Title :

The influence of biological maturity on dynamic force-time variables and vaulting performance in young female gymnasts

Authors:

Sylvia Moeskops[1]
Jon L. Oliver[1,2]
Paul J. Read[4,10]
John B. Cronin[2]
Gregory D. Myer[5,6,7,8]
G. Gregory Haff[8,9]
Rhodri S. Lloyd[1,2,3]

Affiliations:

[1] Youth Physical Development Unit, Cardiff School of Sport, Cardiff Metropolitan University, Cardiff, UK

[2] Sports Performance Research Institute New Zealand (SPRINZ), AUT University, Auckland, NZ

[3] Centre for Sport Science and Human Performance, Waikato Institute of Technology, Hamilton, NZ

[4] Athlete Health and Performance Research Centre, Aspetar Orthopaedic and Sports Medicine Hospital, Doha, Qatar

[5] Division of Sports Medicine, Cincinnati Children's Hospital, Cincinnati, Ohio, USA

[6] Department of Pediatrics and Orthopaedic Surgery, College of Medicine, University of Cincinnati, Cincinnati, Ohio, USA

[7] The Micheli Center for Sports Injury Prevention, Boston, MA, USA

[8] Centre for Exercise and Sports Science, Edith Cowan University, Joondalup, Western Australia

[9] Australian Centre for Research into Injury in Sport and its Prevention (ACRISP), Edith Cowan University, Joondalup, Western Australia

[10] School of Sport and Exercise, University of Gloucestershire, Gloucester, United Kingdom.

Corresponding Author:
Sylvia Moeskops
Cardiff School of Sport, Cardiff Metropolitan University
Cyncoed Campus, Cyncoed Road
Cardiff, UK
Tel: +44(0)2920 416566
Email: smoeskops@cardiffmet.ac.uk

Title :

The influence of biological maturity on dynamic force-time variables and vaulting performance in young female gymnasts

INTRODUCTION

Jumping and rebounding are important prerequisites that underpin the high impact loading gymnastics skills (e.g. acrobatic series, tumbling etc.) (Suchomel et al. 2016). Further, three of the four artistic disciplines that female gymnasts compete in (vault, beam and floor exercise) are heavily reliant on explosive lower-limb rebounding and jumping activities, which all utilize various expressions of the stretch-shortening cycle (SSC) (Moeskops et al. 2019). Consequently, rebounding and jumping performance of artistic gymnasts are commonly assessed to identify key determinants of the sport (Dallas G et al. 2013; Marina et al. 2013; Marina M. and F.A. 2013; Suchomel et al. 2016), determine physical profiles (Pion et al. 2015; Vandorpe et al. 2012) and evaluate the efficacy of training interventions (Colclough et al. 2018; Hall et al. 2016; Marina and Jemni 2014; Moeskops et al. 2018b).

The mechanisms that underlie slow-SSC (ground contact time >250) and fast-SSC (ground contact time <250 ms) may differ depending on the force-time characteristics of the movement (Lloyd et al. 2011c) as well as the athlete’s ability to perform efficient SSC mechanics (Turner and Jeffreys 2010). For example, research indicates that the distribution and release of stored elastic energy is influenced by numerous factors including: the magnitude and rate of loading during the eccentric phase, stiffness and compliance of the muscle-tendon complex, and levels of pre-activation (Blazevich 2011; Turner and Jeffreys 2010). Researchers have emphasized the importance of measuring different expressions of SSC function in gymnasts as gymnastics skills involve both slow- and fast-SSC (Moeskops et al. 2018b; Suchomel et al. 2016). Protocols that examine fast-SSC function include drop jumps, repeated-hopping tasks and sprinting (Lloyd et al. 2009; Pedley et al. 2017), whereas slow-SSC tests typically involve countermovement jumps (CMJ) and standing long jumps (Lloyd et al. 2011c). Further, concentric only jumps which do not involve SSC function are frequently used as part of jumping test batteries (i.e. squat jump (SJ)) (Bradshaw and Le Rossignol 2004; Lloyd et al. 2015a; Suchomel et al. 2016). Comparisons of jump height or flight time between CMJ and SJ tests enables researchers to evaluate how effective gymnasts are at utilizing the contribution of the elastic energy during the braking phase (Bradshaw and Le Rossignol 2004; Marina et al. 2013; Suchomel et al. 2016). However, despite the sport having high levels of early specialization, kinetic data in young female gymnasts is limited.

Previous age-related data comparing the jumping ability of female gymnasts aged 9-12 and 13-16 years has shown that jump height, maximal vertical force, as well as maximal and mean power all significantly increase with age (Polishchuk and Mosakowska 2007). Further, previous data has shown an increased age, a faster vault run-up speed and a shorter ground contact time during the handstand push off test, were important predictors of tumbling ability in female gymnasts aged 8-14 years old (Bradshaw and Le Rossignol 2004). Therefore, it appears that jumping performance in gymnasts increases naturally with age; however, assessing physical performance by chronological age as opposed to biological maturity does not account for large inter-individual variation in maturity status within a given age group (Faigenbaum et al. 2020). Research shows maturation influences the development of physical qualities and motor skills in youth, particularly following the pubertal growth spurt (Malina et al. 2004). For example, significant differences in absolute isometric peak force (Moeskops et al. 2018a), vertical jump height (Lloyd et al. 2015a) and sprint speed (Meyers et al. 2017) have been reported between pre- and post-pubertal young athletes. As the timing and tempo of biological maturation differs between individuals of them same chronological age (Malina et al. 2004), analyzing testing data in young athletes according to maturity status has been recommended (Lloyd et al. 2014).

Existing gymnastics literature has often examined jump performance using field-based equipment such as contact mats (Marina et al. 2013; Marina and Torrado 2013; Polishchuk and Mosakowska 2007), or methods which solely report performance outcomes such as jump height (Sleeper et al. 2012; Vandorpe et al. 2012). While these protocols provide surrogate measures of muscular power and SSC function in applied settings, superior insight can be gained from analyzing force-time data (Morin et al. 2019). Specifically, this enables the identification of the mechanical variables that underpin jumping and rebounding performance, and ensures training prescription is more targeted to individual deficits. While some mechanistic (Bradshaw and Le Rossignol 2004; Moeskops et al. (in press)) and age-related jumping and rebounding data in young female gymnasts exists (Bradshaw and Le Rossignol 2004; Polishchuk and Mosakowska 2007), researchers have yet to examine such data in gymnasts grouped by different maturity status. Furthermore, the contribution of maturity and jumping force-time variables to vertical take-off velocity during vaulting performance is yet to be explored. Therefore, the first aim of this study was to examine the influence of maturity status on force-time variables from CMJ, SJ and drop jump (DJ) tests in young female gymnasts. The second aim of this study was to determine how these variables influence take-off velocity during vaulting performance.

METHODS

Participants

One hundred and twenty female artistic gymnasts aged 5–14 years agreed to participate in the study. All participants had >1 years of gymnastics experience and were participating in gymnastics training 2–6 times per week, totaling 2–24 training hours per week. Participants were grouped according to biological maturity using percentage of predicted adult height (%PAH) (Khamis and Roche 1994): <75%PAH, early pre-pubertal ($\text{early}_{\text{pre}}$; n = 54); 76%–

85%PAH, late pre-pubertal (late$_{pre}$; n = 47); and 86%–95%PAH, pubertal (n = 19). The groups were also matched by gymnastics-specific training hours per week (~11 h/w). Descriptive data for participants grouped by maturity status are shown in *table 1*. Participants reported no injuries at the time of testing and were instructed to refrain from strenuous activity 24 hours before testing. Written informed parental consent and participant assent were obtained after ethical approval was granted by the local University Research Ethics Committee.

