

**THE EFFECTS OF GROWTH, MATURATION AND
TRAINING ON STRENGTH AND POWER
DEVELOPMENT IN YOUNG ARTISTIC FEMALE
GYMNASTS**

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A thesis submitted to the School of Sport and Health Sciences at Cardiff
Metropolitan University in fulfilment of the requirements for the degree of
Doctor of Philosophy in December 2020

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Abstract

Female artistic gymnastics demands a combination of physical abilities including strength, power and speed to perform a diverse set of skills. Although gymnasts' training typically commences early in the prepubertal years, very little is known about how these physical qualities develop due to the interaction of maturation and training and how these measures influence vaulting performance. Chapter 3 showed that within- and between-session measures of absolute (PF_{abs}) and relative peak force (PF_{rel}) from an isometric mid-thigh pull (IMTP) test were reliable for both pre-peak height velocity [PHV] ($CV \leq 9.4\%$, $ICC \geq 0.87$) and post-PHV ($CV \leq 7.3\%$, $ICC \geq 0.92$). However, systematic bias was evident between-sessions 1 and 2 in the pre-PHV group. Therefore, the IMTP was deemed a reliable method of measuring peak force in pre- and post-PHV female athletes, providing that pre-PHV athletes attend an additional familiarisation session.

Chapters 4-6 revealed that the majority of absolute isometric and dynamic force-time variables from the IMTP and jumping protocols increase with maturation. The IMTP results showed PF_{abs} and absolute force at various time epochs were significantly greater in the most mature cohort compared to the least mature group of gymnasts ($p < 0.05$; all $d > 0.60$). Vertical jumping performance improved with biological maturity, as evidenced by the most mature gymnasts' producing significantly more absolute force ($p < 0.05$; all $d > 0.78$), impulse ($p < 0.05$; all $d > 0.75$), power ($p < 0.05$; all $d > 0.91$) and jump heights ($p < 0.05$; all $d > 0.70$) than the least mature group. No significant differences were observed in PF_{rel} across the jumping tests, although measures of relative peak power (PP_{rel}) did significantly increase with maturity. All sprint-speed measures, standing long jump (SLJ) distance and vaulting vertical take-off velocity were significantly greater in the more mature gymnasts ($p < .001$; $d > 0.65$). Thus,

maturation appears to have a significant influence on absolute isometric and dynamic force-time variables, sprint speed and vaulting vertical take-off velocity.

Chapters 4-6 also indicated that across all tests, peak speed during a 20 m sprint protocol has the strongest association with vaulting vertical take-off velocity ($R^2 = 59\%$) and also identified the ratio of vertical to horizontal take-off velocity ($\text{Ratio}_{\text{vert-hori}}$) as a secondary determinant ($R^2 = 12\%$). Multiple regression analyses also revealed that of the jumping protocols, ground contact time (GCT) and centre of mass displacement ($\text{COM}\Delta$) from the drop jump [DJ] (14%), combined with maturity status (41%) had the highest predictive ability of vertical take-off velocity ($R^2 = 55\%$). However, the IMTP failed to explain a large amount of variance ($R^2 = 15\%$). Data indicate that maturation influences vaulting vertical take-off velocity in young female gymnasts. Furthermore, our results highlight the importance of targeting peak sprint speed alongside take-off technique to develop gymnasts' ability to transfer linear speed to vertical take-off velocity.

Study 4 (chapter 7) showed young female gymnasts significantly improved various kinetic determinants of strength and power, sprint speed and vaulting take-off velocity after participating in 10-months of supplementary neuromuscular training (GYM+NMT); changes that were not typically evident in the gymnastics-training only (GYM) or maturity-matched control (CON) groups. Analyses revealed that the observed significant adaptations in the GYM+NMT training group occurred at different stages of the 10-month training program and varied in magnitude ($p < 0.05$; $g = 0.44-1.15$). Isometric PF_{abs} , horizontal jump distance and $\text{Peak}_{\text{momentum}}$ during sprinting significantly improved at each testing session from baseline. After 7-months of NMT, significant improvements were shown in isometric PF_{rel} , CMJ height and RSI and jump height in the DJ. The NMT stimulus took longer to transfer to sprinting and

vaulting performance, with peak sprint speed, spring-like behaviour in the DJ, and vaulting vertical take-off velocity significantly improving after 10-months. Overall, the findings from this study indicate that supplementary NMT can stimulate improvements in strength, power, speed and vaulting performance above and beyond those achieved through gymnastics training alone.

Acknowledgments

Completing this thesis over the past four years has been a very challenging and hugely rewarding learning experience. I am truly grateful for the support I have received from so many people along the way.

I must first thank Professor Rhodri Lloyd as my Director of Studies for his continuous support and outstanding guidance throughout this process. I feel very fortunate to have been supervised by him right through from my undergraduate studies to my Masters and now PhD; eight years and counting! I will always be grateful for his mentoring and expertise in both an academic context and in an applied coaching setting. His hard work and passion for research is inspiring and I feel fortunate to consider him both as a colleague and friend.

