The influence of biological maturity and competitive level on isometric force-time curve variables and vaulting performance in young female gymnasts

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

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

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

[3]Athlete Health and Performance Research Center, Aspetar Orthopaedic and Sports Medicine Hospital, Doha, Qatar

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

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

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

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

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

[9]Australian Center 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, smoeskops@cardiffmet.ac.uk.

INTRODUCTION

Young artistic gymnasts who develop high levels of muscular strength can enhance performance and reduce the risk of gymnastics-related injury (2, 11, 26, 29, 34, 35). Many complex gymnastic skills are underpinned by the ability to jump, rebound, accelerate, and decelerate (29). Young gymnasts therefore require the capacity to produce and rapidly absorb high forces to proficiently and safely perform dynamic actions (27, 29), especially in light of high anterior cruciate ligament (ACL) injury rates of competitive female gymnasts compared with other sports (2, 4, 15).

Elite or competitive female gymnastics is recognized as an early specialization sport. Evidence suggests that coaches intuitively select later-maturing individuals who are typically shorter in stature for their chronological age (24). Further, muscular strength assessments are often included in talent identification testing batteries for elite-orientated and competitive pre-pubescent gymnasts (17, 41). While gymnastics training itself provides a stimulus that enhances muscular strength (5, 26), natural improvements in strength also occur during childhood and adolescence due to growth and maturation (21, 25) which can be attributed to increases in muscle size, changes in muscle architecture, and improvements in motor unit recruitment (21, 33). Thus, accounting for biological maturity when testing and monitoring young athletes seems warranted.

Previous researchers studying in young female gymnasts have reported increases in lower limb muscular strength and power that occur with advancing chronological age and/or competitive level (3, 8, 37). However, these studies failed to report the biological maturity of participants. Owing to differences in the timing and tempo of biological maturation between individuals of the same chronological age (25), analyzing how physical qualities develop from a maturity perspective seems warranted (20–22). However, the manner in which muscular strength differs between young female gymnasts of different maturity status remains unknown.

Another limitation with existing gymnastics literature is that strength and power variables are often measured using jumping protocols or gymnastics-specific tests, which solely provide performance outcome measures (e.g., jump height, distance) (8, 37, 41) or report numbers of repetitions completed for an exercise (e.g., leg lifts to the bar) (37), respectively. While these field-based tests have been used to reflect surrogate measures of muscular strength and power, use of jump height as an indicator of lower limb maximal power has recently been questioned due to several confounding factors, such as body mass, push-off distance, and individual and optimal force-velocity profiles (30). Importantly, force-time data enables identification of mechanical variables that are associated with superior performance of athletic tasks (e.g., jumping and accelerating) needed to perform gymnastics skills, such as vaulting and tumbling (11, 29). For example, previous kinetic data in adult female gymnasts shows significant resistance training-induced increases in peak power output in countermovement jump and squat jump tests; which would enable greater flight times for execution of more advanced skills, resulting in higher scores during competitions (11). Further, data indicate that qualities such as relative peak force during an isometric-mid thigh pull (IMTP) test have been used to group athletes as stronger or weaker (i.e., stronger athletes = relative peak force > 29.4 N/kg) to evaluate the effectiveness of training interventions (36). While some mechanistic data are available for young gymnasts using dynamic jumping protocols, such as peak force, peak power and rate of force development from squat, countermovement and drop jumps (3, 38), few studies have explored force-time curve variables of this population during isometric strength tests.

The IMTP is a commonly used force-time curve diagnostic tool that allows researchers to collect large amounts of information (e.g., peak force, force at various time epochs, rate of force development) in a time-efficient manner with minimal fatigue (6, 13, 14, 18). The test position optimizes the length-tension relationship of isometric muscular contractions by replicating the start of the second pull during a clean/power clean in weightlifting (6, 12). Owing to isolation of joint angles and low technical requirements of performing the test, IMTP is a safe and reliable option for assessing the maximal strength capacities of youth and has been acknowledged as a preferential mode of assessment for non-strength and conditioned trained youth (7, 28, 36). Furthermore, the IMTP test has been significantly correlated with a range of dynamic athletic tasks including; sprint speed (39), vertical jump performance and 1RM squats (18), albeit in non-gymnastic populations. Large-scale IMTP force-time curve datasets could be used to provide benchmarks into the strength and power capacities of young gymnasts, although no studies to date have examined IMTP force-time variables in young female gymnasts.

While some age-related data exist for measures of muscular strength and power in young female gymnasts (3), these physical qualities have yet to be examined by maturity status. In addition, relationships between IMTP force-time curve variables and key metrics that underpin gymnastic skills are unknown. Therefore, the aims of this study were to explore the influence of maturity status and competitive level on isometric force-time variables in young female gymnasts and to determine associations between isometric force-time variables and take-off velocity during vaulting performance.

METHODS

Experimental Approach to the Problem

This study used a cross-sectional design to examine isometric force-time curve variables and vaulting performance in young artistic female gymnasts. Given the nature of this early specialization sport, it is likely that demographics of young gymnasts differ markedly in both maturity status and technical ability. Therefore, data were analyzed in two ways: with the sample grouped by biological maturity, and with the sample grouped by competitive level. Regression analyses were performed to determine the predictive ability of isometric force-time variables and biological maturity on vaulting performance. All participants attended one testing session in which anthropometric, IMTP, and vaulting performance data were collected. Three trials of each test were completed, with the best of three trials used for further analyses.

Subjects

This study included 120 female artistic gymnasts aged 5–14 years. All participants had >1 year of gymnastics experience and were participating in gymnastics training 2–6 times per week, totaling 2–24 training hours per week. All participants were from gymnastics clubs in South Wales and were not receiving formalized strength and conditioning provision at the time of testing. Participant's gymnastics training sessions comprised of standard gymnastics conditioning activities and time allocated to all disciplines of artistic gymnastics, comprising of vault, bars beam and the floor exercise. Participants were initially grouped according to biological maturity using percentage of predicted adult height (%PAH) (19): <75%PAH, early pre-pubertal (n = 54); 76%–85%PAH, late pre-pubertal (n = 47); and 86%–95%PAH, pubertal (n = 19). As a secondary analysis, participants were grouped according to their competitive level of gymnastics: elite (n = 10), national (n = 41), regional (n

= 48), and recreational (n = 21). Competitive levels were defined by the classifications presented in Table 1. Participants reported no injuries at the time of testing and were instructed to refrain from strenuous activity 24 hours before testing. Ethical approval for the study was granted by the Ethics Board. Subjects were informed of the benefits and risks of the investigation prior to signing institutionally approved informed assent documents. As all subjects were under the age of 18 years (mean age 9.8 ± 2.1), signed parental permission was also obtained.

