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Development and Reliability of Countermovement Jump Performance in Youth Athletes at Pre-, Circa- and Post-Peak Height Velocity

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ABSTRACT

The purpose of this study was to establish the intrasession reliability of various outcome, propulsion and braking phase countermovement jump (CMJ) variables and to compare the mean differences in youth athletes at different stages of maturity. Thirty male participants, aged 10-16 years, were grouped as either pre-, circa- or post-peak height velocity (PHV) according to their percentage of predicted adult height. All participants performed 3 CMJ trials on a force plate, sampling at 1000 Hz. A one-way ANOVA identified statistically significant differences between maturity groups for all CMJ variables (P <0.05) excluding propulsion peak rate of force development (RFD), braking peak velocity and countermovement depth. Post-hoc analysis revealed that the significant differences in CMJ variables were between the pre- to post- and circa- to post-PHV groups (P <0.05), with moderate to very large effect sizes. Relative and absolute reliability improved with maturity as the post-PHV group demonstrated superior reliability scores (ICC = 0.627-0.984; CV% = 3.25-21.55) compared to circa- (ICC = 0.570-0.998; CV% = 1.82-20.05) and pre-PHV groups (ICC = 0.851-0.988; CV% = 2.16-14.12). In summary, these results suggest that the biggest differences in CMJ performance are observed between pre- to post- and circa- to post-PHV, and that careful consideration is warranted when selecting variables in youth athletes at pre- and circa-PHV, given the lower reliability scores observed.

Keywords: countermovement jump, force plate, intrasession reliability, youth athlete, biological maturation.

INTRODUCTION

There is now a recognised consensus supporting the regular inclusion of strength and conditioning (S&C) in children and adolescents with the aim of developing physical qualities such as muscular strength and power (19,32,47). As a result, an increased emphasis has been placed on performance testing to optimise training interventions, create accurate player profiles, monitor fatigue and positively influence a child's long-term development, both in research and practice (33,45,49). With this in mind, identifying an appropriate performance test and reliable variables is of particular interest to S&C and sports science practitioners who work with youth athletes.

The countermovement jump (CMJ) is frequently used to assess and monitor lower body neuromuscular function due to its ease of implementation and the low risk of injury it offers (5). From a developmental perspective, previous research has observed improvements of 7% per year in jump height (JH) between under 12 to under 16 soccer players (52) and approximately 2 cm annually in under 13 to under 15 rugby players (48). An adolescent performance surge in JH appears to begin 1.5 years before peak height velocity (PHV) with further peaks occurring shortly after the time of PHV to 1 year post-PHV (39). Radnor et al. (40) recently supported these observations with similar JHs found in pre- and circa-PHV groups, before increasing at post-PHV. These findings suggest that JH increases following PHV and may be as a result of increases in muscle cross-sectional, preactivation, tendon stiffness and decreases in agonist-antagonist co-contraction leading to a more effective stretch-shortening cycle (39,41,50).

The peaks in JH that occur before and after PHV are thought to straddle a period of reduced development (21,22,39). This period is thought to be best explained by the occurrence of "adolescent awkwardness" (39), which refers to a temporary disruption in motor skill performance as a result of rapid growth in limb length and body mass (25). An awareness of this developmental phenomenon is important as it is recommended that training volume-loads are modified to avoid excessive stress and to facilitate the re-learning of previously acquired skills and movement patterns (20). Despite previous research highlighting these patterns of development during growth and maturation, monitoring JH alone is limited as it does not describe jump strategy (1,5). Therefore, expanding analyses to include braking ("eccentric") and propulsion ("concentric") phase variables has been recommended to simultaneously monitor jump strategy as well as outcome (5,6,17).

Given the wealth of data that can be obtained from CMJ force-time analyses, selecting reliable variables is of paramount importance. Despite the limitations noted above, JH has demonstrated acceptable reliability in 10 to 15 year-olds (intraclass correlation coefficient [ICC] = 0.84-0.96; coefficient of variation percentage [CV%] = 5.56-7.9) (23,34,35), although it appears to vary slightly more in younger children between the age of 6 and 10 years' (ICC = 0.81-0.93; CV% = 5.80-11.07) (23). Through detailed analyses of CMJ performance, Meylan et al. (34) reported an overall trend towards greater reliability in propulsion phase variables when compared to braking phase variables (ICC = 0.74-0.98 vs 0.74-0.97; CV% 2.1-13.5 vs 4.6-15.6). More recently, Ruf et al. (44) observed a maturity gradient whereby CMJ variables were more reliable in the post-PHV group followed by circa- and pre-PHV groups. The variables that demonstrated the greatest reliability across maturity groups were JH, propulsive impulse and velocity (ICC = >0.71; CV% = <5.8), followed by reactive strength index modified (RSI_{mod}), countermovement depth and leg stiffness (ICC = >0.74; CV% = <13.0). Braking phase variables such as impulse, velocity and time demonstrated the poorest reliability scores within maturity groups (ICC = 0.49-0.85; CV% = 8.5-28.8). Collectively, these investigations suggest that the braking phase is more susceptible to lower reliability and greater variability in youth populations; however, force plate sampling frequencies of 400 and 500 Hz were used which is significantly less than current recommendations of ≥1000 Hz (46).

With the gaps identified in mind, the aim of this study was to establish the intrasession reliability of various outcome, propulsion and braking phase CMJ variables and to compare the mean values in youth athletes at pre-, circa- and post-PHV. Given the developmental trends in CMJ performance as children mature, it was hypothesised that the largest changes in performance would be observed between the pre- to post-PHV and circa- to post-PHV groups and that CMJ variables would be most reliable in pre- and post-PHV groups with a decline in the circa-PHV group associated with a period of "adolescent awkwardness".

METHODS

Study Design

This study used a cross-sectional design to evaluate the intrasession reliability of various CMJ variables in youth athletes at pre-, circa- and post-PHV. Further analysis was conducted to compare the mean differences in performance between maturity groups.