Insert table 1 near here

Study Design

This study used a cross-sectional design to examine jumping characteristics and vaulting performance in young artistic female gymnasts. All participants attended one testing session whereby anthropometric, SJ, CMJ, DJ and vaulting performance data were collected. Before testing commenced, participants performed a standardized 10-minute dynamic warm-up led by the principal researcher, which included relevant activation and mobilization exercises, before advancing to one set of three SJ, CMJ and pogo hops. Familiarization of each testing protocol took place at the beginning of the testing session, which involved a demonstration and provision of standardized, child-friendly coaching cues. Participants then practiced the protocol until the principal investigator was satisfied with their technical competency.

Anthropometrics

Anthropometric data were collected, including standing and sitting height using a stadiometer to the nearest 0.1 cm (SECA, 321, Vogel & Halke, Hamburg, Germany) and body mass using scales to the nearest 0.1 kg (SECA, 321, Vogel & Halke, Hamburg, Germany). Standing height (m), body mass (kg), chronological age and parental height were used to determine participants' biological maturity status, using %PAH (Khamis and Roche 1994).

Jumping protocols

All jumping data were collected in a laboratory using two force plates sampling at a frequency of 1000 Hz (PASCO, 2 Axis force platforms, Roseville, CA 95747, USA). Participants were instructed to "*stay as still as a statue*" to optimize the stabilization of body weight during the first second of each test, before being given a countdown of "*3, 2, 1 go.*" Gymnasts were instructed to keep their hands on their hips throughout and keep their legs extended during the flight phase of the jump. Three trials of each jumping protocol were completed with a minimum of 60 seconds passive rest between trials, to enable sufficient recovery (Suchomel et al. 2016). All jumping data were filtered (MATLAB, R2018a or Labview LVRTE2014SP1; National Instruments) using a low-pass 4th order recursive Butterworth filter. Based on residual analysis (Winter 2009), the most appropriate cut-off frequency was found to be 13 Hz. For the SJ and CMJ, the best trial selected for further analysis was determined by the highest jump. For the DJ, the best trial was determined by the highest spring-like behavior correlation (i.e. a perfect inverse relationship is indicated by $r = -1.0$), which represents spring-mass model behavior (Pedley et al. 2017). All relative measures were calculated using body mass. Further information (abbreviations, units and descriptions) on the variables calculated from the SJ, CMJ and DJ tests can be found in *supplementary tables 1-3*.

Squat jump

The SJ protocol required each participant to start in a semi-squat position with approximately 90° of knee flexion (determined subjectively by the rater) (Lloyd et al. 2015b; Suchomel et al. 2016). Gymnasts were instructed to keep their hands on their hips and jump for maximum height after a countdown of "*3, 2, 1 jump*." Trials were discounted and repeated if the following occurred: a visible countermovement was present (either with the chest or lower limbs), hands did not remain on hips throughout the test, or if the lower limbs flexed during the flight phase. All SJ trials were analyzed by the same researcher using custom built analysis software (Labview, LVRTE2014SP1; National Instruments). Body weight was calculated by averaging the first second of force during the motionless period at the start of the jump when the participant was in the semi-squat position. Body weight plus 5 standard deviations (*sd*) was then used to identify the initiation of the jump (Dos'Santos et al. 2017). Variables calculated included: jump height (JH), peak velocity (V_{peak}), relative vertical impulse ($Impulse_{rel}$), absolute peak force (PF_{abs}), relative peak force (PF_{rel}), absolute peak power (PP_{abs}), relative peak power (PP_{rel}), absolute rate of force development (RFD_{abs}) and relative rate of force development (RFD_{rel}). Using the highest RFD during a 20 ms time sampling window, absolute peak rate of force development ($pRFD_{abs}$) and relative peak rate of force development ($pRFD_{rel}$) were also calculated.

Countermovement jump

The CMJ protocol required each participant to squat to a self-selected knee, hip and ankle flexion angle and immediately jump for maximum height (Suchomel et al. 2016). Trials were discounted and repeated if the gymnast's hands did not remain on their hips or, if their lower limbs flexed during the flight phase. All CMJ variables were calculated using a spreadsheet run through Microsoft Excel for Mac version 16.9 (Chavda et al. 2018). To identify the initiation of the jump, the first force value less than 5 SD of body weight was used to increase the accuracy of the correct start point (Chavda et al. 2018). Furthermore, to optimize the accuracy of the velocity calculations (and in-turn the displacement and power calculations), the point of integration was identified as -30 ms from the initiation of the gymnasts' jump, increasing the likelihood of the velocity being zero (Chavda et al. 2018; Owens et al. 2014). To account for participant- or force plate-related noise, 5 SD of 300 ms flight force was used to identify the take-off and landing threshold (Chavda et al. 2018). Variables calculated included: jump height (JH), absolute peak force (PF_{abs}), relative peak force $_{(}PF_{rel}$), braking average impulse ($Impulse_{Brake}$), propulsive average impulse ($Impulse_{Prop}$), duration of braking phase ($Time_{brake}$), duration of propulsive phase ($Time_{prop}$), absolute peak power (PP_{abs}), relative peak power (PP_{rel}), braking average power ($Power_{brake}$) and propulsive average power ($Power_{prop}$). It should be noted that braking phase starts at the end of the unweighting phase (when impulse drops below the bodyweight baseline) and ends when the athlete's velocity reaches zero or, when the impulse above baseline is equal to the impulse created during the unweighting phase (Chavda et al. 2018). Further, the propulsive phase occurs immediately after the braking phase and ends at the point of take-off and the athlete's has velocity has peaked just before 'flight' (Chavda et al. 2018).

Drop jump

The DJ protocol required the participants to step out and off a 30 cm platform (positioned 10 cm from the contact area), land on two force plates, and rebound as high as possible with a fast ground contact time (Pedley et al. 2017). Participants were cued to *"step out off of the box and rebound as high and as fast as possible"* (Pedley et al. 2017). Trials where the gymnasts noticeably stepped down or jumped up from the platform were discounted and repeated. All DJ data were analyzed by the principal researcher using a custom-built Matlab (MATLAB, R2018a) analysis software. Variables calculated included: jump height (JH), ground contact time (GCT), reactive strength index (RSI), centre of mass displacement (ΔCOM), relative vertical leg stiffness ($Stiffness_{rel}$) spring-like correlation (SLC), take-off velocity (TOV), braking average power (Power$_{brake}$), propulsive average power (Power$_{prop}$), braking average work (Work$_{brake}$) and propulsive average work (Work$_{prop}$).

Vaulting

Two-dimensional video analysis was used to determine the gymnasts' vertical take-off velocity ($m \cdot s^{-1}$) from the springboard during the execution of the straight vault. One stationary high-speed camera (Sony, RX10 mark 3) operating at 250 Hz and a shutter speed of 1/500 of a second, was positioned 6 m perpendicular to the springboard where take-off occurred. The vaulting springboard was positioned 30 cm from the landing mat for all participants and adjusted after each trial to the same position using permanent floor markers. The approach run up distance was determined by the standard vaulting run-up distances for specific chronological age ranges; 10 m for 5-8-year-olds, 12.5 m for 8-13-year-olds and 15 m for 14-17-year-olds. All gymnasts performed three straight jump vaults from a springboard (Continental, Fast-lift Model) onto a landing mat (Continental, Safety Mat). The straight vault is the most basic of vaulting exercises and was chosen to ensure all gymnasts were capable of performing the skill regardless of competitive level or maturity status. An additional thin mat (Continental, Supplementary Soft-Landing Mat) which was shorter in length was placed on top of the landing mat, to encourage the gymnasts to perform the vault for maximum vertical jump height. All gymnasts received the standardized instruction *"perform your highest straight jump to land on the thin mat."* Trials were discounted and repeated if a participant; flexed their lower-limbs during the flight phase, fell forwards or backwards upon landing, or if they landed past the top mat. After each testing session, calibration was completed using a 4.0 m high calibration rod marked with 1 m intervals. All vaulting videos were analyzed using digitizing analysis software (Tracker v.5.0.5) by the principal researcher. Digitizing was performed using a marker that was placed on the gymnasts' greater trochanter at the time of testing to increase accuracy. Vaulting coordinate data were filtered (MATLAB, R2018a) using a low-pass 4th order recursive Butterworth filter. Based on residual analysis (Winter 2009), the most appropriate cut-off frequency was found to be 10 Hz. Vertical take-off velocity from the springboard was calculated using the Central Difference Method (Winter 2009). The best vault was determined as the highest straight jump (using the hip marker position) which was used for further analyses.