Table 1 Group definitions for competitive levels of gymnastics

Group	Definition
Recreational	Gymnasts who have not participated in grades and have not been identified to compete at any of the above levels
Regional	Gymnasts who have competed in regional grades or have been identified to potentially compete at this level (for those who are <10 years old)
National	Gymnasts who have competed in national grades or have been identified to potentially compete at this level (for those who are <10 years old)
Elite	Gymnasts who have competed in compulsory elite grades or are in the national squad

Procedures

Before testing commenced, all participants performed a standardized 10-minute dynamic warm-up led by the principle researcher, including relevant activation and mobilization exercises and three sets of squat jumps, countermovement jumps, and pogo hops. Familiarization of each testing protocol took place at the beginning of the testing session. The researcher provided a demonstration and gave standardized, child-friendly coaching cues. Individuals then practiced the protocol until the researcher was satisfied with the gymnasts' technical competency.

Anthropometrics—

Anthropometric data including standing and sitting height were collected using a stadiometer to the nearest 0.1 cm (SECA 321, Vogel & Halke, Hamburg, Germany). Body mass was measured 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 (19). Descriptive data for each maturity group are presented in Table 2.

Table 2 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
Early pre-pubertal	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-pubertal	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
Recreational	21	9.6 ± 2.6	134.8 ± 14.4	71.1 ± 6.1	63.7 ± 8.6	33.5 ± 11.6	76.2 ± 9.3	4.4 ± 1.8
Regional	48	9.8 ± 1.8	135.4 ± 11.3	72.2 ± 5.5	63.1 ± 6.4	32.3 ± 9.7	77.1 ± 6.9	9.8 ± 3.1^
National	41	10.0 ± 2.2	135.5 ± 13.0	71.5 ± 6.1	64.0 ± 7.3	31.2 ± 8.3	78.0 ± 8.3	14.4 ± 4.1 [Ψ]
Elite	10	8.6 ± 1.5	127.3 ± 9.9	59.2 ± 6.2	27.2 ± 6.0	27.2 ± 6.0	72.8 ± 5.1	18.9 ± 4.0[▢]

[a] = Significantly greater than the early pre-pubertal group;
[b] = significantly greater than early and late pre-pubertal groups;
^= significantly greater than the recreational group;
[Ψ]= significantly greater than recreational and regional groups;
[▢]= significantly greater than all groups.

Isometric mid-thigh pull protocol—

All IMTP data were collected in a laboratory using a custom-built IMTP testing device with two force plates sampling at a frequency of 1000 Hz (9287BA, Kistler Instruments AG, Winterthur, Switzerland). The customized IMTP rig allowed incremental (1-cm) bar height adjustments to accommodate gymnasts of different statures. To increase reliability between trials, foot position was standardized using a customized 2-figure grid reference system, in which each participant's heel and forefoot position was repeated using adhesive markers (28). Each gymnast's IMTP set-up position replicated the second pull of a power clean (Figure 1) to optimize production of maximal force and rate of force development (31). In addition, feet were hip-width apart, bar positioned at mid-thigh, torso upright with a neutral spine, knee angle of 135° ± 5°, and hip angle of 140° ± 5° (28). Lifting straps were used to secure the gymnast to the bar to reduce likelihood of grip strength being a limiting factor for performance (13). Participants were instructed to "stand still like a statue and avoid pulling the bar" to optimize stabilization of body weight during the 3 s of each test, before initiating the pull (28). All gymnasts received the standardized instruction of "pull as hard and as fast as possible until I say stop" (13) and were instructed to pull equally with both hands. A countdown of "3, 2, 1, pull" was given to each participant, and verbal encouragement was provided throughout the 5 s data capture period while the gymnast worked maximally. Trials were discounted and repeated if the participant lost grip or if a visible countermovement was present. A minimum of 2 min of passive rest was provided between each trial to ensure sufficient recovery (14). All isometric force-time curves were analyzed by the same researcher using custom-built Labview (LVRTE2014SP1, National Instruments, Austin, TX, USA) analysis software (13). Initiation of the pull was determined using the visual onset method, which has been previously recommended (23). The following variables were processed for which reliability data has previously been reported (28):

- Absolute peak force (PF_{abs}): maximum force (N) generated during the 5 s protocol
- Relative peak force (PF_{rel}): maximum force generated during the 5 s protocol divided by athlete's body mass (N/kg)
- Force at 30, 50, 90, 100, 150, 200, and 250 ms: force (N) produced at each time sampling interval calculated from initiation of the pull
- Absolute rate of force development (RFD_{abs}): rate at which force developed during a maximal contraction ($N \cdot s^{-1}$); RFD was calculated from slope of the force-time curve during predetermined time bands: 0–50, 0–90, 0–100, 0–150, 0–200, and 0–250 ms (13)
- Relative rate of force development (RFD_{rel}): rate at which force developed during a maximal contraction ($N \cdot s^{-1}$) divided by athlete's body weight (N); RFD_{rel} was calculated for each predetermined time band: 0–50, 0–90, 0–100, 0–150, 0–200, and 0–250 ms
- Peak rate of force development ($pRFD_{abs}$): highest RFD during a 20-ms time sampling window (13)
- Relative peak rate of force development ($pRFD_{rel}$): highest RFD during a specific time sampling window divided by athlete's body weight (N)

Previous research has reported within-session reliability statistics for all IMTP in young female athletes for all variables presented in the current study (28). Acceptable reliability was reported for PF_{abs} and PF_{rel} (CV ≤ 7.5%), while analyses of force at specific time epochs revealed CVs between (CV = 22–33%). Greater variability was reported for RFD-related variables (CV ≥ 32%); therefore, results for these variables should be interpreted with an understanding of the heightened noise (28).