Participants

Thirty male participants between the age of 10 and 16 years' volunteered to take part in this study (Table 1). Participants were a mixture of defenders, midfielders and attackers from a university soccer club and were classified as 'trained/developmental' according to recent recommendations (26). No participants had previous experience with S&C training, screening or testing prior to the study; however, all were involved in ~5 hours of soccer training or competition per week. Parental consent and participant assent were obtained following

Table 1. Participant characteristics

Characteristics	Pre-PHV (n = 10)		Circa-PHV (n = 10)		Post-PHV (n = 10)	
	Mean	SD	Mean	SD	Mean	SD
Age (years)	11.70	0.48	12.90*	0.88	15.10**	0.57
Height (cm)	149.72	4.53	156.94	11.79	174.01**	7.58
Body Mass (kg)	41.01	5.87	51.72†	11.06	65.70††	9.21
PAH%	84.48	1.89	90.23*	2.07	97.76**	1.41

*Note: PHV, peak-height velocity; SD, standard deviation; PAH%, percentage of predicted adult height. †Significantly greater than the pre-PHV group (P < 0.05); *significantly greater than the pre-PHV group (P < 0.001); **significantly greater than the circa-PHV group (P < 0.001); ††significantly greater than the circa-PHV group (P < 0.05).*

ethical approval from the Plymouth Marjon University research ethics committee in accordance with the Declaration of Helsinki.

Procedures

All testing procedures took place within a 1 week time frame whereby participants were required to attend the biomechanics laboratory on 2 separate occasions. The first of these was to collect anthropometric data and familiarise participants with the CMJ. Participants were instructed to undergo no physical exertion on the days of testing with maintenance of normal dietary intake advised in the 72 hours preceding testing. The main testing session consisted of 3 CMJs, separated by a minimum of 1 minute of rest. To ensure ecological validity, participants wore their standard training attire, including footwear of their choosing.

Anthropometry and Maturity Status

Standing height was measured to the nearest 0.1 cm with the use of an electronic stadiometre (SECA, 360, Voel & Halke, Hamburg, Germany). Body mass was measured to the nearest 0.1 kg using a body composition analyser (SECA, mBCA 515, Voel & Halke, Hamburg, Germany).

To estimate biological maturity, participant's standing height, body mass, chronological age at observation and mid-parent height were used (15). When predicting adult height of males between 4 and 17.5 years, the median error associated with the Khamis-Roche method is 2.2 cm (15). The standing height of participant's biological parents was collected by a member of the research team, or where collection was not possible, self-reported by the parents and subsequently adjusted for overestimation using the equation provided by Epstein et al. (9) (Equation [1]).

Male adult height (inches) = 2.316 + ((0.955 x height [inches]) [1]

Percentage of predicted adult height was calculated by dividing current height by predicted adult height and multiplying by 100 (15). For analysis based upon maturity, participants were split into 3 groups: pre-PHV (<88%); circa-PHV (88-95%); and post-PHV (>95%) (34).

Countermovement Jump

Following the collection of anthropometric measurements, participants completed a 10 minute standardised warm-up to prepare the lower body musculature for jumping (i.e., squats, lunges etc.). The intensity gradually increased over the duration of the warm-up before finishing with submaximal CMJs. Participants then performed 3 maximal CMJs, separated by a minimum of 60 seconds rest between trials, with hands on their hips to limit the influence of the upper body on jump performance. The CMJ depth and stance were self-selected by the participant to avoid any alterations in their preferred jump strategy. The same verbal cues were given before each trial, "jump as high and as fast as possible". Any CMJs that were unintentionally completed with the inclusion of an arm swing or knee flexion during the flight phase were omitted and additional jumps were performed.

All CMJ trials were recorded on a Kistler type 9286AA force plate using Bioware 5.11 software (Kistler Instruments Inc., Amherst, NY, USA), sampling at 1000 Hz. Participants were instructed to stand upright and still for the initial 1 second of data collection to enable the subsequent determination of bodyweight. The raw vertical ground reaction force (vGRF) data for each jump were exported as text files and analysed using a customised Microsoft Excel spreadsheet (version 2212, Microsoft Corp., Redmond, WA, USA).

Data Analysis

Before analysis, the initial 1 second of vGRF data was inspected to ensure that the assumptions of 0 velocity and displacement were satisfied. Bodyweight was then established in this portion of the data before being subtracted from vGRF at every time point to obtain net force. Acceleration was calculated from the vGRF data using Newton's 2nd Law (ΣF = m·a). Centre of mass (COM) velocity was determined by dividing net force by body mass and then integrating the product using the trapezoid rule (46). Instantaneous power was calculated by multiplying vGRF and velocity data at each point and COM displacement was determined by double integration of the vGRF data (8,36).

The initiation of the CMJ was considered to have occurred 30 milliseconds before the instant at which vGRF had decreased by 5*standard deviation (SD) of bodyweight (37). The unweighting phase was calculated as the duration between the onset of movement and when vGRF returned to bodyweight. The time period between the instants of peak negative and 0.00 $m{\cdot}s^{-1}$ COM velocity was defined as the braking phase. The propulsive phase was deemed to have occurred between the moment that COM velocity exceeded 0.01 $m{\cdot}s^{-1}$ and the point of take-off (30,31). Take-off was identified when vGRF fell below a threshold equal to 5*SD of the flight phase residual force. The SD of the flight phase residual force was calculated across the middle 50% of the flight phase duration when the force plate was unloaded (38).

Four "outcome" variables were selected to capture CMJ performance: JH, derived from velocity at take-off (36); RSI_{mod}, calculated as JH divided by time to take-off (TTO); take-off momentum, calculated by multiplying take-off velocity by participants body mass (29), take-off velocity, calculated as the COM velocity at the point of take-off and TTO, representing the time duration from the onset of movement to take-off. Take-off momentum was preferred to propulsion impulse given that it is likely to be more widely understood by sport coaches, practitioners and athletes (29).