Statistical Analyses

Descriptive statistics (mean values ± *sd*) were calculated for all variables from the jumping and vaulting data for each maturity group. Between-group differences in jumping and vaulting variables were assessed using a one-way analysis of variance (ANOVA). Homogeneity of variance was assessed via Levene's statistic, and where violated, Welch's adjustment was used to correct the F-ratio. Post-hoc analysis was used to identify the groups that were significantly different to one another using either Bonferroni or Games-Howell test, where equal variances were and were not assumed, respectively. Effect sizes (Cohen's *d*) were also calculated to establish the magnitude of any between-group differences (Cohen 1988) using the following classifications: trivial < 0.2; small 0.2 – 0.59; 0.6 – 1.19 moderate; 1.2 – 2.0 large; 2.0 – 4.0 very large; > 4.0 nearly perfect (Hopkins et al. 2009). Pearson correlation coefficients were used to determine the strength of relationships between all jump test variables and vertical take-off velocity for the whole sample. The strength of these relationships was classified as either: < 0.2 no relationship; 0.2 – 0.45 weak; 0.46 – 0.7 moderate; > 0.7 strong, based on previous recommendations (O'Donoghue 2012). For each jump test, stepwise multiple regression analyses were employed separately to establish the contribution of jump variables and maturity status (%PAH) on vertical take-off velocity from the spring board across the entire sample. The assumption of independent errors during the multiple regression analyses was tested via a series of Durbin-Watson tests, whilst multi-collinearity was tested using variance inflation factor (VIF) and tolerance diagnostics (0.2 tolerance cut-off). All significance values were accepted at $p < 0.05$ and all statistical procedures were conducted using SPSS v.24 for Macintosh.

RESULTS

Squat jump

Data showed small to moderate, non-significant between-group differences for JH ($p > 0.05$; f*igure 1*). Results for all other SJ variables are presented in *table 2*. Small to moderate significant increases in V_{peak}, $Impulse_{rel}$, PP_{abs} and PP_{rel} between the $early_{pre}$ and pubertal groups and between the $early_{pre}$ and $late_{pre}$ groups were observed ($p < 0.05$). For PF_{abs}, there was a moderate significant increase between the $early_{pre}$ and pubertal and $late_{pre}$ groups ($p < 0.05$). No significant differences were indicated between any of the groups for PF_{rel} and all effect sizes were trivial. RFD_{abs} showed small-moderate significant increases between the $early_{pre}$ and pubertal groups ($p < 0.05$) and $late_{pre}$ groups ($p < 0.05$). Between-group differences for all other RFD variables (RFD_{rel}, $pRFD_{abs}$ and $pRFD_{rel}$) were all found to be non-significant and trivial or small. No significant differences were found between the $late_{pre}$ and pubertal for any variables, and all effect sizes were trivial to small.

Insert Figure 1 near hear

Insert Table 2 near here

Countermovement jump

Moderate significant increases in JH were found between the $early_{pre}$ and pubertal groups ($p < 0.05$; *figure 1*) and $late_{pre}$ groups ($p < 0.05$; *figure 1*). Results for all other CMJ variables are presented in *table 3*. Moderate to large significant increases were present between the pubertal group and both the early$_{pre}$ and late$_{pre}$ groups for PF$_{abs,}$ Impulse$_{brake,}$ Impulse$_{prop,}$ PP$_{abs,}$ Power$_{brake}$ and Power$_{prop}$ ($p < 0.05$). For these variables, moderate to large increases were also found between the early$_{pre}$ and late$_{pre}$ groups ($p < 0.05$). Significant moderate increases in PP$_{rel}$ were present between the early$_{pre}$ and late$_{pre}$ and between the early$_{pre}$ and pubertal groups ($p < 0.05$). Non-significant, trivial to small between-group differences were reported for PF$_{rel}$, Time$_{brake}$ and Time$_{prop}$ ($p > 0.05$).

Insert Table 3 near here

Drop jump results

Moderate significant increases in JH were shown between the early$_{pre}$ and pubertal groups ($p < 0.05$; *figure 1*); while, small significant increases were found between the early$_{pre}$ and late$_{pre}$ groups ($p < 0.05$; *figure 1*). The remaining DJ variables are displayed in *table 4*. Moderate significant increases in stiffness$_{rel}$ were found between the early$_{pre}$ and pubertal groups only ($p < 0.05$). For ΔCOM, a small, significant increase was present between the early$_{pre}$ and pubertal groups ($p < 0.05$) as well as the early$_{pre}$ and late$_{pre}$ groups ($p < 0.05$). Large, significant increases in Power$_{brake}$, Power$_{prop}$, Work$_{brake}$ and Work$_{prop}$ were found between the early$_{pre}$ and pubertal groups ($p < 0.05$) and moderate, significant increases between the early$_{pre}$ and late$_{pre}$ groups ($p < 0.05$). No significant differences were found between any groups for GCT, RSI, SLC and TOV and effect sizes ranged from trivial to moderate. Differences for all DJ variables between the late$_{pre}$ and pubertal groups were non-significant and trivial to moderate.

Insert Table 4 near here

Vaulting

Moderate, significant increases in vaulting vertical take-off velocity were found between the $\text{early}_{\text{pre}}$ and late_{pre} groups ($p < 0.05$) and between the $\text{early}_{\text{pre}}$ and pubertal groups ($p < 0.05$). However, no significant differences were observed between the late_{pre} and pubertal groups for vertical take-off velocity and effect sizes were trivial.

Regression analyses

Multiple stepwise regression analysis outputs for each jumping test across the whole sample is shown in *table 5*. For the SJ test, regression analysis showed that variation in vertical take-off velocity during vaulting performance was best explained by %PAH (41%) and greater PP_{abs} (4%), accounting for 45% of the total variance. While %PAH (41%) and higher JH (3%) were the best predictors from the CMJ test, explaining 44% of the total variance. Finally, the DJ test was found to have highest explained total variance (55%) and was best explained by %PAH (41%), reduced GCT (10%) and greater ΔCOM (4%).

Insert Table 5 near here

DISCUSSION

This study examined the influence of maturity status on force-time variables from CMJ, SJ and DJ tests and the influence of these variables on vaulting performance in young female gymnasts. Overall, the main findings of this study were that jumping performance (i.e. jump height being the outcome measure) improves with biological maturity. This was evidenced by the most mature gymnasts' producing significantly more $\text{impulse}_{\text{prop}}$, power (both peak and average power) and faster V_{peak} than the least mature group, resulting in the greater jump heights in all jump tests. While, no significant differences were observed in relative peak force across multiple tests, measures of relative peak power did significantly increase. Jumping variables across the different tests explained only a small amount of the variance in vertical take-off velocity during vaulting which appeared to be more strongly associated with %PAH, indicating its potential role in vaulting performance.