Vaulting—

Two-dimensional video analysis was used to determine gymnasts' vertical take-off velocity (m/s) from the springboard during execution of the straight vault. During vaulting trials, one stationary high-speed

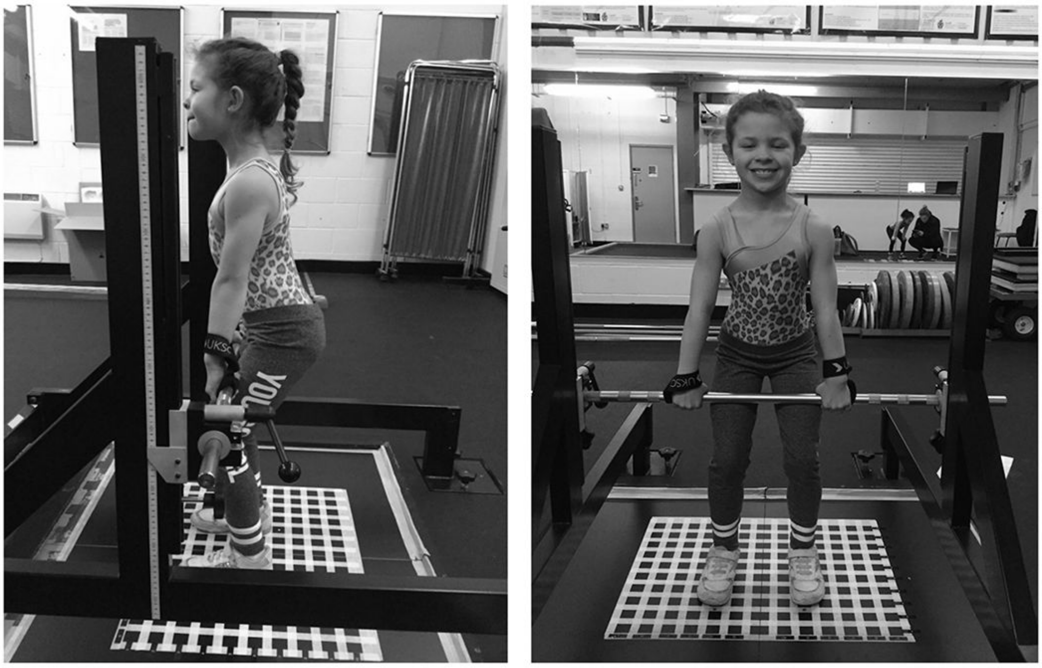

Figure 1 Isometric mid-thigh pull set up position anterior and lateral view (Moeskops et al., 2018)

camera (RX10 mark 3, Sony, Tokyo, Japan) operating at 250 Hz and a shutter speed of 1/500 of a second was positioned 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 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 (Fast-lift Model, Continental, West Yorkshire, UK) onto a landing mat (Safety Mat, Continental). The straight vault is the most basic vaulting exercise and was chosen to ensure all gymnasts were capable of performing the skill regardless of competitive level or maturity status. An additional thin mat (Supplementary Soft-Landing Mat, Continental, Country) that was shorter in length was placed on top of the landing mat to encourage gymnasts to perform the vault for maximum vertical jump height. All gymnasts received a standardized instruction to “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 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 same researcher. Digitizing was performed using a marker that was placed on the gymnasts' greater trochanter at the time of testing to increase accuracy. Vaulting data were filtered (MATLAB, R2018a) using a low-pass, 4th-order recursive Butterworth filter. Based on residual analysis (43), the most appropriate cut-off frequency was 10 Hz. Vertical take-off velocity from the springboard was calculated using the central difference method (43). The best vault was determined as the highest straight jump and was used for further analyses.

Statistical Analyses

Descriptive statistics (mean values ± SD) were calculated for all kinetic variables from the IMTP and vertical take-off velocity from the spring-board during vaulting for each maturity group and competitive group. Differences in IMTP and vaulting variables between maturity groups were assessed using 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 analyses were used to identify groups that were significantly different from one another using either Bonferroni or Games-Howell post-hoc analyses, where equal variances were and were not assumed, respectively. Differences in IMTP and vaulting variables between competitive-level groups were assessed using multivariate analysis of covariance (MANCOVA) to control for maturity (using %PAH as a covariate). Effect sizes (Cohen's d) were also calculated to establish the magnitude of between-group differences using the following classifications: <0.2, trivial; 0.2–0.59, small; 0.6–1.19, moderate; 1.2–1.99, large; 2.0–4.0, very large; >4.0, nearly perfect (16). Pearson correlation coefficients were used to determine the strength of relationships between all IMTP test variables and vertical take-off velocity for the whole sample. The strength of these relationships was classified based on previous recommendations (32): <0.2, no relationship; 0.2–0.45, weak; 0.45–0.7, moderate; >0.7, strong. Stepwise multiple regression analyses were used to establish the contribution of IMTP variables and maturity status (%PAH) to vertical take-off velocity from the springboard across the entire sample. The assumption of independent errors during multiple regression analyses was tested via a series of Durbin-Watson tests, and multi-collinearity was tested using variance inflation factor and tolerance diagnostics. All significance values were accepted at $p < 0.05$, and all statistical procedures were conducted using SPSS v.24 for Macintosh.

RESULTS

Grouped by maturity status

IMTP variables for early and late pre-pubertal and pubertal groups are displayed in Figure 3 and Table 3. For PF_{abs}, there was a large significant increase between early pre-pubertal and pubertal groups ($p < 0.01$; $d = 1.2$) and a moderate significant increase between early and late pre-pubertal groups ($p < 0.01$; $d = 0.6$). No significant differences were found for PF_{abs} between late pre-pubertal and pubertal groups, but a moderate effect size was evident ($d = 0.7$). There were no significant differences between any groups for PF_{rel}, and all effect sizes were trivial ($d = 0.05–0.15$).