My gratitude also goes to my expert supervisory team, who have played an integral part in the completion of this thesis. Professor Jon Oliver has developed my understanding of data analyses and statistics and provided me with many valuable insights along the way. I will always be thankful as well for the guidance, feedback and expertise that Dr. Paul Read, Professor Greg Myer, Professor John Cronin, Professor Greg Haff and Dr. Isabel Moore have given me when reviewing this thesis.

I would not be in the position of now being able to conclude my work, without the help of all those who assisted with the endless amounts of data collection required. Researching with youth populations inevitably involves testing during evenings and weekends, so I am extremely grateful to those who gave up their time. Steph Morris and Tom Mathews were brilliant at troubleshooting equipment and have been huge a support throughout the process! I must also thank Dr John Radnor and Nakul Kumar who helped at the majority of testing sessions as well.

The support and love from my close family and friends throughout this process has been essential. My mum has provided me with endless amounts of love, support and wisdom. The passion I have for gymnastics was fostered by her from a young age, mostly in an endeavour to use up my energy!

My final thanks goes to my partner PJ, who has encouraged me at every step along the way and always tries to instil me with confidence. His love for Excel and writing Macros has at times been proved to be surprisingly useful! I am looking forward to the next chapter in our life together.

Publications and Presentations from the Thesis

Peer-reviewed journal articles

Moeskops, S., Oliver, JL., Read, PJ., Cronin, JB., Myer, GD. and Lloyd, RS. The physiological demands of youth artistic gymnastics; applications to strength and conditioning. *Strength Cond J.* 2018;41(1):1-13

Moeskops, S., Oliver, JL., Read, PJ., Cronin, JB., Myer, GD., Haff, GH. and Lloyd, RS. Within- and between-session reliability of the isometric mid-thigh pull in young female athletes. *J Strength Con Res.* 2018;32(7):1892–1901

Moeskops, S., Oliver, JL., Read, PJ., Cronin, JB., Myer, GD., Haff, GH. and Lloyd, RS. The influence of biological maturity and competitive level on isometric force-time curve variables and vaulting performance in young female gymnasts. *J Strength Con Res.* 2020;34(8) 2136–2145.

Moeskops, S., Oliver, JL., Read, PJ., Cronin, JB., Myer, GD., Haff, GH., Moore, IS. and Lloyd, RS. The influence of biological maturity on dynamic force-time time variables and vaulting performance in young female gymnasts. *J Sci Sport Ex.* 2020;1-11

Moeskops, S., Oliver, JL., Read, PJ., Myer, GD., Haff, GH. and Lloyd, RS. (in press) The influence of biological maturity on sprint speed, standing long jump and vaulting performance in young female gymnasts. *Int J Sport Physiol.*

Moeskops, S., Oliver, JL., Read, PJ., Cronin, JB., Myer, GD. and Lloyd, RS. Practical strategies for integrating strength and conditioning into early sport specialization athletes *Strength Cond J.* under review

Moeskops, S., Oliver, JL. Read, PJ. Cronin, JB. Myer, JD. and Lloyd, RS. The effects of a 10-month neuromuscular training program on isometric and dynamic force-time characteristics, speed and vaulting take-off velocity in young female gymnasts. *Med Sci Sports Exerc.* under preparation

Oral presentations

Project SPRING: Developing strength and power in young female gymnasts. Middlesex University Student Conference. March 2020.

Strength and Conditioning for Young Female Gymnasts: Research and Practical Applications. Hartpury University. November 2020.

Poster presentations

Moeskops, S., Oliver, JL., Read, PJ., Cronin, JB., Myer, GD., Haff, GH. and Lloyd, RS. (2018) The effects of maturity status on isometric mid-thigh pull kinetics in young female gymnasts. Proceeding of the UKSCA's 11th Annual Conference, Double Tree by Hilton, Milton Keynes, August 2018.

Moeskops, S., Oliver, JL., Read, PJ., Cronin, JB., Myer, GD., Haff, GH., Morris, SJ. and Lloyd, RS. (2019) The effects of a 12-week neuromuscular training intervention on isometric mid- thigh pull kinetics and drop jump performance in trained young female. Proceeding of the UKSCA's 12th Annual Conference, Double Tree by Hilton, Milton Keynes, June 2019.

Moeskops, S., Oliver, JL., Read, PJ., Cronin, JB., Myer, GD., Haff, GH. and Lloyd, RS. (2020) Effects of a 9-Month Neuromuscular Training Programme on Isometric and Dynamic Force-Time Characteristics and Vaulting Take-Off Velocity in Trained Young Female Gymnasts. Proceedings of the National Strength and Conditioning Association (NSCA). National Conference.

