***.005***
Height (cm)	***150.9 ± 6.5***	***160.0 ± 4.7***	***.020***
Body mass (kg)	***44.9 ± 5.8***	***58.0 ± 7.5***	***.011***
Fat-free mass (kg)	***35.4 ± 4.2***	***44.7 ± 5.3***	***.012***
Thigh muscle cross-sectional area (cm^2)	62.5 ± 7.7	72.9 ± 8.5	.080
Unweighting phase			
Duration (s)	0.28 ± 0.03	0.30 ± 0.02	.222
Low force (%BW)	***28 ± 8***	***40 ± 7***	***.024***
Braking phase			
Duration (s)	0.18 ± 0.03	0.21 ± 0.03	.210
Countermovement depth (m)	0.26 ± 0.04	0.26 ± 0.05	.981
Peak braking power ($W{\cdot}kg^{-1}$)	5.42 ± 1.28	4.08 ± 1.00	.085
Force at low position (%BW)	***237 ± 24***	***209 ± 18***	***.049***
Braking RFD (%BW·s^{-1})	***538 ± 125***	***383 ± 81***	***.043***
Eccentric force (%BW)	***213 ± 33***	***169 ± 22***	***.017***
Eccentric stiffness ($N{\cdot}m^{-1}$)	4151 ± 1453	4108 ± 1015	.958
Propulsive phase			
Duration (s)	0.27 ± 0.03	0.29 ± 0.06	.768
Peak propulsive power ($W{\cdot}kg^{-1}$)	39.91 ± 4.19	44.02 ± 6.05	.295
Mean propulsive force (%BW)	172 ± 9	182 ± 11	.146
Performance metrics			
Jump height (m)	0.19 ± 0.02	0.23 ± 0.03	.073
RSI	0.55 ± 0.07	0.55 ± 0.05	.994

Note: Bold and italicized values indicate a statistically significant difference between groups ($P \leq .05$).
Abbreviations: BW, body weight (N); RFD, rate of force development; RSI, reactive strength index.

Table 2). During the braking phase, the LP group had greater force at the low position, braking RFD, and eccentric force than the NLP group ($P \leq .050$, Table 2). There were no differences for propulsive or performance metrics between groups ($P \geq .073$, Table 2).

There was a main effect for PT and MP, such that the NLP group had greater PT and MP than the LP group collapsed across velocity ($P \leq .046$, Figure 2). For PT, there was a main effect such that PT decreased systematically from 60-300°·s^{-1} collapsed across group ($P \leq .009$, Figure 2A). For MP, there was a main effect such that MP increased to 240°·s^{-1} ($P < .001$), then decreased from 240-300°·s^{-1} collapsed across group ($P < .001$, Figure 2B).

Relationships between CMJ metrics and isokinetic metrics for the LP and NLP groups are presented in Tables 3 and 4, respectively. For the LP group, none of the 9 unweighting/braking phase metrics, 3 propulsive phase metrics, or 2 performance metrics were correlated with isokinetic PT at any of the 5 speeds ($|r|$ = 0.002-0.404, Table 3). In contrast, for the NLP group 3 of 9 unweighting/braking phase metrics, 2 of 3 propulsive phase metrics, and 2 of 2 performance metrics exhibited low to high correlations with isokinetic PT at all 5 velocities (r = 0.462-0.826, Table 4). Similar relationships were seen between CMJ metrics and isokinetic MP. For the LP group, only 3 jump metrics exhibited moderate relationships with isokinetic MP at 60°·s^{-1}, 120°·s^{-1}, 240°·s^{-1}, and 300°·s^{-1} ($|r|$ = 0.541-0.598, Table 3). In contrast, for the NLP group, 3 of 9 unweighting/braking phase metrics, 2 of 3 propulsive phase metrics, and 2 of 2 performance metrics exhibited low to high correlations with isokinetic MP at all 5 velocities (r = 0.421-0.743, Table 4). Of note, all correlations were strongest at the 2 highest isokinetic velocities ($|r|$ = 0.418-0.826, Tables 3 and 4).