Table 3 Maturity group analysis for all variables from the IMTP test (mean ± SD)

Group	Absolute force at 50 ms (N)	Absolute force at 90ms (N)	Absolute force at 150ms (N)	Absolute force at 200ms (N)	Absolute force at 250ms (N)
Early pre-pubertal	241.4 ± 78.1	275.9 ± 97.3	338.0 ± 143.0	405.8 ± 189.6	469.5 ± 227.2
Late pre-pubertal	311.7 ± 94.1[a]	338.0 ± 97.9[a]	409.2 ± 131.7	479.6 ± 162.4	551.0 ± 183.7
Pubertal	380.5 ± 90.1[a]	404.8 ± 98.2[a]	465.0 ± 109.0[a]	535.6 ± 130.2[a]	362.5 ± 166.9[a]
	Relative force at 50 ms (N/kg)	**Relative force at 90ms (N/kg)**	**Relative force at 150ms (N/kg)**	**Relative force at 200ms (N/kg)**	**Relative force at 250ms (N/kg)**
Early pre-pubertal	9.01 ± 2.10	10.34 ± 3.02	12.60 ± 4.50	15.07 ± 6.10	17.42 ± 7.51
Late pre-pubertal	9.35 ± 2.03	10.19 ± 2.26	12.39 ± 3.44	14.60 ± 4.71	16.86 ± 5.59
Pubertal	9.26 ± 1.91	9.86 ± 2.17	11.36 ± 2.72	13.16 ± 3.55	15.61 ± 4.73
	RFD_{abs} 0-50 (N/s)	**RFD_{abs} 0-90 (N/s)**	**RFD_{abs} 0-150 (N/s)**	**RFD_{abs} 0-200 (N/s)**	**RFD_{abs} 0-250 (N/s)**
Early pre-pubertal	433.2 ± 479.9	623.8 ± 68305	788.4 ± 727.0	930.4 ± 772.9	998.9 ± 769.6
Late pre-pubertal	242.0 ± 200.8	427.0 ± 389.7	730.8 ± 633.7	900.5 ± 686.1	1005.7 ± 657.6
Pubertal	268.8 ± 204.8	419.5 ± 379.7	652.8 ± 482.5	842.5 ± 530.7	1061.6 ± 604.0
	RFD_{rel} 0-50 (N/s)	**RFD_{rel} 0-90 (N/s)**	**RFD_{rel} 0-150 (N/s)**	**RFD_{rel} 0-200 (N/s)**	**RFD_{rel} 0-250 (N/s)**
Early pre-pubertal	1.7 ± 2.0[c]	2.4 ± 2.8[c]	3.0 ± 2.7[b]	3.5 ± 2.9[b]	3.8 ± 2.9
Late pre-pubertal	0.8 ± 0.7	1.4 ± 1.3	2.3 ± 2.0	2.9 ± 2.2	3.2 ± 2.1
Pubertal	0.7 ± 0.5	1.1 ± 1.0	1.7 ± 1.3	2.2 ± 1.4	2.7 ± 1.7

[a] = significantly greater than the early pre-pubertal group ($p < 0.05$)
[b] = significantly greater than the pubertal group ($p < 0.05$)
[c] = significantly greater than late pre-pubertal and pubertal groups ($p < 0.05$).
RFDabs = absolute rate of force development; pRFDabs = absolute peak rate of force development; RFDrel = relative rate of force development; pRFDrel = relative peak rate of force development

Absolute force measured at different time epochs showed significant, moderate to large increases between early pre-pubertal and pubertal groups for all time intervals ($p < 0.05$; $d = 0.7–1.4$). Significant, moderate differences were present between early and late pre-pubertal groups for absolute force at 50- and 90-ms time epochs only ($p < 0.05$; $d = 0.8$ and 0.6, respectively). However, small effect sizes were observed for force at 150–250-ms time epochs ($d = 0.4–0.5$). There were no significant differences between late pre-pubertal and pubertal groups for absolute force at 50–250-ms time epochs, although moderate to small effect sizes were found ($d = 0.36–0.7$). No significant

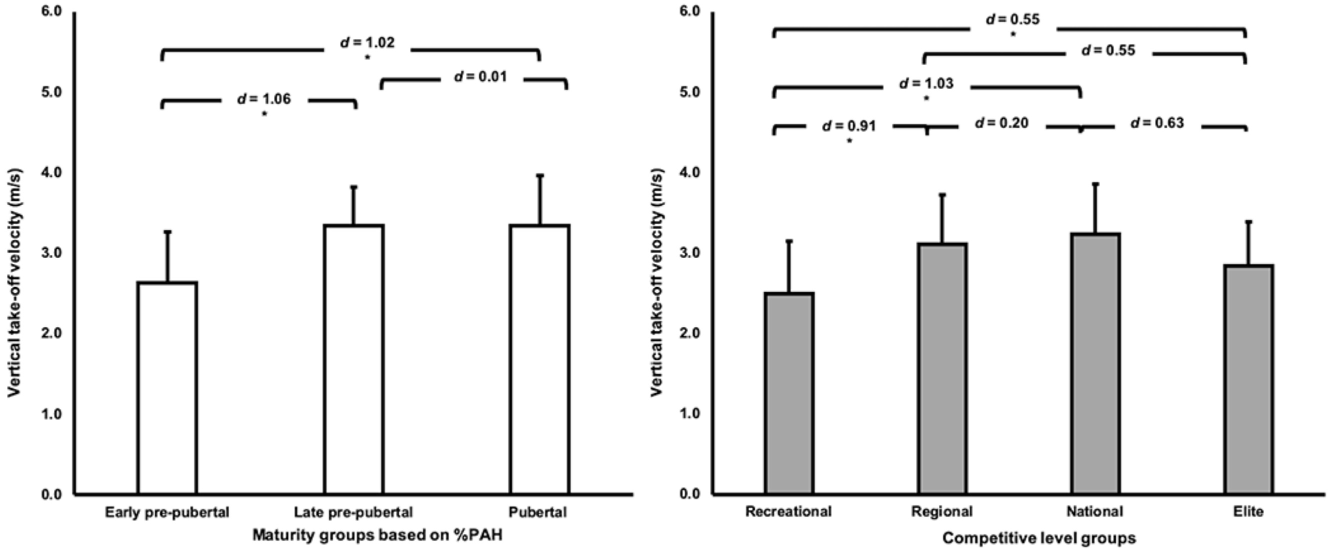

Figure 2 Maturity group analysis for absolute peak force, relative peak force, absolute peak RFD, and relative peak RFD. RFD = rate of force development.