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Abbreviations and Nomenclature

AMSC	Athletic motor skill competencies
ANCOVA	Analysis of covariance
ANOVA	Analysis of variance COM Centre of mass
CMJ	Countermovement jump
CV	Coefficient of variation
DJ	Drop jump
FT	Flight time
GCT	Ground contact time
JH	Jump height
ICC	Intra-class correlation
Impulse _{brake}	Braking impulse
Impulse _{prop}	Propulsive impulse
IMTP	Isometric mid-thigh pull
LTAD	Long-term athletic development
NMT	Neuromuscular training
PAH	Predicted adult height
PF _{abs}	Absolute peak force
PF _{rel}	Relative peak force
PHV	Peak height velocity
Power _{brake}	Braking average power
Power _{prop}	Propulsive average power
pRFD	Peak rate of force development
PW	Propulsive work
PWV	Peak weight velocity
Ratio _{vert-hori}	Ratio of vertical to horizontal take-off velocity
RFD _{abs}	Absolute rate of force development
RFD _{rel}	Relative rate of force development
RSI	Reactive strength index
SJ	Squat jump
SLC	Spring-like correlation
SLJ	Standing long jump
SSC	Stretch-shortening cycle
Stiffness _{rel}	Relative vertical stiffness
SWC	Smallest worthwhile change
Time _{brake}	Braking phase duration
Time _{prop}	Propulsive phase duration
TPF	Time to peak force
TPRFD	Time to peak rate of force development
Work _{brake}	Braking average work
Work _{prop}	Propulsive average work
1RM	One repetition maximum
ΔCOM	Centre of mass displacement

Chapter 1:

Introduction

1.1 OVERVIEW

Artistic gymnastics is a subdiscipline of gymnastics that has become increasingly popular in recent years (123), attracting high participation rates within the sport amongst children and adolescents (81, 94). Female artistic gymnastics involves four different apparatus; the vault, asymmetric bars, balance beam and floor exercise. While the physiological and technical skill requirements of each apparatus differ markedly (123), the sport demands a combination of physical abilities including: strength, power, speed, flexibility, balance and co-ordination (274). With the exception of the asymmetric bars, maximizing lower-limb strength, power and speed in gymnastics is important for generating longer flight times to allow the performance of complex vaults and acrobatic sequences on the beam and floor exercise (24). Existing research in youth indicates that the natural development of these physical qualities and motor skills is non-linear, with growth- and maturity-related adaptations varying across different stages of development (156, 170). Given that female gymnasts' training typically commences early in the prepubertal years (32, 267), understanding the potential effects of the biological processes that occur as gymnasts grow and mature on measures of strength, power and speed is warranted.

Unlike many other sports, physical preparation for gymnasts is prioritised by technical coaches from a young age and typically involves high training volumes of body-weight, skill-driven activities (276). Whilst the importance of training specificity is recognised in gymnastics (279), relevant, supplementary neuromuscular training (NMT), which develops gymnasts' strength, power and speed, could enhance gymnasts' performance beyond gymnastics training alone.

However, the effectiveness of strength and conditioning training programmes in young female gymnasts (and female youth overall) remains a very under-researched topic. Furthermore, very few studies in youth have examined training responses to longer-term training interventions. Given the growing interest in long-term athletic development (LTAD), and the need for youth to engage in long-term strength and conditioning, establishing better insights into the potential role of longer duration training programmes which are implemented early in childhood is important.

1.1.1 Assessing strength, power and speed in young female athlete

Successful performance of athletic tasks (e.g. accelerating, jumping, rebounding) in many sports rely on the ability to express force at various velocities in a skilful manner (155). Consequently, assessments of strength, power and speed are often included in testing batteries to determine physical profiles of young athletes (197, 274, 290). Current paediatric research has explored these physical qualities using dynamic jumping and sprinting protocols, with some studies reporting reliability data in youth across various stages of biological maturity (161, 196, 235). However, research examining maximal muscular strength in young athletes is more limited and has typically involved one repetition maximum (1RM) or predictive RM tests (72, 152). The isometric mid-thigh pull (IMTP) is a commonly used force-time diagnostic tool for assessing the maximal force producing capacities of adult athletes (98, 137, 190). Unlike the RM tests, IMTP data can provide useful kinetic measures (e.g. peak force, rate of force development), is time-efficient, and can be performed with those who have a lower training age or cannot consistently perform exercise techniques correctly (97, 130). Whilst numerous variables from the IMTP test have been shown to be highly reliable in adult populations (43, 52, 97, 98), minimal data exists in adolescents and none at present in children. One study in adolescent male soccer players found peak force to be highly reliable and demonstrated more

variability in time-specific force values (58); however, these data only reflect adolescent male athletes. **Therefore, the reliability of the IMTP in female child and adolescent athletes is currently unknown.**

1.1.2 Influence of growth and maturation on strength, power and speed in young females

On the journey to reaching full maturity, young athletes will experience growth and maturation, which influences the natural development of physical fitness and motor skill performance (68). Empirical evidence shows that differences in strength, power and speed exist between children and adolescents (170, 309); however, the development of these physical qualities follows a nonlinear process, which is highly variable between individuals (68). For example, research shows youth experience both steady and rapid periods of development (i.e. *preadolescent* and *adolescent spurts*) which are underpinned by various adaptations that are likely to influence their physical performance (68, 309). However, unlike males, females gain natural increases in fat mass during adolescence which may negatively impact certain physical qualities, such as relative strength levels (217) and consequently, aspects of performance (68, 170). Therefore, superior insight could be gained by interpreting performance testing results in relation to biological maturity as this would provide practitioners with useful information to prescribe more individualised training programmes. With this knowledge, practitioners could also be better equipped to distinguish between training-induced adaptations and those resulting from growth and maturation. Unfortunately, very limited data of this nature exists in young females, especially in young female gymnasts, with existing studies grouping gymnasts according to chronological age (24, 286). **Cumulatively, how measures of strength, power and speed differ between stages of biological maturity in female gymnasts remains unclear.**