Small and moderate increases in JH, albeit non-significant, were reported between the least mature group and the $late_{pre}$ and pubertal groups for the SJ testing. Our findings are consistent with previous SJ data, which found no significant difference in jump height between under-11s and under-13s (both groups were pre-peak height velocity (PHV)), albeit in male youth soccer players (Lloyd et al. 2015a). In contrast, SJ jump height was significantly greater between under-16s (post-PHV) and both less mature groups of boys (Lloyd et al. 2015a). With further growth and maturation, post-pubertal female gymnasts could produce greater amounts of force, impulse and power, resulting in significantly higher jump heights than less mature girls. However, the natural increases in fat-mass females experience with biological maturation could negatively impact jumping height (Malina et al. 2004).

The observed increases in jump height can be explained by the significant increases in $Impulse_{rel}$ and V_{peak} young gymnasts experience with maturity. $Impulse_{rel}$ provides insight into athletes' velocity capacity, which directly influences vertical jumping performance (Kirby et al. 2011; Turner et al. 2020). Further, significant increases in PF_{abs}, PP_{abs}, and RFD_{abs} were evident between the least mature group of gymnasts and both $late_{pre}$ and pubertal groups. These results are likely due to the maturity-associated increases in force-producing capabilities that occur as children approach adolescence (Radnor et al. 2018). However, when normalized to body mass, only $Impulse_{rel}$ and PP_{rel} significantly increased with maturity between the $early_{pre}$ and more mature groups, while all other relative measures (PF_{rel}, RFD_{rel} and $pRFD_{rel}$) remained unchanged. This finding corroborates with existing age-related SJ literature, which has shown a significant age effect for PP_{rel} but not PF_{rel} in young female gymnasts (Bradshaw and Le Rossignol 2004). Given that the amount of relative force produced appears stable with advancing maturity, these data could indicate that maturity-related increases in SJ height may be attributed to faster movement velocities as evidenced by the difference in PP_{rel} and V_{peak}. Specifically, these increases in movement velocity appear to be due to greater changes in contraction distance which, might be driven by growth (i.e. longer levers and fascicle lengths) and jumping strategy (i.e. taller, more mature gymnasts move a greater distance to get to a similar optimal depth prior to push-off) (Asai and Aoki 1996; Radnor et al. 2018).

Small to moderate significant increases in CMJ height between successive maturity groups was found in this study. These results support previous researchers who have shown CMJ height increases with advancing age and maturity throughout childhood and adolescence (Hammami et al. 2016; Lloyd and Cronin 2014; Lloyd et al. 2011b; Malina et al. 2004). While data from the present study aligns with existing literature, less is known about the underlying kinetics. Moderate to large increases were reported in absolute kinetic variables (PF_{abs}, $Impulse_{brake}$, $Impulse_{prop}$, PP_{abs}, $Power_{brake}$ and $Power_{prop}$) between successive groups. It is therefore likely that the significantly greater impulse more mature gymnasts produced resulted in higher jump heights, than their immature counterparts. This is further evidenced by the moderate to large significant increases in $Impulse_{brake}$ and $Impulse_{prop}$ gymnasts experience with increasing maturity while, the duration of these phases remains unchanged.

For PF_{rel} and PP_{rel} a similar pattern to the results from the SJ was observed, with no significant differences between any groups for PF_{rel} and only a significant increase in PP_{rel} from the least mature gymnasts to the $late_{pre}$ and pubertal groups, respectively. Previous data in young female gymnasts has also shown PF_{rel} is unchanged with maturation during this period of development, albeit during an isometric mid-thigh pull protocol (Moeskops et al. (in press)). Together, these results suggest young female gymnasts could benefit from strength and conditioning that offers an alternative training stimulus to enhance relative strength and movement velocity, beyond that of sport-specific training.

Maturation appears to enhance young gymnasts' ability to rebound higher during the DJ protocol, evidenced by moderate, significant increases in jump height between the early$_{pre}$ group and both late$_{pre}$ and pubertal cohorts of gymnasts. The significantly greater amount of PF, work, power and stiffness$_{rel}$ more mature gymnasts produce, likely explains their superior ability to jump higher than their more immature peers. All maturity groups were able to meet the required GCT < 250 ms for fast-SSC function which is noteworthy, and may reflect selection and/or training effect of gymnastics in this population. Fast-SSC actions are thought to promote greater movement speed via mechanisms inclusive of; elastic energy reutilization, greater pre-activation, stretch-reflex contributions and greater neural excitation (Bosco et al. 1987; Komi and Bosco 1978; Lloyd et al. 2011a; Radnor et al. 2018). Thus, maturity-related increases in kinetic variables in this study are likely attributed to structural and neural adaptations (Radnor et al. 2018). Specifically, natural increases in tendon CSA and stiffness (Kubo K et al. 2014; O'Brien et al. 2010), increases in preactivation (Lazaridis. S et al. 2010; Oliver and Smith 2010), reduced co-contraction ratios (Lazaridis. S et al. 2010) and so forth, may enhance SSC function in youth. However, it should be noted that no significant differences between the two most mature groups for jump height, or any other DJ variables were detected which, could be due to the significant increases in %PAH and body mass in the more mature cohort.

The results for RSI and SLC revealed no significant differences between all maturity groups, although some small increases with advancing maturity were present. Specifically, the trend of increasing RSI with maturation appears to be driven by primarily increases in jump height as no significant differences in GCT were observed. While RSI can increase through a potentially undesirable strategy (i.e. as it is a ratio determined by JH and GCT), the inclusion of the SLC allows further evaluation of athletes' SSC capabilities (Pedley et al. 2017). Current research suggests that spring-like behavior is represented by a SLC of above 0.8, whereby effective SSC mechanisms facilitate storage and reutilization of elastic energy within connective tissues (Pauda et al. 2005). Importantly, data from this study shows that all three cohorts of gymnasts display good spring-like behavior (> 0.9), and this remains stable throughout the development period examined.

Regression analyses

Based upon our data it appears that maturation most strongly influences vertical take-off velocity during vaulting, evidenced by %PAH appearing in all regression equations and explaining ~41% of variance in each jumping test. Further, regression analysis revealed only one other variable predicted vertical take-off velocity during vaulting performance from the SJ and CMJ tests, PP_{abs} (4%) and JH (3%) respectively. However, for the DJ protocol both a shorter GCT (10%) and greater ΔCOM (4%) were identified as predictors. Together with %PAH, these variables explained 55% of common variance in vertical take-off velocity, resulting in the DJ test explaining the most variance in the vault straight jump. These results are perhaps unsurprising given the similarities between the gymnasts' interaction with spring-board during take-off and the drop jump protocol, albeit on different types of surfaces. From a dynamic correspondence perspective, both require fast-SSC function owing to the constrained amount of time in contact with the ground or spring-board (Motoshima 2015; Pedley et al.

2017). These results highlight the importance of maturation and the ability to produce high amounts of force at faster rates for successful vaulting performance in young female gymnasts.

One limitation of this study is that the between group differences reported for the maturity groups were identified from a cross-sectional data set. Therefore, future research is required to track the natural development of youth female gymnasts across a longitudinal timeframe (i.e. from pre- to post-puberty) to confirm this study's findings. While the authors recognize this limitation, the current study makes a significant and novel contribution to the pediatric (and gymnastics) literature by examining differences in jump kinetics during jumping and vaulting, which can be used to help inform training prescription.