4 | DISCUSSION

To our knowledge, this is the first study to quantify unweighting phase, braking phase, propulsive phase, and performance

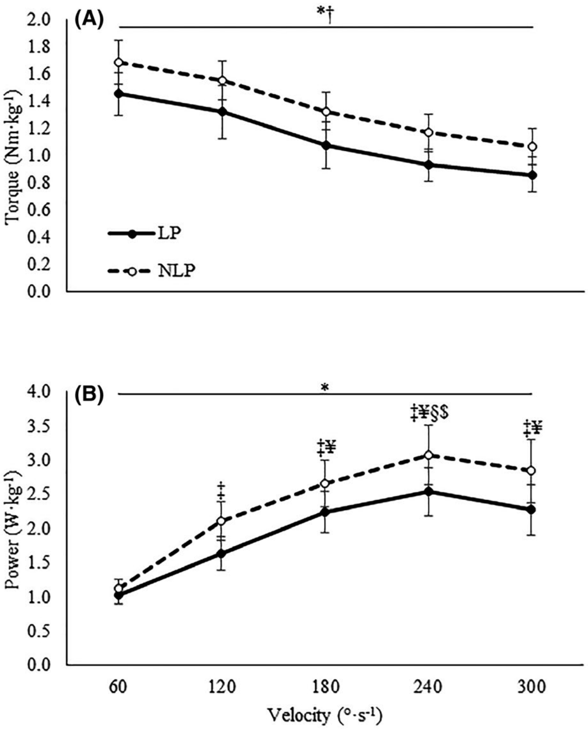

FIGURE 2 Means ± 95% confidence intervals for A) peak torque and B) mean power across isokinetic angular velocities for the groups in which countermovement jump peak force occurred at the low position (LP) and did not occur at the low position (NLP). * Indicates NLP was greater than LP collapsed across velocity, † indicates systematic decreases across velocity collapsed across group, ‡ indicates greater than $60°\cdot s^{-1}$ collapsed across group, ¥ indicates greater than $120°\cdot s^{-1}$ collapsed across group, § indicates greater than $180°\cdot s^{-1}$ collapsed across group, $ indicates greater than $300°\cdot s^{-1}$ collapsed across group ($P \leq .05$)

metrics during CMJs in youth athletes. The primary results of this study demonstrated that 16 of 39 subjects achieved peak force at the low position of the countermovement, while 23 of 39 subjects achieved peak force after the low position of the countermovement. Furthermore, although the NLP group was older and had greater maturity offset, height, weight, and FFM than the LP group, they exhibited less efficient CMJ metrics (Table 2). Specifically, the LP group had greater unweighting, force at the low position, braking RFD, and eccentric force than the NLP group (Table 2). Interestingly, the NLP group exhibited greater isokinetic PT and MP (Figure 2) but this did not translate into higher jumps or greater force or power during the jumps. Furthermore, isokinetic knee extension PT and MP exhibited stronger correlations with CMJ force and power in the NLP group versus the LP group (Tables 3 and 4). This may reflect less efficient elastic energy storage/utilization and greater reliance on concentric strength during the propulsive phase of the CMJ for the NLP group. Thus, the present study provides novel information in youth athletes indicating that peak force coinciding with the low position of the CMJ may reflect a more biomechanically efficient jump.

Several studies[4,8,10,15,33-37] have suggested that greater unweighting may lead to more efficient braking phase, propulsive phase, and performance metrics during CMJs. Recently, in NCAA Division I athletes, McHugh et al[4] reported that subjects unweighted themselves to 19% of their body weight when peak force coincided with the low position of the countermovement compared to only 32% of body weight when peak force did not coincide with the low position of the countermovement. Similarly, in female children, Floría et al[15] demonstrated that high-performing jumpers had a peak force that coincided with the low position and greater unweighting at the initiation of the CMJ (≈ 60% versus 70%). In the present study, the LP group unweighted themselves to 28% of body weight compared to only 40% for the NLP group (Table 2). Furthermore, similar to McHugh et al[4] and Floría et al,[15] in the present study there were no differences in countermovement depth, despite significant differences in unweighting. In conjunction with previous studies,[4,15] it is possible that the ability to unweight oneself at the beginning of the CMJ is more important than the depth of the countermovement itself. Thus, in youth athletes, peak force coinciding with the low position of the countermovement may reflect greater unweighting, which should improve metrics during the subsequent phases of the CMJ.