1.1.3 Relationships between indices of strength, power and speed on vaulting performance

Of the available literature, investigations into the predictors of vaulting performance in gymnasts have demonstrated the importance of run-up speed (25, 249), squat jump power (24) and the visual targeting abilities of gymnasts (21, 25). However, the relationship between strength, power and speed indices, and vaulting vertical take-off velocity in young female gymnasts has yet to be fully explored. Whilst some research has explored the influence of chronological age on aspects of vaulting performance (24, 26), currently no studies have examined the impact of biological maturity on vaulting performance in young female gymnasts. Establishing the key determinants of vaulting take-off velocity and the influence of biological maturation on vaulting performance would enable practitioners to subsequently target these physical qualities and develop more individualized training programmes for gymnasts. **It is clear that the relationship between indices of strength, power and speed on vaulting performance in young female gymnasts of different maturity status is yet to be fully explored.**

1.1.4 Effects of long-term neuromuscular training on measures of strength, power and speed in young female athletes

One training mode that aims to elicit adaptations through combining a range of training methods is NMT, which includes resistance training, plyometrics, speed, dynamic balance/stabilization and postural control (66). Despite a growing body of research showing the benefits of neuromuscular training provision for enhancing physical performance measures in youth (57, 66, 240), minimal data exists in young female athletes. Furthermore, the efficacy of NMT on measures of strength, power and speed and sport-specific performance measures

(e.g. vaulting vertical take-off velocity) in female youth is very limited. Another limitation of current NMT studies in youth-based research is that training interventions have been primarily short-term in nature (57, 66, 209, 240). Overall, longitudinal research designs exploring the efficacy of NMT in young athletes remains an under-researched topic in paediatric literature, particularly in females. Training programmes that promote LTAD and improvements in physical qualities that transfer to sport-specific performance (strength, power and speed), would therefore be desirable. **Thus, the effects of a longer-term NMT program on measures of strength, power and speed and vaulting take-off velocity in female gymnasts is yet to be determined.**

1.2 AIMS AND OBJECTIVES

In light of the existing evidence within the paediatric and gymnastics-based research, the aim of the current thesis is to investigate the influence of growth, maturation and training upon measures of strength, power and speed, and the influence of these variables on vaulting take-off velocity in a sample of young female gymnasts.

In order to explore and address existing gaps in knowledge identified in *section 1.1*, the specific aims of the thesis are as follows:

1. Establish the within- and between-session reliability of the IMTP protocol in pre- and post-peak height velocity (PHV) females.
2. Investigate the influence of maturity status on isometric and dynamic force-time variables, standing long jump performance (SLJ), sprint speed and vaulting vertical take-off velocity in a large cohort of young female gymnasts of different maturity status.
3. Determine the relationships between isometric and dynamic force-time variables, SLJ performance sprint speed and vaulting take-off velocity in young female gymnasts.

4. Examine the effects of a 10-month NMT programme on isometric and dynamic force-time variables, sprint speed and vaulting vertical take-off velocity in young female gymnasts.

1.3 ORIGINALITY, SIGNIFICANCE AND RIGOUR

1.3.1 Originality

Originality relates to the extent to which research introduces a new way of thinking, or makes a distinctive and transformative development to previous literature. Existing research within young female gymnastics has typically failed to account for maturity status and instead analysed data in relation to chronological age. Similarly, these studies have invariably involved field-based measures of strength, power and speed that only provide performance-based outcome variables (e.g. jump height, number of repetitions, sprint time). Additionally, the existing evidence base has only provided insights into the short-term effects of training interventions (<12 weeks), which make it difficult to truly understand the interaction between growth, maturation and training. This thesis presents a series of novel studies that provide kinetic analyses of strength, power and speed capabilities in young female gymnasts of varying maturity status. Furthermore, the thesis shows how long-term training and maturity interact to influence the development of these physical attributes and impact upon vaulting take-off velocity. Thus, the combined works are deemed novel and original, mainly due to the combination of the population that has previously been under-represented in the literature, the advanced measurement techniques used to assess strength, power, speed and vaulting performance, and the long-term duration of the training intervention.

1.3.2 Significance

Significance relates to the extent that research has exerted, or is likely to exert, on an academic field or applied practice. The majority of the studies from the current thesis have already been published and this would indicate that the research has started to reach the academic field and influence practice. *Chapter 3* provides between- and within-reliability data for the IMTP that can be used as a source of reference for the typical noise expected in the test by pre- and post-PHV females. The findings from *chapters 4-6* will provide researchers and practitioners with natural development data that could be used to distinguish between training-induced adaptations and those resulting from natural growth and maturation. Additionally, the data could also be used in practice for the purposes of benchmarking. Furthermore, these studies also identify relationships between measures of strength, power, speed and vaulting take-off velocity, and this information can be used to enhance the design of individualised training interventions. To date, no similar data exists in this population and therefore data emanating from these studies will be able to directly influence practice, as well as help frame future research questions for academics. *Chapter 7* provides evidence on the effectiveness of a 10-month NMT intervention in a population of young female gymnasts. By tracking and comparing the results of the three groups (GYM+NMT, GYM and CON) on a quarterly basis, these data will provide practitioners with novel insights into how these measures change in youth females, across a longer-term duration. Minimal data of this nature exists in this population and therefore, this study will increase the evidence-base for practitioners in a previously under-researched area. Together, the outcomes of the three studies have the potential to influence both scientific research and applied practice within the fields of paediatric strength and conditioning and LTAD.