CONCLUSION

This study shows the value of using a jumping test battery that includes underpinning mechanical variables in young female gymnasts at different stages of maturation. Many absolute kinetic variables appear to significantly increase with advancing maturity across multiple tests however, we observed no differences in relative peak force while relative power and velocity significantly increased. Further, no significant differences were observed between maturity groups in braking and propulsive phase times for the CMJ test, or GCT for the DJ. Overall, this suggests more mature gymnasts have a higher movement velocity due to greater contraction distances over similar amounts of time. Therefore, as relative measures of strength do not appear to naturally increase with maturation, strength and conditioning provision for youth female gymnasts should target this physical quality throughout childhood and adolescence. This finding supports previous gymnastics-based literature which has demonstrated the effectiveness of resistance training interventions to increase levels of muscular strength and consequently, jumping performance (Marina and Jemni 2014; Michel et al. 2014). Providing technical competency is maintained, long-term training programs should aim to provide gymnasts with an effective training stimulus that differs to their sports-specific training in an integrative and individual manner (e.g. using higher loading schemes via resistance training, weightlifting derivatives etc.).

As this study has shown biological maturation influences vertical take-off velocity during vaulting, practitioners should monitor and consider maturational status in testing batteries for youth gymnasts. Further, greater absolute peak power during the SJ, higher CMJ height and shorter GCTs and greater ΔCOM during the DJ, appear to be the most important variables for vaulting performance in the jumping tests examined. Targeting performance improvements in these measures within the training programs of young gymnasts seems logical. However, it is crucial that training programs are always developed holistically and must be inclusive of exercises which enhance gymnasts' overall athleticism and reduce the relative risk of gymnastics-related injuries.

Table 1. Descriptive statistics for all anthropometric variables (mean ± *sd*)

Group	*N*	Age (years)	Standing height (cm)	Sitting height (cm)	Leg length (cm)	Body mass (Kg)	Predicted % adult height	Training hours per week
$\text{Early}_{\text{pre}}$	54	7.9 ± 1.1	124.5 ± 8.8	66.9 ± 3.8	57.7 ± 5.5	25.2 ± 4.5	70.1 ± 4.0	11.3 ± 5.2
Late_{pre}	47	10.7 ± 0.8^a	139.8 ± 6.8^a	73.9 ± 4.1^a	65.9 ± 3.9^a	33.8 ± 6.4^a	79.8 ± 2.8^a	11.1 ± 5.3
Pubertal	19	12.8 ± 0.8^b	150.4 ± 5.6^b	78.2 ± 2.7^b	72.3 ± 2.7^b	45.1 ± 9.5^b	89.2 ± 3.2^b	11.0 ± 6.1

Significant at the level of $p < 0.05$

^{a} = significantly greater than the early pre-pubertal group; ^{b} = significantly greater than the early and late pre-pubertal groups

Table 2. Maturity group analysis of variables from the squat jump test (mean ± *sd*)

				Between group effect size (*d*)		
Test Variable	**Early$_{pre}$**	**Late$_{pre}$**	**Pubertal**	Early$_{pre}$ - Late$_{pre}$	Late$_{pre}$ - Pubertal	Early$_{pre}$ - Pubertal
V_{peak} (m·s^{-1})	1.97 ± 0.21	2.12 ± 0.17[a]	2.14 ± 0.12[a]	0.53	0.05	0.55
$Impulse_{rel}$ (m·s^{-1})	1.72 ± 0.27	1.85 ± 0.34[a]	1.98 ± 0.15[a]	0.37	0.34	0.75
PF_{abs} (N)	591.14 ± 206.91	756.25 ± 174.99[a]	793.18 ± 208.40[a]	0.76	0.18	0.84
PF_{rel} (N·kg^{-1})	21.77 ± 3.41	21.54 ± 2.42	21.74 ± 1.40	0.06	0.06	0.02
PP_{abs} (W)	933.37 ± 1302.96	1302.96 ± 387.24[a]	1360.64 ± 479.61[a]	0.89	0.09	0.91
PP_{rel} (W·kg^{-1})	33.39 ± 5.71	36.65 ± 4.42[a]	37.44 ± 3.24[a]	0.48	0.13	0.60
RFD_{abs} (N·s^{-1})	1160.20 ± 499.91	1457.19 ± 518.07[a]	1571.72 ± 549.38[a]	0.55	0.21	0.68
RFD_{rel} (N·kg^{-1}·s^{-1})	43.81 ± 18.09	42.14 ± 14.05	43.51 ± 13.11	0.10	0.09	0.05
$pRFD_{abs}$ (N·s^{-1})	3691.94 ± 4264.53	4069.38 ± 4303.35	3710.09 ± 1905.21	0.09	0.10	0.02
$pRFD_{rel}$ (N·kg^{-1}·s^{-1})	135.56 ± 132.10	119.41 ± 138.07	102.98 ± 46.63	0.12	0.14	0.26

Significant at the level of $p < 0.05$

[a] = significantly greater than the early pre-pubertal group

V_{peak} = peak velocity; $Impulse_{rel}$ = relative vertical net impulse; PF_{abs} = absolute peak force; PF_{rel} = relative peak force; PP_{abs} = absolute peak power; PP_{rel} = relative peak power; RFD_{abs} = absolute rate of force development; RFD_{rel} = relative rate of force development; $pRFD_{abs}$ = Absolute peak rate of force development

Small effect size (0.20-0.59); Moderate effect size (0.60-1.19); Large effect size (1.20-2.00)

Table 3. Maturity group analysis of variables from the countermovement jump test (mean ± *sd*)

				Between group effect size (*d*)		
Test Variable	**Early$_{pre}$**	**Late$_{pre}$**	**Pubertal**	Early$_{pre}$ - Late$_{pre}$	Late$_{pre}$ - Pubertal	Early$_{pre}$ - Pubertal
PF$_{abs}$ (N)	350.84 ± 115.05	508.94 ± 156.42[a]	607.86 ± 111.55[b]	1.01	0.66	1.52
PF$_{rel}$ (N·kg^{-1})	13.95 ± 3.72	14.87 ± 3.08	14.11 ± 3.25	0.27	0.25	0.04
Impulseb$_{rake}$ (Ns)	22.07 ± 9.27	32.63 ± 9.03[a]	46.14 ± 9.17[b]	1.00	1.24	1.67
Time$_{brake}$ (s)	0.373 ± 0.187	0.457 ± 0.434	0.358 ± 0.205	0.26	0.26	0.07
Impulse$_{prop}$ (Ns)	46.16 ± 10.83	68.32 ± 15.53[a]	88.45 ± 14.29[b]	1.29	1.14	1.82
Time$_{prop}$ (s)	0.248 ± 0.068	0.246 ± 0.053	0.253 ± 0.062	0.03	0.13	0.07
PP$_{abs}$ (W)	894.37 ± 234.39	1343.09 ± 337.62[a]	1756.29 ± 303.03[b]	1.23	1.14	1.85
PP$_{rel}$ (W·kg^{-1})	35.35 ± 5.01	39.23 ± 4.97[a]	40.35 ± 4.95[a]	0.73	0.23	0.73
Power$_{brake}$ (W)	-99.12 ± 40.14	-135.32 ± 54.66[a]	-200.12 ± 63.63[b]	0.72	1.01	1.51
Power$_{prop}$ (W)	490.71 ± 148.27	726.78 ± 200.30[a]	947.21 ± 117.43[b]	1.12	1.07	1.77

Significant at the level of $p < 0.05$

[a] = significantly greater than the early pre-pubertal group; [b] = significantly greater than the early pre-pubertal, and the late pre-pubertal groups