Countermovement depth was quantified as the change in displacement between the onset of movement and the end of the braking phase and was included to supplement TTO and explain whether differences in RSI_{mod} scores were influenced by depth or time. The duration of braking and propulsion phases were calculated to provide insight into how long force was applied over each phase of the CMJ, relative to TTO. Braking and propulsion mean, and peak force, velocity and power were defined as the average and maximal values, respectively, attained during braking and propulsion phases of the CMJ. Peak and mean power across the braking and propulsion phase was calculated as the maximal and average values, respectively (8). Braking impulse was calculated as the area under the net force-time curve using the trapezoid rule. Mean braking and propulsion rate of force development (RFD) were calculated as the average vGRF divided by the change in time from the beginning to end of each phase. Peak braking and propulsion RFD were calculated as the maximum vGRF divided by the change in time from beginning to end of each phase. These variables were included to provide an in-depth insight into the mechanics underpinning CMJ performance.

Statistical Analyses

Descriptive statistics (mean ± SD) were computed for all CMJ variables at pre-, circa- and post-PHV. The normality of distribution for each variable was examined using the Shapiro-Wilk test. One-way analysis of variance (ANOVA) with Tukey post-hoc analysis was utilised to determine the differences between the 3 maturity groups for physical characteristics and CMJ variables. An alpha value of $P < 0.05$ was applied to indicate statistical significance. Effect sizes were calculated to interpret the magnitude of between-group effects for all CMJ variables according to Hedge's g statistic, with the following thresholds applied: <0.20, trivial; 0.20-0.59, small; 0.60-1.19, moderate; 1.20-1.69, large and >1.70, very large (11).

Relative reliability was determined via a two-way mixed effects ICC (absolute agreement), along with the upper and lower 95% confidence intervals (CI_{95}). Based on the lower CI_{95} of the ICC estimate, values were interpreted as: <0.5, poor; 0.5 to 0.75, moderate, 0.75 to 0.90, good and >0.9, excellent (16). Absolute reliability of each variable was calculated using CV% and typical error of measurement (TE) with their respective upper and lower CI_{95}. To account for within-participant variability across the 3 maturity groups, the CV% was calculated via the root mean square method (√SD/mean^2*100) (12). The TE was calculated as the SD of the differences between trials divided by the square root of 2 (2). Based on the upper CI_{95}, a CV of ≤10% and ≤5% was considered to represent good and excellent reliability, respectively. Statistical analyses associated with the ICC and ANOVA were performed using the Statistical Package for Social Sciences software (version 28; SPSS Inc., Chicago, IL, USA). The remainder of statistical analyses were completed using Microsoft Excel (Version 2212, Microsoft Corp., Redmond, WA, USA).

RESULTS

Physical Characteristics

All data were normally distributed (P >0.05). Analysis revealed a statistically significant difference between maturity groups for age ($F_{2, 27}$ =58.500, *P* <0.001), height ($F_{2, 27}$ = 21.521, *P* <0.001), body mass ($F_{2, 27}$ = 19.032, *P* <0.001) and percentage of predicted adult height (PAH%) ($F_{2, 27}$ = 135.197, *P* <0.001) (Table 1). Age increased significantly between pre- to circa-, circa- to post- and pre- to post-PHV groups (*P* <0.001). Height increased significantly between pre- to post- and circa- to post-PHV groups (*P* <0.001) but not pre- to circa-PHV groups. Body mass was significantly greater in the circa- vs pre-PHV group (*P* = 0.033), post- vs circa-PHV group (*P* = 0.005) and post- vs pre-PHV group (*P* <0.001). A significant increase in PAH% was noted between pre- to circa-, circa- to post- and pre- to post-PHV groups (*P* < 0.001).

Countermovement Jump

Descriptive statistics for CMJ variables across maturity groups are presented with the respective one-way ANOVA results in Table 2. Statistically significant differences existed between groups for JH ($F_{2, 27}$ = 14.163, *P* <0.001), RSI_{mod} ($F_{2, 27}$ = 18.870, *P* <0.001), take-off momentum ($F_{2, 27}$ = 30.857, *P* <0.001), take-off velocity ($F_{2,27}$ = 14.196, *P* <0.001) and TTO ($F_{2, 27}$ = 7.812, *P* = 0.002). Between group differences were statistically significant for propulsive phase time ($F_{2, 27}$ = 6.413, *P* = 0.005), peak force ($F_{2, 27}$ = 15.986, *P* <0.001), mean force ($F_{2, 27}$ = 20.430, *P* <0.001), peak velocity ($F_{2, 27}$ = 13.806, *P* <0.001), mean velocity ($F_{2, 27}$ = 25.628, *P* <0.001), peak power ($F_{2, 27}$ = 28.883, *P* <0.001), mean power ($F_{2, 27}$ = 32.663, *P* <0.001) and mean RFD ($F_{2, 27}$ = 8.037, *P* = 0.002). Between group differences were also statistically significant for braking phase time ($F_{2, 27}$ = 9.668, *P* <0.001), peak force ($F_{2, 27}$ = 17.702, *P* <0.001), mean force ($F_{2, 27}$ = 20.197, *P* <0.001), mean velocity ($F_{2, 27}$ = 3.419, *P* = 0.047), peak power ($F_{2, 27}$ = 17.587, *P* <0.001), mean power ($F_{2, 27}$ = 23.456, *P* <0.001), impulse ($F_{2, 27}$ = 17.392, *P* <0.001), mean RFD ($F_{2, 27}$ = 6.624, *P* = 0.005) and peak RFD ($F_{2, 27}$ = 6.746, *P* = 0.004).

Outcome Variables

JH was statistically greater in the post-PHV group compared to the pre- (*P* <0.001) and circa-PHV groups (*P* = 0.004). RSI_{mod} was statistically greater in the post-PHV group compared to the pre- (*P* <0.001) and circa-PHV groups (*P* <0.001). Take-off momentum was statistically greater in circa-PHV compared to pre-PHV (*P* = 0.020) and post-PHV compared to circa- (*P* <0.001) and pre-PHV (*P* <0.001). Take-off velocity was statistically greater in the post- vs pre- (*P* <0.001) and circa-groups (*P* = 0.004). TTO was significantly greater in the circa-PHV compared with the pre-PHV group (*P* <0.001).