1.3.3 Rigour

Rigour refers to the clear expression of the purpose of the research, the appropriateness of the research design, the intricacy of selected methodologies, and the strength of evidence presented. The current thesis presents a series of logical, interrelated studies that contain logical research questions that ultimately address the proposed aims in *section 1.2*. Some of the notable strengths of the research designs within this thesis include the comprehensive analysis of within- and between-session reliability of the IMTP, and the use of advanced measurement techniques (e.g. kinetic analysis) for strength, power and speed assessments. Furthermore, two-dimensional video analysis was used to assess vaulting performance, which allowed the impact and transfer of training on sporting performance to be explored. Biological maturation of the sample population was accounted for in all studies, which involved estimating percentage of predicted adult height using prediction equations from the somatic data collected. Another noteworthy strength of this thesis was the ambitious research design of the training intervention, which encompassed a 10-month training intervention, multiple experimental groups and a control group, and quarterly testing of maturity status, physical performance, and vaulting take off velocity. A range of appropriate and relevant statistical analysis methods (e.g. reliability, correlations, linear regressions, analysis of variances) have also been utilized to assist in the correct interpretation of the findings from within each study.

1.4 THESIS ORGANIZATION

The focus of this thesis is to further the understanding of the role of growth, maturation and training on vaulting performance in young female gymnasts. *Figure 1.1* provides a schematic of the thesis organization.

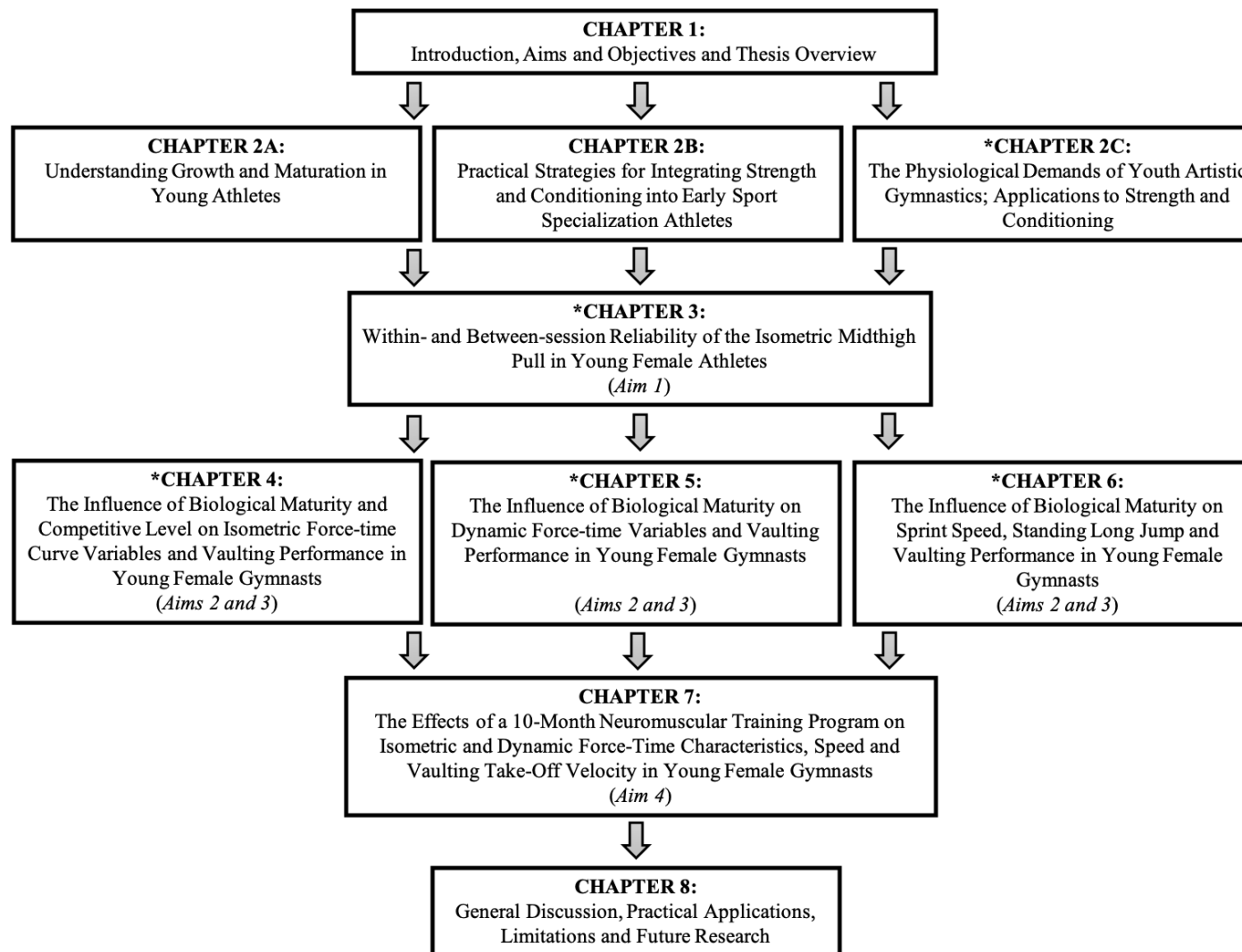


Figure 1. 1 Schematic of the organisation of the thesis (* = published studies)