differences were found between groups for relative force at different time epochs, RFD_{abs} at various sampling intervals and $pRFD_{abs}$ and all effect sizes were trivial or small (d = 0.02–0.4). Interestingly, RFD_{rel} at 0–50 and 0–90 N/s sampling intervals of the early pre-pubertal group was significantly greater than both the late pre-pubertal and pubertal groups ($p < 0.05$; d = 0.47–0.57) and significantly greater than the pubertal group at 0–150 and 0–200 N/s epochs ($p < 0.05$; d = 0.25–0.58). Further, early and late pre-pubertal groups had significant small to moderate increases in $pRFD_{rel}$ compared to the pubertal group ($p < 0.05$; d = 0.3 and 0.6, respectively). Results for vertical take-off velocity from the springboard are shown in Figure 3a, the pubertal ($p < 0.05$; d = 1.02) and late pre-pubertal groups ($p < 0.05$; d = 1.06) were observed to have significantly greater velocity than the early pre-prepubertal group (d = 0.01). No significant differences were evident between late pre-pubertal and pubertal groups for any IMTP or vaulting variables.

Grouped by competitive level

IMTP variables for recreational, regional, national, and elite groups are displayed in Figure 4 and Table 4. No significant differences were found among all groups for PF_{abs} and absolute force at different time epochs, and all effect sizes were trivial to small (d = 0.01–0.4). PF_{rel} and relative force at different time epochs showed a trend of increasing with competitive level, and although these increases did not reach statistical significance, trivial to moderate effect sizes were found (d = 0.05–0.71).

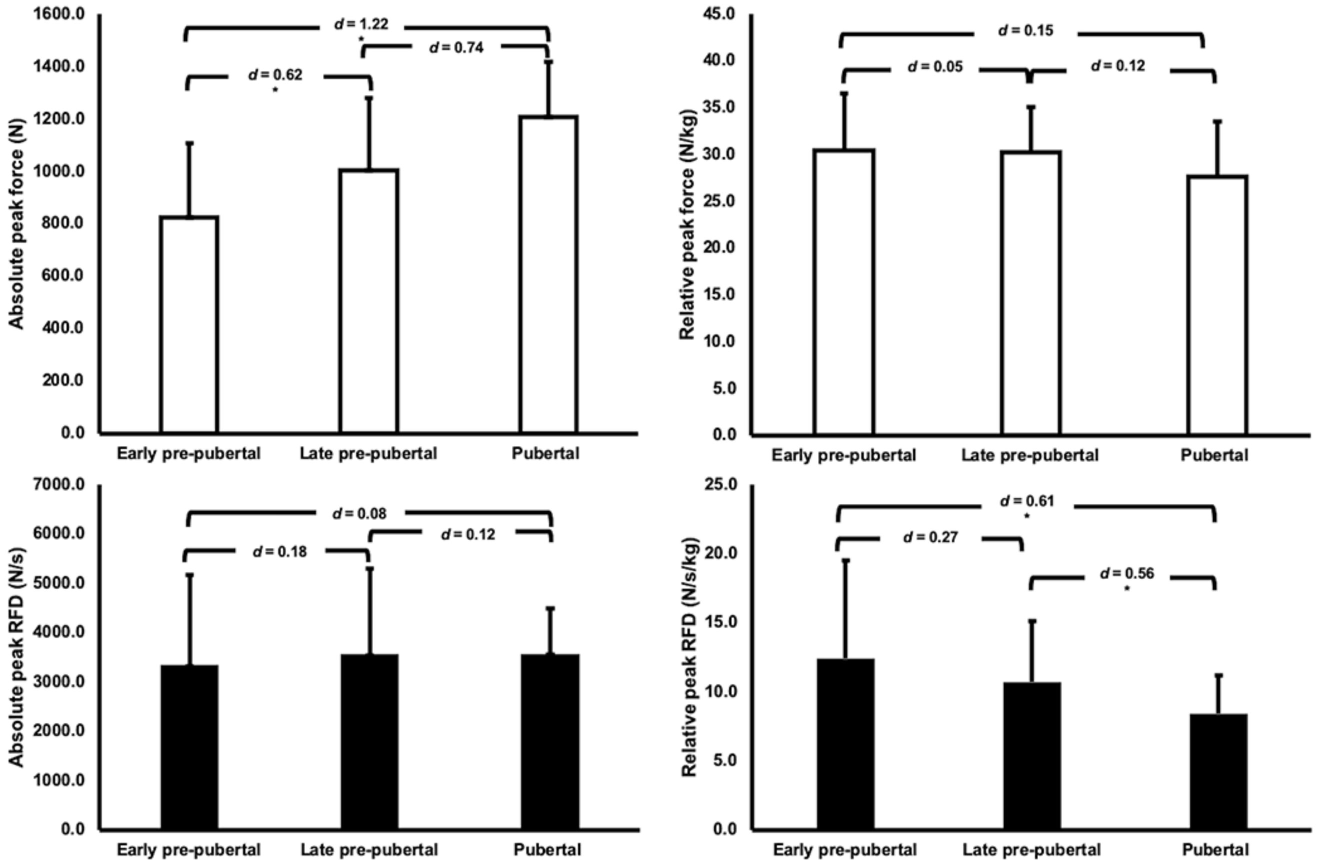

Figure 3 A and B) Maturity and competitive level group analysis for vertical takeoff velocity from the spring board during vaulting performance.