Propulsion Phase Variables

Propulsion time was statistically greater in circa-PHV group compared to the pre-PHV group (*P* = 0.004). Peak and mean propulsion force were statistically greater in the post-PHV group compared to circa- (*P* <0.001) and pre-PHV groups (*P* <0.001). Peak propulsion velocity was statistically greater in the post-PHV group compared to circa- (*P* = 0.004) and pre-PHV groups (*P*<0.001). Mean propulsion velocity was statistically greater in the post-PHV group compared to circa- (*P* <0.001) and pre-PHV groups (*P* <0.001). Peak and mean propulsion power were statistically greater in the post-PHV group compared to circa- (*P* <0.001) and pre-PHV groups (*P* <0.001). Mean propulsion RFD was statistically greater in the post-PHV group compared to the circa- (*P* = 0.002) and pre-PHV groups (*P* = 0.029).

Braking Phase Variables

Braking time was statistically greater in the post-PHV group compared with the circa- (*P* = 0.006) and pre-PHV groups (*P* <0.001). Peak and mean braking force were statistically greater in the post-PHV group compared to circa- (*P* <0.001) and pre-PHV groups (*P* <0.001). Peak and mean braking power were statistically greater in the post-PHV group compared to circa- (*P* <0.001) and pre-PHV groups (*P* <0.001). Braking impulse was statistically greater in the post-PHV group compared to circa- (*P* <0.001) and pre-PHV groups (*P* <0.001). Peak and mean braking RFD were statistically greater in the post-PHV group compared to the circa-PHV group (*P* = 0.003).

Reliability Analyses

Table 2. Maturity group data for CMJ variables and effect sizes (ES) with 95% confidence intervals (CI_{95}) for between-group differences

Variable	Pre-PHV		Circa-PHV		Post-PHV		Pre- vs Circa-PHV	Circa- vs Post-PHV	Pre- vs Post-PHV
	Mean	SD	Mean	SD	Mean	SD	g (CI_{95})	g (CI_{95})	g (CI_{95})
Outcome									
JH (m)	0.19	0.04	0.22	0.06	0.30	0.05	0.70 (-0.27, 1.67)	1.35* (0.30, 2.40)	2.36** (1.11, 3.62)
RSI_{mod} (ratio)	0.61	0.07	0.54	0.12	0.92	0.21	-0.74 (-1.71, 0.23)	2.12** (0.92, 3.32)	1.84** (0.70, 2.98)
Take-off Momentum (kg·m/s)	78.62	7.71	108.69	31.02	159.46	24.52	1.27* (0.23, 2.31)	1.74** (0.62, 2.86)	4.26** (2.50, 6.02)
Take-off Velocity ($m \cdot s^{-1}$)	1.91	0.20	2.07	0.25	2.42	0.21	0.69 (-0.28, 1.66)	1.47* (0.40, 2.54)	2.41** (1.15, 3.67)
TTO (s)	0.58	0.11	0.74	0.08	0.67	0.08	1.63* (0.53, 2.73)	-0.84 (-1.83, 0.14)	0.88 (-0.11, 1.87)
Propulsion Phase									
Time (s)	0.18	0.03	0.23	0.03	0.20	0.03	1.54* (0.46, 2.62)	-0.74 (-1.72, 0.23)	0.79 (-0.19, 1.77)
Peak Force (N)	1148.83	241.87	1195.84	215.91	1877.51	454.95	0.20 (-0.75, 1.14)	1.83** (0.70, 2.97)	1.92** (0.76, 3.07)
Mean Force (N)	852.21	160.90	975.91	196.66	1452.75	288.26	0.66 (-0.31, 1.63)	1.85** (0.71, 2.99)	2.46** (1.19, 3.74)
Peak Velocity ($m \cdot s^{-1}$)	2.04	0.21	2.19	0.24	2.54	0.20	0.63 (-0.33, 1.60)	1.51* (0.43, 2.59)	2.33** (1.08, 3.57)
Mean Velocity ($m \cdot s^{-1}$)	1.27	0.08	1.27	0.14	1.57	0.09	-0.01 (-0.95, 0.93)	2.43** (1.16, 3.70)	3.29** (1.81, 4.78)
Peak Power (W)	1569.32	166.51	2059.43	588.10	3324.16	691.37	1.09 (0.07, 2.10)	1.89** (0.74, 3.04)	3.34** (1.84, 4.84)
Mean Power (W)	924.25	100.34	1134.64	327.49	1992.35	420.37	0.83 (-0.15, 1.82)	2.18** (0.97, 3.39)	3.35** (1.85, 4.85)
Peak RFD ($N.s^{-1}$)	8787.98	3477.69	6639.85	2032.07	10163.630	7412.94	-0.72 (-1.70, 0.25)	0.62 (-0.34, 1.59)	0.23 (-0.72, 1.17)
Mean RFD ($N.s^{-1}$)	5668.716	2280.09	4397.242	1060.55	8616.19	3340.76	-0.68 (-1.65, 0.28)	1.63* (0.53, 2.73)	0.99* (-0.01, 1.99)
Braking Phase									
Time (s)	0.12	0.04	0.17	0.03	0.13	0.02	1.59* (0.49, 2.68)	-1.73 (-2.85, -0.61)	0.30* (-0.65, 1.24)
Countermovement Depth (m)	0.17	0.05	0.23	0.06	0.22	0.05	0.92 (-0.08, 1.91)	-0.05 (-0.99, 0.89)	0.93 (-0.06, 1.93)
Peak Force (N)	998.65	243.60	1049.66	250.05	1706.33	376.98	0.20 (-0.74, 1.14)	1.97** (0.80, 3.13)	2.14** (0.93, 3.34)
Mean Force (N)	703.85	122.75	788.78	183.56	1176.40	213.31	0.52 (-0.44, 1.48)	1.87** (0.72, 3.01)	2.60** (1.29, 3.91)
Peak Velocity ($m \cdot s^{-1}$)	0.90	0.22	0.88	0.17	1.02	0.12	-0.12 (-1.06, 0.82)	0.91 (-0.08, 1.91)	0.62 (-0.34, 1.59)
Mean Velocity ($m \cdot s^{-1}$)	0.57	0.12	0.57	0.11	0.67	0.08	-0.01 (-0.95, 0.93)	1.05 (0.04, 2.06)	1.00 (-0.01, 2.00)
Peak Power (W)	481.24	108.49	571.26	219.98	918.46	175.39	0.50 (-0.46, 1.45)	1.67** (0.56, 2.78)	2.87** (1.50, 4.25)
Mean Power (W)	339.73	64.54	429.43	152.36	695.16	127.08	0.73 (-0.24, 1.71)	1.81** (0.68, 2.95)	3.38** (1.87, 4.89)
Impulse (N.s)	35.48	5.83	47.50	16.27	66.98	11.71	0.94 (-0.05, 1.94)	1.32* (0.27, 2.36)	3.26** (1.78, 4.74)
Peak RFD ($N.s^{-1}$)	10956.760	3836.58	7941.237	1699.11	16071.32	7583.44	-0.97 (-1.97, 0.03)	1.42* (0.35, 2.48)	0.82 (-0.17, 1.80)
Mean RFD ($N.s^{-1}$)	5976.87	3886.74	3194.89	1214.82	8847.12	4426.60	-0.93 (-1.92, 0.07)	1.67* (0.56, 2.77)	0.66 (-0.31, 1.63)