Chapter 1 introduces the overall theme of the thesis, establishes the aims and objectives and discusses the originality, significance and rigour of the research. **Chapter 2a** provides a review of current literature for the available methods of assessing biological maturation, as well as the influence of growth and maturation on physical performance measures and injury risk in youth. **Chapter 2b** critically analyses the current research on early specialization athletes and explores the notion of integrating strength and conditioning within the development pathways of these athletes. **Chapter 2c** provides a narrative review of the physiological demands of artistic gymnastics and critically analyses the literature on appropriate training strategies for these physical qualities in young gymnasts. **Chapter 3** determined the within- and between-session reliability of the IMTP in pre- and post-PHV female athletes across three separate testing sessions. This analysis served to identify the smallest worthwhile change (SWC) and typical error (noise) in the measurements, which were then used to help interpret meaningful changes in force-time variables due to maturation and/or training in subsequent studies. **Chapter 4** employed a cross-sectional analysis to investigate the differences in IMTP force-time variables in young female gymnasts grouped by both biological maturity and by competitive level. Regression analyses were also performed to determine the predictive ability of IMTP force-time variables and biological maturity on vaulting vertical take-off velocity. **Chapter 5** used a cross-sectional analysis to examine the influence of biological maturity on dynamic force-time variables using squat jump, countermovement jump and drop jump tests, as well as regression analyses to determine how these variables influence vaulting vertical take-off velocity. **Chapter 6** examined the influence of biological maturity on sprint speed and standing long jump performance, utilising a cross-sectional analysis research design. Regression analyses were also used to determine how these variables, in addition to biological maturity, influence vaulting performance. **Chapter 7** applied a longitudinal research design to examine the effects of a 10-month NMT intervention on measures of strength, power, speed and vaulting

performance. This study tested and analysed group changes in performance on a quarterly basis across three different groups; gymnastics and NMT (GYM+NMT), gymnastics only (GYM) and a maturity-matched control (CON). **Chapter 8** provides an overall discussion of the thesis, findings, revisiting the aims of the thesis in the context of the conducted empirical work. Furthermore, this chapter provides an overview of areas for future research.

Chapters 2a-c: Prelude

The series of reviews presented in Chapters 2a-c aim to critically evaluate the literature relevant to the empirical studies in Chapters 3-7. Firstly, Chapter 2a aimed to explore current methods of assessing biological maturation in young athletes, as well as establishing how growth and maturation influence physical performance and training; fundamental principles that are referred to throughout the thesis. Secondly, Chapter 2b explored the integration of strength and conditioning into the development programs of young athletes who specialise early, in the prepubertal years. Research shows that an increasing number of young athletes are choosing, or being encouraged, to specialise at an early age in a single sport and female artistic gymnastics is a sport that is renowned with high rates of early specialisation. Finally, given that artistic gymnastics involves a series of complex events that can expose young gymnasts to relatively high forces and complex skills from a young age, Chapter 2c sought to examine the available literature on the physiological demands of youth artistic gymnastics and identify potential training strategies for these athletes. Cumulatively, these independent, yet interrelated reviews have provided a comprehensive overview of relevant literature related to the combined works presented within the thesis.

Chapter 2a:

Understanding Growth and Maturation in Young Athletes

2a.1 INTRODUCTION

Unique to childhood and adolescence, young athletes will experience growth and maturation which influence the natural development of physical fitness qualities and skill mastery (68, 170). *Growth* and *maturation* represent different natural biological processes that children and adolescents experience on the pathway to adulthood (68). *Growth* has been defined as an increase in the size of the body as a whole or region of the body (170). Tissue growth is a non-linear process which results from an increase in hyperplasia (cell number), hypertrophy (cell size) and accretion (cellular material) (289). *Maturation* refers to the process of becoming fully mature (e.g. skeletal and sexual maturation) and is known to be highly variable between individuals in terms of magnitude, timing and tempo (170, 289). Using chronological age as a reference, interindividual variation in biological maturation allows young athletes to be categorized as either early-, on-time, or late-maturers (157). Research also indicates that coaches may favour the selection of individuals who present as being early- or late-maturers in certain sports (e.g. preference of late-maturers in gymnastics) due to desirable anthropometric or physiological traits (169).