Mathematically, the greater the unweighting of a given mass, the greater the force necessary during the subsequent braking phase to reach the velocity needed for propulsion.[38,39] Indeed, in the present study the LP group exhibited greater force at the low position, braking RFD, and eccentric force (Table 2) than the NLP group, which is in agreement with previous findings in adults[4] and female children.[15] Interestingly, the LP and NLP group had similar eccentric stiffness, jump height, and RSI, which contrasts the recent findings of McHugh et al[4] which showed that LP jumps exhibited greater eccentric stiffness, jump height, and RSI. As stated by McHugh et al,[4] "the countermovement has been modeled as a spring, with eccentric stiffness analogous to compressing the spring." Thus, the greater unweighting, and subsequent braking phase forces, should compress the "spring" to a greater degree for the LP group, which was not the case in the present study. Previous studies[40,41] have demonstrated strong relationships between passive musculotendinous stiffness and muscle CSA. Thus, it is possible the lack of differences in CSA between the LP and NLP groups may account for the lack of differences in eccentric stiffness (Table 2), which suggests underlying factors other than muscle size may cause differences in unweighting and braking phase forces, although further research is necessary.

It is possible that the sudden growth the NLP group is experiencing may negatively influence execution of the CMJ. The NLP group was approximately 13 –years old and at their age of peak height velocity (growth spurt), which has been suggested as a time during which youth may have "adolescent awkwardness" during physical activity.[42] In fact, Read et al[42] reported a slight reduction in hopping performance from age 12 to 13 years, which subsequently improved from ages 14 to 18 years. The authors suggested this phenomenon may be due to a stage of "adolescent awkwardness" during which motor control patterns are compromised. Thus, in the present study the older, more mature NLP group may be in a period of "adolescent awkwardness" during which they have an inhibited ability of the nervous system to coordinate a biomechanically efficient CMJ. Additionally, changes in the force-length properties of skeletal muscle and musculotendinous stiffness occur during growth and development, which may alter the technical execution of the CMJ, although future studies are needed to gain a further understanding. Interestingly, despite the more efficient unweighting and braking phase metrics of the LP group, both groups had similar propulsive and performance metrics, and the NLP group was stronger and exhibited stronger relationships between isokinetic PT, MP, and CMJ metrics.

Several studies have reported significant relationships between isokinetic strength, power, and CMJ metrics in adults[43-46] and children.[16-18] Most recently, Gillen et al[18] found that normalized isokinetic PT consistently predicted, with moderate to high relationships, CMJ power and jump height. Similarly, in adolescent females[16] and preadolescent males[17] previous studies have reported significant relationships between isokinetic strength, CMJ propulsive power, and jump height. However, these studies did not specifically examine the force-time curves to determine where peak force occurred relative to the low position of the countermovement. Thus, the separation of youth athletes into LP and NLP groups in the present study provides unique insights into the relationship between isokinetic PT, MP, and CMJ metrics not reported previously. In the present study, the NLP group exhibited low to high relationships between 3 of 9 unweighting/braking phase metrics, 2 of 3 propulsive phase metrics, and 2 of 2 performance metrics and isokinetic PT and MP (Table 4). In contrast, the LP group exhibited very few relationships between CMJ metrics and isokinetic PT and MP despite more efficient unweighting and braking phase metrics (Table 3). It is possible that the NLP group achieved greater isokinetic PT and MP due to growth and development-related differences, despite no differences for CMJ propulsive and performance metrics. Thus, the greater isokinetic strength and power of the NLP group, more efficient unweighting and braking phase metrics of the LP group, and similar CMJ propulsive and performance metrics between groups may suggest that the NLP group may have been more reliant on concentric force production for CMJ propulsion, while the LP group may have been more reliant on elastic energy storage/utilization.

A recent study by Boullosa et al[47] suggested that a high relationship between eccentric force or the force at the low position and concentric power may reflect greater elastic energy storage and utilization. This is in contrast with the hypothesis proposed in the present study as one would expect a high relationship between eccentric force or force at the low position and isokinetic strength/power if indeed differences in elastic energy storage and utilization were present. Therefore, the fewer relationships between jump metrics and concentric, isokinetic PT and MP may not necessarily reflect differences in elastic energy utilization in children, though further research is needed to understand these unique findings. Thus, although CMJ profiles that fit a more LP profile have been hypothesized to reflect differences in elastic energy utilization in adults,[4] the same may necessarily not be true in children. This highlights the importance of further research using these CMJ analysis techniques in adults and children to better understand the underlying physiological mechanisms leading to more efficient CMJ profiles.