*Note: JH, jump height; RSI_{mod}, reactive strength index modified; TTO, time to take-off; RFD, rate of force development.*Significant between-group differences (P <0.05); **significant between-group differences (P <0.001).*

The ICC, CV% and TE results for pre-, circa- and post-PHV groups are presented in Tables 3, 4 and 5, alongside their corresponding CI_{95}, respectively. JH, take-off momentum, take-off velocity, peak and mean propulsion force, peak and mean braking force, peak propulsion velocity and peak and mean power demonstrated good to excellent reliability across all maturity groups (ICC = 0.914-0.998 [CI_{95} = 0.753-0.999]; CV% = 1.82-6.76 [CI_{95} = 0.74-8.75]). The CMJ variables were found to be the most reliable in the post-PHV group (ICC = 0.851-0.988 [CI_{95} = 0.582-0.997]; CV% = 2.16-14.12 [CI_{95} = 0.41-21.12]), followed by the circa- (ICC = 0.570-0.998 [CI_{95} = -0.211-0.999]; CV% = 1.82-20.05 [CI_{95} = 0.74-24.80]) and pre-PHV groups (ICC = 0.627-0.984 [CI_{95} = 0.015-0.996]; CV% = 3.25-21.55 [CI_{95} = 1.25-27.03]). Peak and mean RFD showed poor absolute reliability across all maturity groups (CV% = 8.64 [CI_{95} = 6.63-14.11] to 21.55 [CI_{95} = 13.32-27.03]).

Table 3. Reliability statistics for pre-PHV maturity group

Variable	ICC (CI_{95})	CV% (CI_{95})	TE (CI_{95})
Outcome			
JH (m)	0.965 (0.900, 0.990)	6.76 (2.12, 8.75)	0.01 (0.01, 0.02)
RSI_{mod} (ratio)	0.627 (0.015, 0.895)	8.91 (2.43, 11.34)	0.06 (0.04, 0.11)
Take-off Momentum (kg·m/s)	0.957 (0.878, 0.988)	3.48 (1.08, 4.50)	3.02 (2.08, 5.51)
Take-off Velocity (m·s^{-1})	0.962 (0.891, 0.990)	3.43 (1.07, 4.43)	0.07 (0.05, 0.13)
TTO (s)	0.887 (0.675, 0.969)	7.87 (3.76, 9.77)	0.06 (0.04, 0.11)
Propulsion Phase			
Time (s)	0.894 (0.699, 0.971)	8.05 (5.33, 10.65)	0.02 (0.01, 0.04)
Peak Force (N)	0.973 (0.917, 0.993)	5.49 (3.10, 7.29)	69.68 (47.93, 127.21)
Mean Force (N)	0.984 (0.955, 0.996)	3.72 (2.07, 4.75)	35.56 (24.46, 64.92)
Peak Velocity (m·s^{-1})	0.965 (0.900, 0.990)	3.25 (1.25, 4.64)	0.07 (0.05, 0.13)
Mean Velocity (m·s^{-1})	0.850 (0.572, 0.959)	3.99 (1.47, 5.53)	0.06 (0.04, 0.10)
Peak Power (W)	0.921 (0.778, 0.979)	4.66 (1.54, 6.29)	84.69 (58.25, 154.61)
Mean Power (W)	0.915 (0.755, 0.977)	5.16 (3.33, 5.92)	54.60 (37.55, 99.68)
Peak RFD (N.s^{-1})	0.923 (0.773, 0.979)	19.38 (10.50, 24.92)	1651.44 (1135.92, 3014.88)
Mean RFD (N.s^{-1})	0.959 (0.831, 0.990)	13.34 (10.21, 15.97)	780.64 (536.95, 1425.15)
Braking Phase			
Time (s)	0.910 (0.737, 0.976)	11.41 (5.19, 15.63)	0.02 (0.01, 0.04)
Countermovement Depth (m)	0.950 (0.858, 0.986)	9.50 (6.33, 12.49)	0.02 (0.01, 0.03)
Peak Force (N)	0.969 (0.886, 0.992)	6.53 (4.88, 6.90)	73.05 (50.25, 133.37)
Mean Force (N)	0.975 (0.914, 0.994)	3.96 (1.71, 5.02)	32.65 (22.46, 59.60)
Peak Velocity (m·s^{-1})	0.941 (0.831, 0.984)	6.74 (4.00, 8.86)	0.08 (0.05, 0.14)
Mean Velocity (m·s^{-1})	0.951 (0.859, 0.987)	5.56 (3.60, 6.77)	0.04 (0.03, 0.07)
Peak Power (W)	0.861 (0.609, 0.962)	9.96 (3.07, 13.59)	56.25 (38.69, 102.69)
Mean Power (W)	0.888 (0.685, 0.969)	8.22 (2.53, 10.87)	32.75 (22.53, 59.79)
Impulse (N.s)	0.865 (0.622, 0.963)	7.60 (3.48, 10.49)	3.17 (2.18, 5.79)
Peak RFD (N.s^{-1})	0.959 (0.878, 0.989)	11.58 (7.38, 14.70)	1363.00 (937.52, 2488.31)
Mean RFD (N.s^{-1})	0.969 (0.888, 0.992)	21.55 (13.32, 27.03)	1160.82 (798.45, 2119.21)