There is now a recognised consensus regarding the importance of developmentally appropriate training programmes that accommodate the highly individualized nature of biological maturation in youth (151). Considering young athletes' stage of maturation alongside their training age and technical competency aids programming decisions and provides useful information when interpreting testing data (151, 152). Further, being able to differentiate between changes in physical performance that are due to biological maturation or training

exposure enables practitioners to validate the effectiveness of their training provision. Therefore, strength and conditioning practitioners working with young athletes should have an awareness of the different methods of assessing biological maturity and how to utilize these data in youth populations.

2a.1.1 Methods of assessing biological maturation

Existing assessments of biological maturation in youth have been categorized into skeletal, sexual or somatic measures. Each method of assessment uses different indicators of maturity and the process of quantifying maturity status varies considerably (170). A brief, critical overview of the most commonly cited assessments for each category are shown in *table 1*.

Table 1. Overview of methods to assess biological maturation in young athletes

Type	Assessment	Advantages	Disadvantages
Skeletal age	<i>Fels Method.</i> This method grades maturity using the hand-wrist. Specialist software calculates skeletal age and estimates the standard error of measurement (266).	<ul style="list-style-type: none"> • A ‘gold standard’ method of assessing biological maturation • The standard error of measurement provided may be beneficial for tracking young athletes long-term. 	<ul style="list-style-type: none"> • Requires trained radiographers to analyse the x-rays reducing its utility in applied settings. • Costly assessment method owing to specialist equipment and software.
	<i>Greulich-Pyle Method.</i> Involves assessing a radiograph of a child’s left wrist against a reference system of x-rays (standard plates in the atlas) in individuals of varying levels of skeletal maturation (92).	<ul style="list-style-type: none"> • More time-efficient than other methods of assessing skeletal age as each bone is not always individually assessed. • A ‘gold standard’ method of assessing biological maturation 	<ul style="list-style-type: none"> • Requires trained radiographers to analyse the x-rays • Accuracy may be reduced as it assumes bone tissue matures in a uniform manner and does not account for individual rates of development of different bones. • This method may be less applicable to diverse ethnicities as it was validated in white children from families with high socioeconomic status.
	<i>Tanner-Whitehouse Method.</i> Involves the assessment of radiographs that includes 13 or 20 (depending on the assessment) bones in the hand-wrist (293-295).	<ul style="list-style-type: none"> • Potentially more ethnically diverse than other assessments of skeletal age. 	<ul style="list-style-type: none"> • Time consuming and costly method of assessment. • Requires experienced radiographers to interpret the x-rays. • Involves more subjective decision making than other methods of skeletal age. • Due to the above reasons, its application in an applied coaching setting is limited.
Sexual age	<i>Tanner Criteria.</i> Only be performed by qualified medical doctors in a clinical setting and informed consent and assent of the child and parent must be attained. This method uses observations of secondary sexual characteristics which are then compared against 5 reference “stages,” Tanner stages 1 (TS1), TS2, TS3, TS4, and TS5 (292).	<ul style="list-style-type: none"> • Option of the individual performing a self-assessment where they compare their own sexual characteristics to the reference system. • Most commonly used assessment of sexual maturation. 	<ul style="list-style-type: none"> • Requires a qualified and experienced medical doctor to perform the assessment in a clinical setting. Therefore, coaches should never perform this assessment with individuals, this method is not useful in supporting applied coaching (157). • Invasive assessment for the children and adolescents. • This method is unable to differentiate between individuals within the same stage and does not provide insight into the tempo of maturation (157). • This method is inapplicable with youth who are not experiencing the pubertal growth spurt, limiting long-term monitoring.

Somatic assessments	<p><i>Growth rates.</i> Simply tracking height longitudinally allows the magnitude and rate of change of height over time (cm per year) to be assessed. This data can be used to identify age at peak height velocity (PHV) and this reflects the maximum rate of growth during the adolescent growth spurt (289).</p>	<ul style="list-style-type: none"> • Simple, non-invasive assessment of height that practitioners can perform approximately every 3-months. • Very time and cost-effective. • As PHV occurs at around the age of 12 in females and 14 in boys, practitioners can easily identify if individuals are early- on-time-, or late-maturers. 	<ul style="list-style-type: none"> • Although this method is simple, it relies on data to be collected regularly and longitudinally to provide coaches with insightful information. • Collecting stature height in applied settings on a regular basis could prove difficult if technical coaches did not buy in to using training time for assessments to take place.
	<p><i>Predicting PHV.</i> This method uses predictive equations (different for males and females) to calculate maturity offset of individuals. It requires the measurement of body mass leg length, standing and sitting height as well as chronological age (years and months) (199).</p>	<ul style="list-style-type: none"> • Simple, non-invasive assessments of anthropometric measures that practitioners can perform themselves. • This method is particularly useful when longitudinal growth data has not been collected and youth can be classified as either pre-, circa- or post-PHV. • Allows practitioners to easily identify those who are early- on-time-, or late-maturers. 	<ul style="list-style-type: none"> • There is a standard error of approximately 6-months with this measure and the error may increase the further individuals are away from PHV. • Involves collection of more anthropometric measures than other somatic methods including, body mass which requires more sensitivity. • Collecting stature in applied settings on a regular basis could prove difficult if technical coaches did not buy in to using training time for assessments to take place. • This calculation is also bias to chronological age at the time of prediction.
	<p><i>Percentage of predictive adult height (PAH) attained.</i> Multiple methods exist for assessing PAH. One commonly used assessment involves predicting final adult height and the percent of adult height an individual has achieved (136). The individual's body mass, standing height and both parents' height (to calculate mid-parental height) are required for the regression equation.</p>	<ul style="list-style-type: none"> • Could be particularly useful in sports whereby stature is a predictor of performance e.g. basketball (289). • Relatively low error of prediction has been reported i.e. 2cm on average (136). • Simple, non-invasive assessments of anthropometric measures that practitioners can perform themselves. • This method is particularly useful when longitudinal growth data has not been collected and youth can be classified as either pre-, circa- or post-PHV. 	<ul style="list-style-type: none"> • Some error associated with the use of self-reported parental height as males tend to over-predict height. While parents could be encouraged to have their measured by practitioners, this might not be feasible in an applied setting. • Involves collection of more anthropometric measures than other somatic methods as well as the collection of parental height. • Collecting stature in applied settings on a regular basis could prove difficult if technical coaches did not buy in to using training time for assessments to take place.