In conclusion, based on the results of the present study, in conjunction with previous studies,[4,15] CMJs in which peak force coincides with the low position of the countermovement may reflect more biomechanically efficient jumps than CMJs in which peak force does not coincide

TABLE 3 Pearson product moment correlation coefficients for the relationships between countermovement jump and isokinetic metrics for jumps in which peak force occurred at the low position

	Unweighting Phase Duration	Low Force	Braking Phase Duration	CM Depth	Braking Power	Force at Low Position	Braking RFD	Eccentric Force	Eccentric Stiffness	Propulsive Phase Duration	Propulsive Power	Mean Propulsive Force	JH	RSI
$60° \cdot s^{-1}$ PT	0.016	0.162	0.491	0.358	0.002	0.024	-0.325	0.036	-0.212	0.374	-0.195	-0.188	0.362	-0.191
$120° \cdot s^{-1}$ PT	-0.059	-0.123	0.277	0.029	0.229	-0.057	-0.249	-0.024	-0.031	0.126	0.069	0.102	0.457	0.034
$180° \cdot s^{-1}$ PT	-0.041	0.162	-0.080	-0.243	0.253	-0.119	-0.101	-0.172	0.249	-0.158	0.093	0.356	0.391	0.201
$240° \cdot s^{-1}$ PT	0.121	0.150	0.090	-0.144	0.332	-0.143	-0.221	-0.200	0.080	-0.110	0.154	0.195	0.304	0.021
$300° \cdot s^{-1}$ PT	0.016	0.316	0.064	-0.050	0.202	0.108	-0.069	0.015	0.116	-0.077	0.133	0.270	0.404	0.089
$60° \cdot s^{-1}$ MP	0.072	-0.228	0.467	0.189	0.297	0.228	-0.160	0.324	-0.268	***0.541***[a]	-0.186	-0.342	0.201	-0.312
$120° \cdot s^{-1}$ MP	-0.133	-0.313	0.283	0.124	0.107	0.044	-0.236	0.140	-0.162	0.304	-0.022	0.024	***0.586***[a]	0.002
$180° \cdot s^{-1}$ MP	0.049	-0.132	-0.104	-0.281	0.431	0.166	0.053	0.173	0.200	0.021	0.152	0.272	0.473	0.135
$240° \cdot s^{-1}$ MP	0.235	-0.018	0.064	-0.275	***0.598***[a]	0.027	-0.096	-0.004	0.156	-0.051	0.203	0.108	0.188	-0.076
$300° \cdot s^{-1}$ MP	0.270	0.136	0.050	-0.275	***0.574***[a]	0.079	-0.021	0.010	0.269	-0.102	0.232	0.135	0.129	-0.063

Note: Highlight represents moderate positive relationship.

Abbreviations: CM, countermovement; JH, jump height; MP, mean power; PT, peak torque; RFD, rate of force development; RSI, reactive strength index.

[a]Indicates a statistically significant relationship ($P \leq .05$).

TABLE 4 Pearson product moment correlation coefficients for the relationships between countermovement jump and isokinetic metrics for jumps in which peak force did not occur at the low position