Note: JH, jump height; RSI_{mod}, reactive strength index modified; TTO, time to take-off; RFD, rate of force development.

Table 4. Reliability statistics for circa-PHV maturity group

Variable	ICC (CI_{95})	CV% (CI_{95})	TE (CI_{95})
	Outcome		
JH (m)	0.988 (0.965, 0.997)	4.79 (2.63, 6.49)	0.01 (0.01, 0.02)
RSI_{mod} (ratio)	0.960 (0.884, 0.989)	7.80 (3.63, 9.00)	0.04 (0.03, 0.08)
Take-off Momentum (kg·m/s)	0.998 (0.994, 0.999)	2.15 (1.00, 2.97)	2.44 (1.68, 4.46)
Take-off Velocity ($m·s^{-1}$)	0.986 (0.961, 0.996)	2.32 (1.19, 3.18)	0.05 (0.04, 0.10)
TTO (s)	0.570 (-0.211, 0.882)	8.61 (7.33, 14.72)	0.09 (0.06, 0.16)
	Propulsion Phase		
Time (s)	0.939 (0.822, 0.983)	5.24 (4.18, 6.20)	0.02 (0.01, 0.03)
Peak Force (N)	0.993 (0.978, 0.998)	2.26 (0.93, 2.78)	32.33 (22.24, 59.03)
Mean Force (N)	0.994 (0.981, 0.998)	2.44 (1.73, 2.88)	27.52 (18.93, 50.24)
Peak Velocity ($m·s^{-1}$)	0.990 (0.971, 0.997)	1.82 (0.74, 2.56)	0.04 (0.03, 0.08)
Mean Velocity ($m·s^{-1}$)	0.985 (0.956, 0.996)	2.30 (0.68, 3.36)	0.03 (0.02, 0.06)
Peak Power (W)	0.997 (0.992, 0.999)	2.66 (1.24, 3.50)	54.78 (37.68, 100.01)
Mean Power (W)	0.995 (0.985, 0.999)	3.30 (1.71, 4.17)	40.78 (28.05, 74.45)
Peak RFD ($N.s^{-1}$)	0.919 (0.769, 0.978)	12.73 (3.30, 16.65)	917.85 (631.33, 1675.63)
Mean RFD ($N.s^{-1}$)	0.912 (0.750, 0.976)	9.68 (4.86, 11.91)	508.69 (349.90, 928.67)
	Braking Phase		
Time (s)	0.785 (0.402, 0.941)	10.61 (1.76, 12.18)	0.02 (0.02, 0.04)
Countermovement Depth (m)	0.965 (0.899, 0.991)	6.56 (3.11, 8.91)	0.02 (0.01, 0.03)
Peak Force (N)	0.965 (0.888, 0.991)	6.24 (2.72, 7.79)	77.24 (53.13, 141.01)
Mean Force (N)	0.972 (0.917, 0.992)	5.29 (2.81, 6.24)	50.73 (34.89, 92.61)
Peak Velocity ($m·s^{-1}$)	0.890 (0.687, 0.970)	10.48 (7.55, 13.32)	0.10 (0.07, 0.18)
Mean Velocity ($m·s^{-1}$)	0.914 (0.753, 0.977)	9.27 (6.90, 11.44)	0.06 (0.04, 0.10)
Peak Power (W)	0.930 (0.796, 0.981)	13.04 (8.53, 16.92)	86.77 (59.68, 158.41)
Mean Power (W)	0.941 (0.818, 0.984)	12.71 (9.29, 15.19)	59.77 (41.11, 109.11)
Impulse (N.s)	0.965 (0.888, 0.991)	9.67 (6.98, 12.23)	5.05 (3.47, 9.22)
Peak RFD ($N.s^{-1}$)	0.860 (0.605, 0.962)	10.89 (5.51, 14.82)	968.29 (666.02, 1767.72)
Mean RFD ($N.s^{-1}$)	0.832 (0.533, 0.954)	20.05 (7.13, 24.80)	738.48 (507.95, 1348.18)

Note: JH, jump height; RSI_{mod}, reactive strength index modified; TTO, time to take-off; RFD, rate of force development.