PF$_{abs}$ = absolute peak force; PF$_{rel}$ = relative peak force; Impulse$_{Brake}$ = braking impulse; Time$_{brake}$ = braking phase duration; Impulse$_{prop}$ = propulsive impulse; Time$_{prop}$ = propulsive phase duration; PP$_{abs}$ = absolute peak power; PP$_{rel}$ = relative peak power; Power$_{brake}$ = braking average power; Power$_{prop}$ = propulsive average power

Small effect size (0.20-0.59); Moderate effect size (0.60-1.19); Large effect size (1.20-2.00)

Table 4. Maturity group analysis of variables from the drop jump test (mean ± *sd*)

Test Variable	**Early$_{pre}$**	**Late$_{pre}$**	**Pubertal**	**Between group effect size (*d*)**		
				Early$_{pre}$ - Late$_{pre}$	Late$_{pre}$ - Pubertal	Early$_{pre}$ - Pubertal
GCT (s)	0.193 ± 0.049	0.191± 0.340	0.214 ± 0.077	0.10	0.32	0.29
RSI	0.80 ± 0.26	0.95 ± 0.29	0.96 ± 0.32	0.43	0.10	0.58
PF (N)	1549.00 ± 382.65	2070.72 ± 472.30^{a}	1918.52 ± 629.35	1.04	0.29	0.78
ΔCOM (cm)	9.91 ± 2.67	11.34 ± 2.58^{a}	12.11 ± 5.40^{a}	0.59	0.01	0.53
Stiffness$_{rel}$ (BW·m^{-1})	14.72 ± 4.58	17.54 ± 5.16	24.27 ± 18.27^{a}	0.18	0.62	0.72
SLC	-0.92 ± 0.05	-0.94 ± 0.05	-0.94 ± 0.05	0.27	0.14	0.27
TOV (m·s^{-1})	1.91 ± 0.19	2.00 ± 0.17	1.84 ± 0.37	0.24	0.66	0.25
Power$_{brake}$ (W)	-901.10 ± 199.90	-1278.17 ± 285.17^{a}	-1402.65 ± 372.30^{a}	0.91	0.43	1.21
Power$_{prop}$ (W)	749.40 ± 176.02	1116.34 ± 259.12^{a}	1252.18 ± 266.50^{a}	1.12	0.49	1.45
Work$_{brake}$ (J)	66.35 ± 17.42	103.60 ± 29.83^{a}	125.59 ± 38.23^{a}	1.14	0.50	1.51
Work$_{prop}$ (J)	46.35 ± 16.45	79.63 ± 29.20^{a}	102.00 ± 50.50^{a}	1.17	0.43	1.40

Significant at the level of $p < 0.05$

^{a} = significantly greater than the early pre-pubertal group

GCT = ground contact time; RSI = reactive strength index; ΔCOM = centre of mass displacement; SLC = spring-like correlation; TOV = take-off velocity; PF$_{abs}$ = absolute peak force; Power$_{brake}$ = braking average power; Power$_{prop}$ = Propulsive average power; Work$_{brake}$ = braking average work; Work$_{prop}$ = propulsive average work; Stiffness$_{rel}$ = relative vertical stiffness

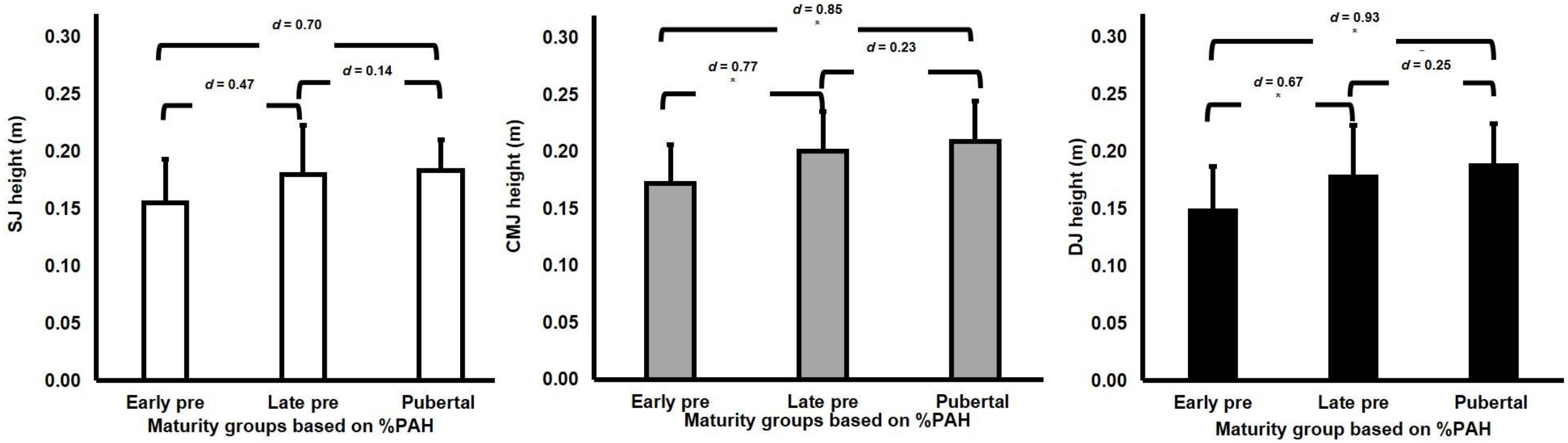
Small effect size (0.20-0.59); Moderate effect size (0.60-1.19); Large effect size (1.20-2.00)

Table 5. Stepwise multiple linear regression equations explaining the variables that significantly ($p < 0.05$) contributed to vertical take-off velocity during vaulting from the SJ, CMJ and DJ tests for all maturity groups.

Jumping protocol	Dependent variable	Independent variables	Regression equation (beta coefficients)	Adjusted R^2 value	Sig. value
SJ	Vertical take-off velocity from springboard	Constant	-0.787		
		%PAH	0.044	0.406	0.000
		PP_{abs}	0.000	0.454	0.003
CMJ	Vertical take-off velocity from springboard	Constant	-1.248		
		%PAH	0.046	0.406	0.000
		JH	3.761	0.435	0.008
DJ	Vertical take-off velocity from springboard	Constant	-0.165		
		%PAH	0.053	0.406	0.000
		GCT	-0.008	0.514	0.000
		ΔCOM	0.067	0.548	0.002

PP_{abs} = Absolute peak power; %PAH = Percent of predicted adult height attained; JH = Jump height; GCT = Ground contact time; ΔCOM = Centre of mass displacement

Fig. 1 Maturity group analysis of jump height (m) from the squat jump, countermovement jump and drop jump tests respectively (mean ± *sd*)



Supplementary information 1. Squat jump variables

Variable	Abbreviation	Units	Description
Jump height	JH	m	The greatest vertical displacement of the centre of mass during the flight time. This was calculated via the flight-time method (Leard et al. 2007).
Peak velocity	V_{peak}	$m{\cdot}s^{-1}$	The fastest vertical speed of the centre of mass during the propulsive phase.
Relative vertical net impulse	$Impulse_{rel}$	$m{\cdot}s^{-1}$	The product of the net vertical impulse divided by the athlete's body mass. This was calculated by removing the vertical impulse exerted through acceleration due to gravity which, was then divided by the subjects' body mass to determine relative net vertical impulse (Kirby et al. 2011).
Absolute peak force	PF_{abs}	N	The largest force generated before take-off.
Relative peak force	PF_{rel}	$N{\cdot}kg^{-1}$	The largest force generated before take-off divided by the athlete's body mass.
Absolute peak power	PP_{abs}	W	The largest power (product of force and velocity) generated before take-off.
Relative peak power	PP_{rel}	$W{\cdot}kg^{-1}$	The largest power (product of force and velocity) generated before take-off divided by the athlete's body mass.
Absolute rate of force development	RFD_{abs}	$N{\cdot}s^{-1}$	The change in absolute force divided by the change in time during the propulsive phase.
Relative rate of force development	RFD_{rel}	$N{\cdot}kg^{-1}$	The absolute rate of force development divided by the athlete's body mass.
Absolute peak rate of force development	$pRFD_{abs}$	$N{\cdot}s^{-1}$	The highest rate of force development during a 20-ms time sampling window.
Relative peak rate of force development	$pRFD_{rel}$	$N{\cdot}s^{-1}\ kg^{-1}$	The highest rate of force development during a 20-ms time sampling window divided by the athlete's body mass.