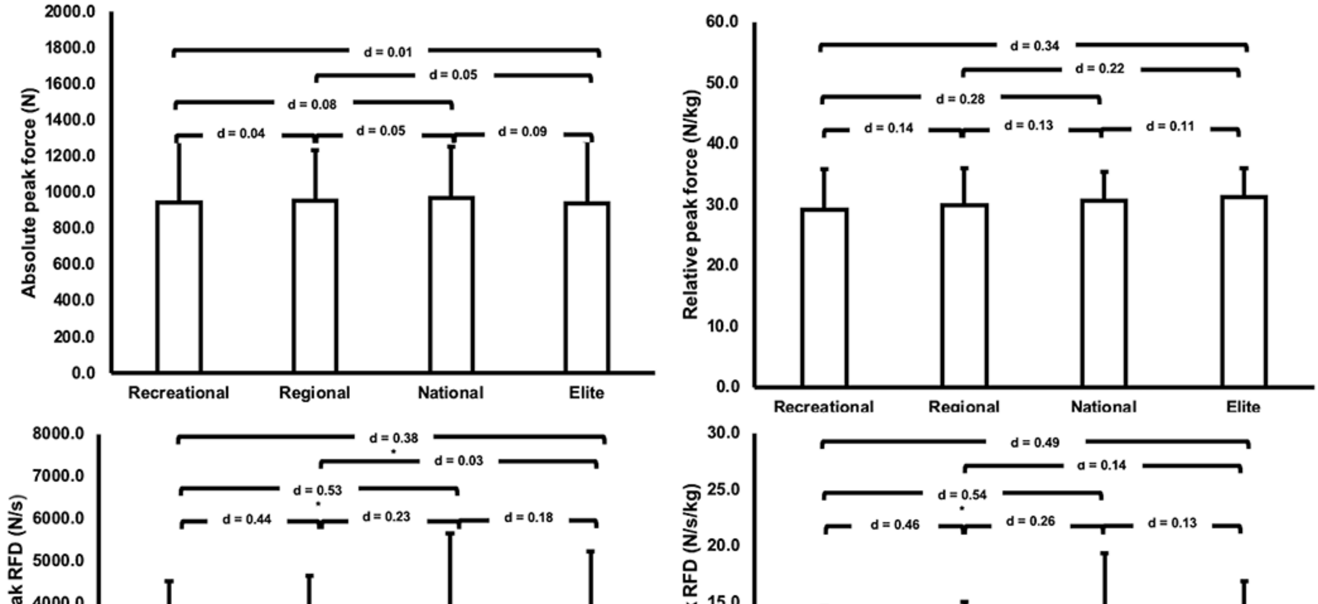

Figure 4 Competitive level group analysis for absolute peak force, relative peak force, absolute peak RFD and relative peak RFD

Table 4 Competitive level group analysis for all variables from the IMTP test, with maturity controlled by %PAH (mean ± SD)

Group	Absolute force at 50ms (N)	Absolute force at 90ms (N)	Absolute force at 150ms (N)	Absolute force at 200ms (N)	Absolute force at 250ms (N)
Recreational	291.3 ± 105.6	317.1 ± 119.9	354.8 ± 138.4	407.2 ± 165.7	646.2 ± 545.5
Regional	292.8 ± 110.7	321.2 ± 115.3	383.0 ± 354.8	448.0 ± 174.6	521.6 ± 196.7
National	295.1 ± 87.9	325.0 ± 94.5	400.2 ± 135.3	477.0 ± 172.5	543.8 ± 207.1
Elite	246.4 ± 85.8	308.0 ± 105.4	407.3 ± 174.0	502.0 ± 221.8	599.2 ± 277.0
	Relative force at 50ms (N/kg)	**Relative force at 90ms (N/kg)**	**Relative force at 150ms (N/kg)**	**Relative force at 200ms (N/kg)**	**Relative force at 250ms (N/kg)**
Recreational	9.1 ± 1.9	10.0 ± 2.9	11.2 ± 3.5	12.9 ± 4.8	15.1 ± 6.4
Regional	9.1 ± 2.1	10.0 ± 2.5	12.0 ± 3.7	14.2 ± 5.1	16.5 ± 6.0
National	9.4 ± 2.1	10.5 ± 2.6	12.9 ± 3.9	15.3 ± 5.0	17.4 ± 6.1
Elite	9.0 ± 1.9	10.5 ± 2.9	13.9 ± 5.1	15.1 ± 6.1	20.3 ± 8.8
	RFD_{abs} 0-50 (N/s)	**RFD_{abs} 0-90 (N/s)**	**RFD_{abs} 0-150 (N/s)**	**RFD_{abs} 0-200 (N/s)**	**RFD_{abs} 0-250 (N/s)**
Recreational	266.6 ± 306.8	434.0 ± 632.8	512.3 ± 498.9	646.2 ± 545.5	782.3 ± 628.0
Regional	303.4 ± 344.9	483.1 ± 526.6	702.5 ± 660.8	851.8 ± 690.5	975.5 ± 678.4
National	399.4 ± 462.2	554.2 ± 542.6	834.3 ± 662.3	1009.4 ± 690.5	1074.8 ± 690.0
Elite	333.4 ± 216.4	669.8 ± 495.5	1064.1 ± 769.2[a]	1271.2 ± 790.0[a]	1405.9 ± 850.0[b]
	RFD_{rel} 0-50 (N/s)	**RFD_{rel} 0-90 (N/s)**	**RFD_{rel} 0-150 (N/s)**	**RFD_{rel} 0-200 (N/s)**	**RFD_{rel} 0-250 (N/s)**
Recreational	0.9 ± 1.2	1.3 ± 0.7	1.7 ± 2.0	2.2 ± 2.2	2.7 ± 2.4
Regional	1.0 ± 1.2	1.6 ± 1.0	2.4 ± 2.3	2.8 ± 2.5	3.2 ± 2.4
National	1.5 ± 2.0	1.6 ± 0.9	2.8 ± 2.3	3.4 ± 2.3	3.6 ± 2.3
Elite	1.2 ± 0.8	2.0 ± 0.7	3.7 ± 2.6	4.4 ± 2.7[a]	4.9 ± 3.0[a]

[a] = significantly greater than the recreational group ($p < 0.05$)
[b] = significantly greater than recreational and regional groups ($p < 0.05$).
RFDabs = absolute rate of force development; pRFDabs = absolute peak rate of force development; RFDrel = relative rate of force development; pRFDrel = relative peak rate of force development