Table 5. Reliability statistics for post-PHV maturity group

Variable	ICC (CI_{95})	CV% (CI_{95})	TE (CI_{95})
	Outcome		
JH (m)	0.972 (0.908, 0.993)	5.22 (2.22,5.67)	0.02 (0.01, 0.03)
RSI_{mod} (ratio)	0.950 (0.847, 0.986)	6.95 (1.20,8.71)	0.08 (0.05, 0.14)
Take-off Momentum (kg·m/s)	0.988 (0.960, 0.997)	2.59 (1.24,2.93)	4.69 (3.22, 8.56)
Take-off Velocity ($m \cdot s^{-1}$)	0.967 (0.896, 0.991)	2.59 (1.11, 2.85)	0.07 (0.05, 0.13)
TTO (s)	0.851 (0.582, 0.959)	6.51 (1.73,9.14)	0.06 (0.04, 0.11)
	Propulsion Phase		
Time (s)	0.960 (0.883, 0.989)	4.43 (0.58,6.16)	0.01 (0.01, 0.02)
Peak Force (N)	0.990 (0.971, 0.997)	3.65 (1.82,5.34)	78.36 (52.93, 150.12)
Mean Force (N)	0.991 (0.976, 0.998)	2.54 (0.61,3.68)	46.05 (31.11, 88.23)
Peak Velocity ($m \cdot s^{-1}$)	0.967 (0.898, 0.991)	2.18 (0.83,2.56)	0.06 (0.04, 0.12)
Mean Velocity ($m \cdot s^{-1}$)	0.938 (0.771, 0.984)	2.17 (0.89,2.76)	0.04 (0.03, 0.08)
Peak Power (W)	0.986 (0.960, 0.996)	3.13 (1.09,4.44)	137.25 (92.70, 262.93)
Mean Power (W)	0.982 (0.944, 0.995)	3.98 (0.51,5.15)	96.49 (65.17, 184.85)
Peak RFD ($N.s^{-1}$)	0.980 (0.944, 0.995)	11.75 (6.79,14.07)	1691.29 (1142.40, 3240.13)
Mean RFD ($N.s^{-1}$)	0.981 (0.946, 0.995)	8.64 (6.63,14.11)	797.88 (538.93, 1528.56)
	Braking Phase		
Time (s)	0.909 (0.734, 0.976)	6.70 (2.75,9.14)	0.01 (0.01, 0.02)
Countermovement Depth (m)	0.940 (0.827, 0.984)	9.57 (8.61,16.54)	0.02 (0.01, 0.04)
Peak Force (N)	0.977 (0.931, 0.994)	5.38 (4.94,9.35)	96.68 (66.50, 176.51)
Mean Force (N)	0.970 (0.892, 0.992)	4.44 (1.62,6.21)	60.92 (41.90, 111.21)
Peak Velocity ($m \cdot s^{-1}$)	0.921 (0.738, 0.979)	5.71 (2.99,7.46)	0.06 (0.04, 0.12)
Mean Velocity ($m \cdot s^{-1}$)	0.937 (0.782, 0.984)	4.84 (2.59,7.47)	0.04 (0.02, 0.06)
Peak Power (W)	0.905 (0.705, 0.975)	9.61 (5.02,12.54)	95.19 (65.47, 173.78)
Mean Power (W)	0.925 (0.737, 0.981)	8.43 (2.25,11.90)	61.31 (42.17, 111.93)
Impulse (N.s)	0.955 (0.842, 0.988)	5.74 (3.10,7.53)	4.30 (2.96, 7.85)
Peak RFD ($N.s^{-1}$)	0.955 (0.871, 0.988)	14.12 (7.43,21.12)	2442.74 (1680.21, 4459.50)
Mean RFD ($N.s^{-1}$)	0.970 (0.904, 0.992)	13.51 (9.91,22.07)	1225.00 (842.60, 2236.38)

Note: JH, jump height; RSI_{mod}, reactive strength index modified; TTO, time to take-off; RFD, rate of force development.

DISCUSSION

The results demonstrate that for most of the CMJ variables, statistically significant differences were observed between pre- to post-PHV and circa- to post-PHV groups but not between pre- and circa-PHV groups (Table 2), supporting our first hypothesis. Relative and absolute reliability of CMJ variables improved with maturity as the post-PHV group demonstrated superior reliability scores compared to circa- and pre-PHV groups; therefore, our second hypothesis is rejected. Despite the maturity-related gradient for reliability scores, there were several CMJ variables that were found to be reliable across all three maturity groups (Tables 3-5). Together, these results suggest that the biggest differences in CMJ performance are observed between pre-/circa- to post-PHV groups, and careful consideration is necessary before selecting and monitoring CMJ variables in youth athletes at pre- and circa-PHV given their lower reliability scores.

In agreement with previous findings in youth athletes, the current investigation found JH to be reliable in pre-, circa- and post-PHV maturity groups (ICC = 0.965-0.988; CV% = 4.79-6.76) (23,34,35,44). RSI_{mod} and take-off momentum were also included as CMJ outcome variables; however, only the latter demonstrated acceptable reliability within all maturity groups as RSI_{mod} did not meet the absolute reliability criteria (upper CI_{95} ≤10%) in the pre-PHV group. Given that RSI_{mod} was quantified as the ratio of JH to TTO, and both braking and propulsive phase time did not meet reliability criteria for CV% and/or ICC scores (lower CI_{95} ≥0.70) in the pre-PHV group, it is likely that this finding is as a result of the greater variability in movement time at this stage of maturity. This is further reinforced by the fact that RSI_{mod} has consistently demonstrated good-excellent reliability in adult populations (10,28,36) and indicates that variability in kinematic measures of CMJ performance may be greater in younger children and adolescents.

Take-off momentum has recently been proposed as an important factor in CMJ testing and monitoring, particularly in collision sports such as rugby league because it includes body mass in its calculation (body mass x take-off velocity) (29). The current study found take-off momentum to demonstrate excellent absolute and good-excellent relative reliability across maturity groups (ICC = 0.957-0.998; CV% = 2.15-3.48). Ultimately, including this variable in CMJ assessments enables practitioners to interpret changes in JH alongside an increase or decrease in body mass (29). In the current study, JH was significantly different between pre- to post-PHV and circa- to post-PHV groups; however, there were no significant differences between pre- and circa-PHV groups (Table 2). Interestingly, there were significant differences for take-off momentum between all maturity groups, suggesting it may be a more appropriate measure of CMJ performance in youth athletes as they experience growth and maturation. More specifically, reporting JH alone may be biased towards lighter athletes and those that do not experience a significant increase in body mass at or around the time of PHV, whereas take-off momentum recognises both body mass and take-off velocity and may therefore be more sensitive to the changes in physical characteristics that occur as children experience growth and maturation (4,19,25). This, of course, needs to be verified by future research that explores both the intra and intersession reliability of take-off momentum in youth athletes at different stages of maturity.