Supplementary information 2. Countermovement jump variables

Variable	**Abbreviation**	**Units**	**Description**
Jump height	JH	m	The greatest vertical displacement of the centre of mass during the flight time. This was calculated using the vertical take-off velocity of the COM method (Chavda et al. 2018).
Absolute peak force	PF_{abs}	N	The largest net force generated before take-off in the concentric phase.
Relative peak force	PF_{rel}	$N{\cdot}kg^{-1}$	The largest net force generated before take-off in the concentric phase divided by the athlete’s body mass.
Braking impulse	$Impulse_{brake}$	Ns	The total area underneath the net force-time curve during the breaking phase (from the end of the unweighting phase to the end of the breaking phase).
Braking phase duration	$Time_{brake}$	s	Time of breaking contraction during the countermovement.
Propulsive impulse	$Impulse_{prop}$	Ns	The total area underneath the net force-time curve during the propulsive phase (from the end of the breaking phase to the end of the propulsive phase).
Propulsive phase duration	$Time_{prop}$	s	Time of propulsive contraction during the jump.
Absolute peak power	PP_{abs}	W	The largest power (product of force and velocity) generated before take-off.
Relative peak power	PP_{rel}	$W{\cdot}kg^{-1}$	The largest power (product of force and velocity) generated before take-off divided by the athlete’s body mass.
Braking average power	$Power_{brake}$	W	The average power generated during the breaking phase of the jump before take-off.
Propulsive average power	$Power_{prop}$	W	The average power generated during the propulsive phase of the jump before take-off.

Supplementary information 3. Drop jump variables

Variable	**Abbreviation**	**Units**	**Description**
Jump height	JH	m	The greatest vertical displacement of the centre of mass during the flight time. This was calculated using methods by Leard (Leard et al. 2007).
Ground contact time	GCT	ms	The time interval of the ground contact of the first landing. This was established using the first data point greater than 15 N (i.e. initial ground contact) and the final data point that exceeded 15 N (take-off).
Reactive strength index	RSI	Arbitrary units	The ratio between jump height (mm) and first ground contact time (ms).
Centre of mass displacement	ΔCOM	cm	The peak vertical displacement of the body's centre of mass during the first ground contact.
Spring-like correlation	SLC	Arbitrary units	The correlation between centre of mass displacement and absolute vertical force throughout the first ground contact.
Take-off velocity	TOV	$m \cdot s^{-1}$	The velocity of the centre of mass at take-off.
Absolute peak force	PF_{abs}	N	The largest vertical force generated before take-off.
Braking average power	$Power_{brake}$	W	The average power between initial ground contact and the timing of the maximal displacement of the centre of mass.
Propulsive average power	$Power_{prop}$	W	The average power from the timing of the lowest point of the centre of mass and the point of take-off.
Braking average work	$Work_{brake}$	J	The average work done between initial ground contact and the timing of the maximal displacement of the centre of mass.
Propulsive average work	$Work_{prop}$	J	The average work between the lowest point of the centre of mass and the point of take-off.
Relative vertical stiffness	$Stiffness_{rel}$	$BW \cdot m^{-1}$	The ratio of relative peak vertical ground reaction force (BW) to maximal vertical displacement of the centre of mass (m) (McMahon and Cheng 1990). In instances where maximal vertical force was also peak landing force, the proceeding force peak following the peak landing force was used for the calculation of leg stiffness.

FIGURE CAPTIONS

Fig. 1 Maturity group analysis of jump height (m) from the squat jump, countermovement jump and drop jump tests respectively (mean ± *sd*)

REFERENCES

Asai H, Aoki J (1996) Force development of dynamic and static contractions in children and adults Int J Sports Med 17:170-174 doi:10.1055/s-2007-972827

Blazevich AJ (ed) (2011) The Stretch-Shortening Cycle (SSC) vol 1. Strength and Conditioning: Biological Principles and Practical Applications vol 1, 1 edn. Wiley-Blackwell, Oxford

Bosco C et al. (1987) The effect of pre-stretch on mechanical efficiency of human skeletal muscle. Acta Physiol Scand 131:323–329.

Bradshaw E, Le Rossignol P (2004) Anthropometric and biomechanical field measures of floor and vault ability in 8 to 14 year old talent-selected gymnasts Sports Biomech 3:249-262 doi:10.1080/14763140408522844

Chavda S et al. (2018) Force-Time characteristics of the countermovement jump: analyzing the curve in excel J Strength Cond 40:66-77

Cohen J (1988) Statistical power analysis for the behavioral sciences. 2nd ed edn. Lawrence Erlbaum, New Jersey

Colclough A, Munro AG, Herrington LC, McMahon JJ, Comfort P (2018) The effects of a four week jump-training program on frontal plane projection angle in female gymnasts Phys Ther Sport 30:29-33 doi:10.1016/j.ptsp.2017.11.003

Dallas G, Zacharogiannis E, Paradisis G (2013) Physiological profile of elite Greek gymnasts J Phys Ed Sport 13:27-32 doi:10.7752/jpes.2013.01005

Dos'Santos T, Jones PA, Comfort P, Thomas C (2017) Effect of different onset thresholds on isometric mid-thigh pull force-time variables J Strength Cond Res 31:3463-3473. doi:10.1519/JSC.0000000000001765

Faigenbaum A, Lloyd R, JL O (2020) Essentials of youth fitness vol 1. Human Kinetics,

Hall E, Bishop DC, Gee TI (2016) Effect of plyometric training on handspring vault performance and functional power in youth female gymnasts PLoS One 11:e0148790 doi:10.1371/journal.pone.0148790

Hammami R, Chaouachi., I. M, Granacher U, Behm D (2016) Associations Between Balance and Muscle Strength, Power Performance in Male Youth Athletes of Different Maturity Status Pediatr Exerc Sci 28:521-534

Hopkins W, Marshall S, Batterham A, Hanin J (2009) Progressive Statistics for Studies in Sports Medicine and Exercise Science Med Sci Sports Exerc 41:3-12

Khamis H, Roche A (1994) Predicting adult stature without using skeletal age - the Khamis-Roche method Pediatrics 94:504-507

Kirby T, McBride J, Haines T, Dayne A (2011) Relative net vertical impulse determines jumping performance Journal of applied biomechanics 27:207

Komi P, Bosco C (1978) Utilization of stored elastic energy in leg extensor muscles by men and women Med Sci Sport 10:261-265

Kubo K, Teshima T, Ikebukuro T, Hirose N, N. T (2014) Tendon properties and muscle architecture for knee extensors and plantar flexors in boys and men Clin Biomech 29:506–511

Lazaridis. S, Bassa. E, Patikas. D, Giakas. G, Gollhofer. A, C. K (2010) Neuromuscular differences between pre- pubescents boys and adult men during drop jump Eur J Appl Physiol 110:67-76