There were significant moderate increases in RFD_{abs} between elite and recreational groups for $pRFD_{abs}$, 0–150, 0–200, and 0–250 ms ($p < 0.05$; $d = 0.4–0.9$) and between elite and regional groups for RFD_{abs} 0–250 ms ($p < 0.02$ $d = 0.6$). A small significant increase in $pRFD_{abs}$ was also observed between national and recreational groups ($p < 0.04$ $d = 0.5$). No other significant differences were observed between groups for any other RFD_{abs} or other time-related variables, and only trivial or small effect sizes were found ($d = 0.16–0.5$). For RFD_{rel} variables, there were significant moderate increases between elite and recreational groups for 0–200 and 0–250 ($p < 0.05$; $d = 0.8–0.87$) and a small significant increase between national and recreational groups for $pRFD_{rel}$ ($p < 0.01$; $d = 0.54$). No other significant differences were present among groups for RFD_{rel} or $pRFD_{rel}$, although trivial to moderate effect sizes were found ($d = 0.13–0.6$). For vertical take-off velocity from the springboard, the recreational group had a significantly lower take-off velocity than all other competitive groups (all, $p < 0.05$; elite, $d = 0.55$; national, $d = 1.03$; regional, $d = 0.91$) as shown in figure 3b.

Correlations and regression analyses

Vertical take-off velocity had weak significant relationships with the following IMTP variables: PF_{abs} ($r = 0.38$; $p < 0.01$), PF_{abs} at 200 ms ($r = 0.40$; $p < 0.01$), PF_{rel} at 50 ms and 150 ms ($r = 0.29$ and $r = 0.36$; $p < 0.01$), and RFD_{abs} between 0–50, 0–150, and 0–250 ms ($r = 0.34$, $r = 0.20$, $r = 0.30$; $p < 0.01$). No other significant relationships were observed between vertical take-off velocity and the remaining IMTP variables. Multiple stepwise regression analysis across the whole sample showed that variation in vertical take-off velocity during vaulting performance was best explained by force at 50 ms (15%) and %PAH (7%), accounting for 22% of total variance.

DISCUSSION

This study is the first to examine differences in IMTP force-time curve variables in young female gymnasts grouped according to biological maturity and competitive level. The main findings of the current study are that PF_{abs} and absolute force at various time epochs are significantly greater in more mature gymnasts. When grouped by competitive level, elite gymnasts produced greater $pRFD_{abs}$ and RFD_{abs} at 0–150, 0–200, and 0–250 ms than those competing at a recreational-level, and all effect sizes were small to moderate. Similarly, elite-level gymnasts had significantly higher RFD_{rel} at 0–200, 0–250 epochs than recreational-level gymnasts. Finally, regression analyses revealed that the IMTP and %PAH explains just 22% of vertical take-off velocity during vaulting performance.

Grouped by biological maturity

This study indicates that biological maturation impacts isometric force-time variables in young female gymnasts. PF_{abs} and force at various time epochs increased with maturity, with the most mature cohort of gymnasts significantly stronger than their more immature peers. A similar pattern was observed between the least mature groups, with the late pre-pubertal group producing significantly more PF_{abs} and force at 50–90 ms than the early pre-pubertal group. Maturity-associated increases in absolute muscular strength in this study are likely attributed to natural development of the neuromuscular system (25). Specifically, growth- and maturity-related increases in muscle size and therefore muscle cross-sectional area enhance force-producing capabilities in youth (25, 33).

When normalized to body mass, significant between-group differences in peak force were not evident, which is consistent with previous IMTP data for pre- and post-peak height velocity in female athletes (28). Specifically, PF_{rel} and relative force at different time epochs in our cohort of young female gymnasts were unchanged with increasing maturity, as there were no significant differences and trivial to small effect sizes between groups. However, previous research in youth female soccer players has shown relative PF during an IMTP decreases with maturational status in pre-, circa-, and post-peak height velocity (9). As artistic gymnastics demands high relative power-to-mass ratios for acrobatic skills (11), it is likely that exposure to gymnastics training (all maturity groups, ~11 h/week) enabled the levels of relative strength to remain stable for gymnasts across maturity groups in the current study. Further, these data indicate that young female gymnasts could benefit from strength and conditioning provision that offers an alternative training stimulus to enhance relative strength beyond that of sport-specific training.

The results for $pRFD_{abs}$ and RFD_{abs} at different time sampling intervals revealed no significant differences between all maturity groups. In light of existing literature, these data indicate that absolute time-dependent variables are less sensitive to changes in biological maturation during the period of development examined. However, our study did not include a post-pubertal group, so how these isometric force-time measures differ as gymnasts become fully mature remains unknown. Previous literature examining child-adult differences suggests adults have greater absolute RFD capabilities than youth due to structural and neuromuscular adaptations, including increases in muscle size (31), fascicle length (1), muscle activation rate (10), and ability to recruit high-threshold type II motor units (10). It is therefore likely that with further growth and maturation, post-pubertal female gymnasts will produce higher RFD_{abs} than less mature girls.

Greater variability has been reported for time-related variables such as RFD (CV = 45-145%) in young females (28); thus, data for such variables should be interpreted with caution. Notwithstanding the heightened variability, the current study indicated that advancing maturity appeared to have a negative effect on relative measures of RFD in young female gymnasts, whereby the least mature group of gymnasts produced significantly greater $pRFD_{rel}$ and RFD_{rel} at every time sampling interval except 0–250 ms. Further, the late pre-pubertal group also produced significantly more $pRFD_{rel}$ than the pubertal group. Although the IMTP is isometric in nature, practitioners should be aware of these potential maturity-related deficits in RFD_{rel}, which could result in concomitant reductions in performance (e.g., more mature female gymnasts may become less able to move their relatively greater mass as quickly, effecting their ability to perform jumps, leaps, etc.).

Grouped by competitive level

As biological maturity has been shown to influence IMTP measures in young gymnasts (e.g. in the present study, increasing PF_{abs} with maturity), %PAH was used as a covariate to control for such differences across competitive level. When grouped by competitive level, we found no significant difference between any groups for PF_{abs} or absolute force at different time epochs, and all effect sizes were either trivial or small. However, we observed a trend of increasing PF_{rel} and relative force at various time epochs with competitive standard, particularly for later time epochs (i.e., 150 ms onwards). The elite-level group produced greater force at 150, 200, and 250 ms than all other competitive groups, and small to moderate effect sizes were present. Similarly, the national-level group also produced more force at these time epochs than regional and recreational groups, with trivial to small effect sizes. While these increases were not statistically significant, higher-level gymnasts appear to possess greater relative maximal force-producing capabilities than their lower-level peers.