Kinetic variables are routinely included in research and practice as they provide an in-depth insight into the mechanics underpinning CMJ execution (3,17). Peak and mean force for the braking and propulsion phase and power for the propulsion phase demonstrated good-excellent relative and absolute reliability in pre-, circa- and post-PHV groups (ICC = 0.965-0.994; CV% = 2.26-6.53). This is not surprising given that these variables are obtained directly from the force-time curve and therefore require far less computational steps than other CMJ data (i.e., kinematic variables) (51). Statistically significant differences were also noted for the aforementioned variables between pre- to post-PHV and circa- to post-PHV, validating previous findings that natural developments in muscle mass and strength as a result of puberty likely contribute to an increase force producing capabilities (41,50). Importantly, this confirms that these variables can be used by practitioners when testing and monitoring CMJ performance in youth athletes at pre-, circa- and post-PHV.

Braking impulse only reached acceptable absolute reliability in the post-PHV group (CV% = 5.74) while RFD-related variables failed to reach an acceptable level of absolute reliability in most of the groups, despite good-excellent relative reliability in all but mean and peak braking RFD at circa-PHV (ICC = 0.832-0.970). These findings may be best explained by the fact that both of these variables include time in their calculation. For example, participants were instructed to self-select their countermovement depth which likely led to a greater variation in braking and propulsive phase time between jumps. Controlling countermovement depth would perhaps facilitate a greater reliability score; however, it would also reduce the ecological validity of the findings, making them less applicable in practice. Although RFD-related variables are considered important when bearing in mind the limited time available to exert force during sporting actions (24), the current study reiterates the need to exercise caution when considering their use in assessing lower-body neuromuscular performance, given the poor absolute reliability scores observed (CV% = 10.89-21.55).

Overall, the results of this study agree with those recently reported (44). Ruf et al. (44) observed the greatest reliability of CMJ variables in post-PHV youth soccer players followed by the circa- and pre-PHV cohorts. Their analysis also revealed greater variability in the braking phase variables, which is consistent with the findings of this study and existing literature (34). Together, this suggests that the braking phase of a CMJ is more variable than the propulsive phase, reflecting the need for greater motor control (13,14). In support of our findings, Jensen et al. (14) observed the degrees of freedom during the propulsive phase to be much less than that of the braking phase. In fact, the movement of the joints and lower limb velocity during downward movement appeared to vary substantially more (14) and is thought to reflect the journey from a more variable to a more stable CMJ pattern as children realise full maturity (42,43). Interestingly, Meylan et al. (34) found little variation in braking phase variables between the ages of 11- and 16-years. However, it was mentioned that the participants in this study were nominated as “outstanding athletes” who were familiar with the CMJ, which may explain why the younger participants displayed less variability than those in the current study. The participants in this study are trained in soccer specific drills, however, do not undertake S&C or plyometric training on a regular basis. Therefore, it is likely that younger, less mature participants who are not very experienced with S&C or plyometric training would benefit from extra emphasis placed on the braking phase of CMJs during familiarisation. Given that verbal instruction has been recommended to improve CMJ braking force generation (18) and is shown to positively influence motor skill learning and performance in adults (53), further investigation is warranted to understand the optimal braking phase instructions for children and adolescents.

In agreement with previous findings (22,39,40), JH did not improve significantly between pre- and circa-PHV, which may confirm a period of “adolescent awkwardness”. Further analysis of the CMJ variables between the pre- and circa-PHV groups reveals a significant increase in TTO and braking and propulsion phase time (Table 2). Additionally, there was a moderate increase in countermovement depth (g = 0.92) and non-significant trivial to moderate changes in peak and mean force, velocity and power in propulsion and braking phases (g = -0.12-0.94). Given that body mass increased significantly between pre- and circa-PHV groups (Table 1), these changes in CMJ variables suggest that participants altered their jump strategy to maximise JH by means of a greater TTO and countermovement depth. Even though a plateau in CMJ performance was observed around the time of PHV, the majority of variables improved significantly between circa- and post-PHV. The only variables to not display significant changes between any of the maturity groups were peak and mean braking velocity. To contextualise this finding, previous studies have noted the importance of a rapid TTO, characterised by a greater braking velocity, towards underpinning a greater JH and RSI_{mod} (7,17,27). With this in mind, future research should look to investigate the relationship between braking velocity and different CMJ outcome measures (i.e., JH, RSI_{mod} and take-off momentum) as children experience growth and maturation.

Some limitations exist in the current study that warrant discussion. Firstly, the participants were assessing during their pre-season period and therefore, the findings may only be representative of these athletes at the specific time of testing. Secondly, this study examined a relatively homogenous group of trained youth soccer players which may have contributed to the reliability scores observed. Finally, it is important to emphasise that any reliability analysis simply establishes the “noise” of a variable within a specific environment. Based on this reliability data, it is not possible to confirm the most efficacious variables in monitoring CMJ performance or detecting neuromuscular fatigue. Rather, this study provides data to highlight the reliability of CMJ variables in youth athletes at different stages of maturity and now it is ultimately up to the practitioner to establish variables that are appropriate for use in their own practice.

CONCLUSION

The results of this investigation suggest that there is a maturity-related gradient for CMJ variables, whereby superior reliability is observed in post-PHV followed by circa- and pre-PHV groups. Despite this, several kinetic variables were found to have good-excellent reliability within all maturity groups (i.e., force, power and impulse) whilst some of the kinematic variables should be used with caution, particularly in the pre- and circa-PHV groups (i.e., time). The greater variability observed in the pre- and circa-PHV groups may be improved via the use of effective coaching cues and instructions, though this requires future investigation. The findings of this study help to guide practitioners in their own CMJ testing and monitoring process, thereby facilitating more accurate decisions in regard to training interventions and fatigue status in youth athletes with reference to their maturity status. Given that the CMJ is reflective of a slow stretch-shortening cycle exercise, future research is recommended to explore the developmental trends and reliability of a fast stretch-shortening cycle exercise (i.e., repeated CMJ) in youth athletes at different stages of maturation.

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