	Unweighting Phase Duration	Low Force	Braking Phase Duration	CM Depth	Braking Power	Force at Low Position	Braking RFD	Eccentric Force	Eccentric Stiffness	Propulsive Phase Duration	Propulsive Power	Mean Propulsive Force	JH	RSI
60°·s^{-1} PT	0.109	-0.212	-0.367	-0.207	0.047	***0.569***[a]	***0.524***[a]	***0.538***[a]	0.371	***-0.455***[a]	***0.561***[a]	***0.662***[a]	***0.569***[a]	***0.624***[a]
120°·s^{-1} PT	0.386	-0.180	-0.363	-0.120	0.054	***0.619***[a]	***0.547***[a]	***0.566***[a]	0.285	-0.405	***0.486***[a]	***0.690***[a]	***0.760***[a]	***0.654***[a]
180°·s^{-1} PT	0.233	-0.284	-0.389	-0.064	0.044	***0.694***[a]	***0.625***[a]	***0.663***[a]	0.352	***-0.484***[a]	***0.565***[a]	***0.721***[a]	***0.690***[a]	***0.697***[a]
240°·s^{-1} PT	0.207	-0.434a	-0.390	0.040	0.2	***0.662***[a]	***0.582***[a]	***0.686***[a]	0.299	***-0.477***[a]	***0.509***[a]	***0.751***[a]	***0.826***[a]	***0.758***[a]
300°·s^{-1} PT	0.291	-0.393	***-0.418***[a]	-0.020	0.168	***0.588***[a]	***0.559***[a]	***0.610***[a]	0.306	-0.388	***0.462***[a]	***0.672***[a]	***0.807***[a]	***0.708***[a]
60°·s^{-1} MP	0.273	-0.186	***-0.523***[a]	-0.267	0.094	***0.439***[a]	***0.501***[a]	***0.422***[a]	0.272	***-0.450***[a]	***0.531***[a]	***0.624***[a]	***0.516***[a]	***0.584***[a]
120°·s^{-1} MP	***0.517***[a]	-0.114	-0.400	-0.079	0.047	***0.468***[a]	***0.481***[a]	***0.421***[a]	0.068	-0.364	***0.502***[a]	***0.644***[a]	***0.679***[a]	***0.564***[a]
180°·s^{-1} MP	***0.438***[a]	-0.160	-0.389	0.020	0.058	***0.540***[a]	***0.513***[a]	***0.495***[a]	0.185	***-0.490***[a]	***0.494***[a]	***0.671***[a]	***0.679***[a]	***0.608***[a]
240°·s^{-1} MP	0.384	-0.247	***-0.441***[a]	-0.048	0.081	***0.531***[a]	***0.533***[a]	***0.515***[a]	0.177	***-0.472***[a]	***0.518***[a]	***0.705***[a]	***0.720***[a]	***0.672***[a]
300°·s^{-1} MP	0.390	-0.236	***-0.455***[a]	-0.008	0.121	***0.561***[a]	***0.545***[a]	***0.537***[a]	0.228	***-0.456***[a]	***0.504***[a]	***0.708***[a]	***0.743***[a]	***0.678***[a]

CM = countermovement, RFD = rate of force development, JH = jump height, RSI = reactive strength index, PT = peak torque, MP = mean power. [a] Indicates a statistically significant relationsh ip ($p \leq 0.05$).
High positive relationship, ***moderate positive relationship***, ***low positive relationship***, ***moderate negative relationship***, ***low negative relationship***.

with the low position of the countermovement. Specifically, in the present study the LP group had more efficient unweighting and braking phase metrics than the NLP group, despite being younger and having lower isokinetic PT and MP. Furthermore, there were no differences in propulsive phase or performance metrics, despite the more efficient unweighting and braking phase metrics of the LP group. It is possible that the NLP group may have been more reliant on concentric force production during the CMJ, as evidenced by stronger relationships between isokinetic PT, MP, and CMJ metrics for the NLP group. Thus, despite being younger and having lower isokinetic strength and power, the LP group achieved a more efficient CMJ profile than the NLP group and did not have inferior jump performances.

5 | PERSPECTIVES

Understanding where peak force occurs relative to the low position may provide practitioners guidance on appropriate training modalities. Specifically, for LP athletes it may be advantageous to focus on strength training, while for NLP athletes, it may be more advantageous to focus on jump technique and plyometric training. Due to the popularity and validity of CMJs in measuring lower-body force and power production, future researchers may wish to analyze hip to knee to ankle sequencing with regard to joint velocities, moments, and power during CMJs as this may provide further insights regarding the biomechanical efficiency of certain force profiles during CMJs. Further research using similar CMJ analysis techniques, while including kinetic and kinematic data, may provide unique insights into the influence of growth and development on force production and biomechanical efficiency during vertical jumps. Future studies should also assess the possible influence the stage of "adolescent awkwardness" may have on the ability or the nervous system to coordinate a biomechanically efficient CMJ.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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