Leard JS, Cirillo MA, Katsnelson E, Kimiatek DA, Miller TW, Trebincevic K, Garbalosa JC (2007) Validity of two alternative systems for measuring vertical jump height J Strength Cond Res 21:1296-1299 doi:10.1519/R-21536.1

Lloyd R, Cronin J (2014) Plyometric development in youth. In: RS L, JL O (eds) Strength and Conditioning for Young Athletes Science and Application, vol 1. Routledge, Oxon, p 100

Lloyd R, Meyers R, Oliver J (2011a) The natural development and trainability of plyometric ability during childhood J Strength Cond Res 3:23-32

Lloyd R, Oliver J, Faigenbaum A, Myer G, De Ste Croix M (2014) Chronological age vs. biological maturation- implications for exercise programming in youth. J Strength Cond Res 28:1454–1464

Lloyd R, Oliver J, Hughes M, Williams C (2011b) The influence of chronological age on periods of accelerated adaptation of stretch-shortening cycle performance in pre and postpubescent boys J Strength Cond Res 25:1889-1897 doi:10.1519/JSC.0b013e3181e7faa8

Lloyd R, Oliver J, Hughes M, Williams C (2011c) Specificity of test selection for the appropriate assessment of different measures of stretch-shortening cycle function in children J Sports Med Phys Fitness 51:595-602

Lloyd R, Oliver J, Hughes M, Williams V (2009) Reliability and validity of field-based measures of leg stiffness and reactive strength index in youths J Sports Sci 27:1565-1573 doi:10.1080/02640410903311572

Lloyd R, Oliver J, Radnor J, Rhodes B, Faigenbaum A, Myer G (2015a) Relationships between functional movement screen scores, maturation and physical performance in young soccer players J Sports Sci 33:11-19 doi:10.1080/02640414.2014.918642

Lloyd R, Radnor J, De Ste Croix M, Cronin J, Oliver J (2015b) Changes in sprint and jump performances after traditional,plyometric, and combined resistance training in male youth pre- and post-peak height velocity J Strength Cond Res 30:1239–1247

Malina R, Bouche R, Bar-Or O (2004) Growth, Maturation, and Physical Activity. Human Kinetics., Champaign

Marina M, Jemni M (2014) Plyometric training performance in elite-oriented prepubertal female gymnasts J Strength Cond Res 28:1015-1025 doi:10.1519/JSC.0000000000000247

Marina M, Jemni M, Rodríguez F (2013) Jumping performance profile of male and female gymnasts J Sports Med Phys Fitness 53:378-386

Marina M, Torrado P (2013) Does gymnastics practice improve vertical jump reliability from the age of 8 to 10 years? J Sports Sci 31:1177-1186 doi:10.1080/02640414.2013.771816

Marina M., F.A. Rg (2013) Usefulness and metabolic implications of a 60 sec repeated jumps test as a predictor of acrobatic jumping performance in gymnasts Biol Sport 30:9-15

McMahon TA, Cheng GC (1990) The mechanics of running: how does stiffness couple with speed? J Biomech 23 Suppl 1:65

Meyers RW, Oliver JL, Hughes MG, Lloyd RS, Cronin JB (2017) Influence of Age, Maturity, and Body Size on the Spatiotemporal Determinants of Maximal Sprint Speed in Boys J Strength Cond Res 31:1009-1016 doi:10.1519/JSC.0000000000001310

Michel M, Monem J, Ferran R (2014) A two-season longitudinal follow-up study of jumps with added weights and counter movement jumps in well-trained pre-pubertal female gymnasts. J Sports Med Phys Fitness 54:731-741

Moeskops S, Oliver J, Read P, Cronin J, Myer G, Haff G, Lloyd R (2018a) Within- and between-reliability of the isometric mid-thigh pull in young female athletes J Strength Cond Res 32:1892-1901

Moeskops S, Oliver J, Read P, Cronin J, Myer G, Haff G, Lloyd R ((in press)) The influence of biological maturity and competitive level on isometric force-time curve variables and vaulting performance in young female gymnasts J Strength Cond

Moeskops S, Oliver J, Read P, Cronin J, Myer G, Lloyd R (2019) The physiological demands of youth artistic gymnastics; applications to strength and conditioning J Strength Cond 41:1-13

Moeskops S, Read P, Oliver J, Lloyd R (2018b) Individual Responses to an 8-Week Neuromuscular Training Intervention in Trained Pre-Pubescent Female Artistic Gymnasts Sports 128

Morin JB, Jimenez-Reyes P, Brughelli M, Samozino P (2019) When Jump Height is not a Good Indicator of Lower Limb Maximal Power Output: Theoretical Demonstration, Experimental Evidence and Practical Solutions Sports Med 49:999-1006 doi:10.1007/s40279-019-01073-1

Motoshima YK, J. Maeda,A. (2015) The Relationship Between The Mechanical Parameters In The Take-Off Of A Vault And The Drop Jump Ability .pdf> Science of Gymnastics Journal 7:37 - 45

O'Brien T, Reeves N, Baltzopoulos V, Jones D, Maganaris C (2010) Muscle-tendon structure and dimensions in adults and children J Anat 216:631-642 doi:10.1111/j.1469-7580.2010.01218.x

O’Donoghue P (2012) Statistics for Sport and Exercise Studies: an Introduction. vol 1. Routledge, London

Oliver J, Smith P (2010) Neural control of leg stiffness during hopping in boys and men J Electromyogr Kinesiol 20:973-979

Owens N, Watkins J, Kilduff L, Bevan H, Bennett M (2014) Development of a criterion method to determine peak mechanical power output in a countermovement jump. J Strength Cond Res 28:1552–1558

Pauda D, Carcia C, Arnold B, Granata K (2005) Gender Differences in Leg Stiffness and Stiffness Recruitment Strategy During Two-Legged Hopping J Motor Behav 37:111-125

Pedley J, Lloyd R, Read P, Moore I, Oliver J (2017) Drop Jump: A Technical Model for Scientific Application J Strength Cond 39:36-44

Pion J, Lenoir M, Vandorpe B, Segers V (2015) Talent in Female Gymnastics: a Survival Analysis Based upon Performance Characteristics Int J Sports Med 36:935-940 doi:10.1055/s-0035-1548887

Polishchuk T, Mosakowska M (2007) The balance and jumping ability of artistic gymnastics competitors of different ages Med Sport Press 13:100-103

Radnor J, Oliver J, Waugh C, Myer G, Moore I, Lloyd R (2018) The Influence of Growth and Maturation on Stretch-Shortening Cycle Function in Youth Sports Med 48:57-71 doi:10.1007/s40279-017-0785-0

Sleeper M, Kenyon L, Casey E (2012) Measuring fitness in female gymnasts: The gymnastics functional measuring tool Int J Sports Phys Ther 7

Suchomel T, Sands W, McNeal J (2016) Comparison of static, countermovement, and drop jumps of the upper and lower extremities in U.S. Junior national team male gymnasts Sc GYM 8:15-30

Turner A et al. (2020) Developing Powerful Athletes, Part 1: Mechanical Underpinnings J Strength Cond 0:1-10

Turner A, Jeffreys I (2010) The Stretch-Shortening Cycle: Proposed Mechanisms and Methods for Enhancement J Strength Cond 32:87-99

Vandorpe B, Vandendriessche JB, Vaeyens R, Pion J, Lefevre J, Philippaerts RM, Lenoir M (2012) The value of a non-sport-specific motor test battery in predicting performance in young female gymnasts J Sports Sci 30:497-505 doi:10.1080/02640414.2012.654399

Winter D (2009) Biomechanics and Motor Control of Human Movement. 4 edn. John Wiley & Sons, Inc., Hoboken, New Jersey