Elite gymnasts produced significantly greater RFD_{abs} values than recreational ($pRFD_{abs}$, 0–150 ms, 0–200 ms, and 0–250 ms) and regional (0–250 ms) gymnasts. Further, national gymnasts produced the highest $pRFD_{abs}$ of all groups, and this was significantly greater than recreational gymnasts, albeit a small difference. A similar trend was observed for RFD_{rel} values, in which higher-level gymnasts produced greater RFD_{rel} than their lower-level counterparts. Small to moderate significant differences were observed between elite and recreational gymnasts for RFD_{rel} at 0–150, 0–200, and 0–250 ms. However, national gymnasts produced significantly higher $pRFD_{rel}$ than the recreational group. Thus, it is conceivable that differences in RFD are a result of higher training loads that young elite gymnasts experience (elite group = 18.9 ± 4.0 hr/week versus recreational group = 4.4 ± 1.8 hr/week) as well as heightened exposure to more forceful muscle actions at higher velocities that are required for more technically advanced skills (11). Cumulatively, these data suggest that the ability to produce higher amounts of force in shorter periods of time could be important variables of high-level young female gymnasts. However, it should be noted that the greater variability of RFD variables during the IMTP, could reduce the likelihood of finding significant differences between maturity or competitive groups, or following training interventions in young females (28). Nevertheless, all significant differences observed in RFD_{abs} measures in the present study were greater than the previously reported typical errors, with the exception of $pRFD_{abs}$ (28).

Correlation analyses

Previous research in adult populations has shown that variables such as PF_{abs}, absolute impulse over 100, 200, and 300 ms, and RFD during the IMTP are significantly correlated with athletic tasks, such as vertical jump performance (PF and peak power) (40), 5-m acceleration, and pro agility time (42). Conversely, regression analyses in the present study revealed that force at 50 ms was the only IMTP variable to predict vertical take-off velocity from the springboard during vaulting performance, accounting for just 15% of variance. Adding %PAH to the model increased explained variance to 22%. Vertical take-off velocity had only weak significant relationships with other IMTP variables. These data indicate that a large proportion (~80%) of variance in vertical take-off velocity during vaulting remains unexplained. Additional variables, potentially obtained from alternative test protocols, could have stronger relationships and explain higher proportions of variance in gymnasts' vertical take-off velocity. Intuitively, tests that more closely reflect dynamic stretch-shortening cycle muscle-tendon actions involved in gymnastics vaulting may have higher predictive capabilities than the IMTP protocol (i.e., jump and sprint tests). While this is the first study to explore predictors of vaulting performance using IMTP force-time curve variables, Bradshaw and Rossignol (3) investigated the best predictors of tumbling and vaulting ability from various tests in 8–14-year-old female gymnasts. Regression analyses revealed that vaulting score was best predicted by faster resultant take-off speed, higher squat jump power, and decreased power during the last 5 jumps of a 30-s continuous jump test (3). Together, these variables explained 80% of common variance, and squat jump force had a strong significant relationship with vaulting ability ($r = 0.72$) (3). However, maturational status of participants was not included in the regression analyses, which could have resulted in explanation of an even higher proportion of variance. Thus, from available literature, dynamic tests may explain higher proportions of variance during vaulting performance than isometric force-time variables from the IMTP, although more research is needed to explore this topic further.

Certain limitations should be noted in this study. For example, differences in IMTP force-time curve variables between maturity groups were presented and inferred in this cross-sectional data set, although future research is required to track the natural development of youth female gymnasts across a longitudinal timeframe to confirm this study’s findings, ideally also incorporating a post-pubertal stage of development. A further limitation is differences in sample sizes of the subgroups when gymnasts were grouped by maturity status or competitive level. Despite these limitations, the current study makes a novel and significant contribution to the pediatric literature, indicating that isometric force production increases with maturation and competitive level but only predicts a small amount of variance in specific gymnastics performance (i.e., vaulting take-off velocity).

Practical applications

The current study shows that the IMTP test can provide useful insight into underpinning mechanical variables (e.g., force-time curve variables) of young female gymnasts’ strength and power expression from different maturity status or competition levels. As we observed a trend of reduced RFD_{rel} with advancing maturity, it is paramount that relative RFD and strength are targeted in the pre-pubertal years and continuously prioritized throughout childhood and adolescence in female gymnasts. Providing technical competency can be maintained and adaptations are sought with a long-term approach, programs should seek to increase RFD_{rel} and PF_{rel} in gymnasts using an integrated approach, with higher loading intensities and volumes. Higher-level young gymnasts were found to produce greater RFD_{abs} and RFD_{rel} than lower-level gymnasts, indicating the ability to produce large amounts of force in short time periods develops with training experience. Given the high volumes of training associated with the sport, it should be noted that strength and conditioning coaches working with young gymnasts must program in an integrative and holistic manner. Where possible, practitioners should work closely with technical coaches to incorporate strength and conditioning activities that have high training relevance for gymnastics (e.g. enhancing rebounding, jumping and landing abilities). Communicating with technical staff to show how exercises transfer positively to sports performance is an integral part of building a holistic athletic development program. Crucially, programs should aim to develop overall athleticism, reduce the relative risk of gymnastics-related injuries and ensure enjoyment remains central to the program.

While force-time data in the IMTP failed to explain high proportions of variance in vaulting take-off velocity, the data can be used in practice to determine overall training effectiveness and is viewed as an appropriate test to assess changes in isometric force capacity in young athletes. Further, these data (in particular, relative force values) could be used for benchmarking purposes to help inform training prescription and ensure the unique demands of individuals are met. For example, practitioners could use z-scores or percentiles to direct training prescription and provide feedback to gymnasts or coaches. For example, in this data set, the 10th, 50th, and 90th percentiles for PF_{rel} were 23.8 N/kg, 29.5 N/kg, and 38.1 N/kg, respectively. Should a gymnast report as a low percentile, training should then be directed to improving relative strength.

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