Skeletal age refers to the degree of maturation according to the ossification of skeletal tissue and is considered to be the ‘gold standard’ method of assessment as it spans across the entire period of growth (157, 170). The process of skeletal maturation involves the transition from a cartilaginous skeleton (beginning prenatally) to a fully developed skeleton of bones which occurs early in adulthood (170). Using standardized x-rays (often in the hand and wrist), radiographers can determine the level of skeletal maturity using the following three indicators: appearance of bone centres (indicating the replacement of cartilage), changes in shape and size of bones, and fusion of the epiphyses with their respective diaphysis (170). Skeletal maturity is commonly assessed using three methods that all use hand-wrist radiography but differ in assessment criteria (68). The *Fels* method was developed using data from a middle-class population in Ohio and involves grading bone of the hand-wrist according to age and sex (266). These measurements are then entered into specialist software which calculates skeletal age (sex and chronological age are weighted accordingly) and estimates the standard error of measurement. It should be noted that the degree of error increases with advancing maturation (68). The *Greulich-Pyle* or *Atlas* method involves comparing the radiograph of a child’s left wrist against a reference system of x-rays (standard plates in the atlas) of individuals of varying levels of skeletal maturity (i.e. from birth to adulthood) (92). Because this method determines skeletal age based on only one wrist-hand reference plate, it does not account for the variation in rate of development of individual bones (68). Further, this method may be less applicable to diverse ethnicities as it was validated in white children from families with high socioeconomic status (157). The *Tanner-Whitehouse* method however, is probably the most ethnically diverse method of skeletal age verification, having been validated in British, European, South American, North American, and Japanese individuals (293-295). This method involves the assessment of radiographs that includes 13 or 20 bones in the hand-wrist (depending on the

assessment). The maturation of individual bones is then subjectively scored by a radiographer, summed and converted to skeletal age.

Sexual age refers to the degree of maturation of an individual reaching full sexual maturity and the ability to reproduce (157, 170). This process begins with sexual differentiation of the embryo, followed by puberty, which describes the transitional period from childhood to adulthood (170). Secondary sex characteristics are the indicators used to determine sexual maturity and differ in males (penis and testes) and females (breast development), with the exception of pubic hair (170). The *Tanner Criteria* method to assess sexual age uses observations of secondary sexual characteristics which are then compared against five reference “stages,” Tanner stages 1 (TS1), TS2, TS3, TS4, and TS5 (292). However, given the invasive nature of this method, only qualified medical clinicians who are trained to assess sexual age are permitted to perform these assessments, providing informed parental consent and child assent has been obtained (157). The applicability of Tanner staging outside of clinical settings is limited (157). Other limitations have been noted, which include being unable to provide insight into the tempo of maturation, its inability to differentiate between individuals within the same stage, and that this method is not applicable with youth who are not experiencing the pubertal growth spurt, thereby limiting long-term monitoring (157). While self-assessment techniques have been developed, the accuracy and validity of these methods have been questioned, with research indicating that males tend to overestimate their sexual development, while females typically underestimate their maturity status (157, 258). For females, age at menarche (the first menstrual cycle) can be used to classify individuals as either pre- or post-menarcheal (68). However, the use of age at menarche in females to determine the onset of puberty is not a valid measure, as the timing of these processes differs within individuals (i.e. a premenarcheal state does not necessarily indicate a prepubertal state) (68,

157). Overall, assessing skeletal or sexual age is limited by the need for trained medical specialists (i.e. radiographers, physicians), expensive equipment, and invasive procedures. Therefore, for those working with young athletes, somatic assessments of biological maturity are likely to be most appropriate, owing to their simplicity, accessibility (i.e. in terms of equipment, cost and expertise) and non-invasive nature (289).

Somatic age refers to the degree of growth in overall stature (157). Of note, assessments available to estimate biological maturity require various amounts of information and different data collection periods. For example, using growth curves to examine the rate of growth requires the simple measurement of height over time, and can be used to identify the adolescent growth spurt and various other important events (e.g. peak height velocity (PHV)) (*figure 1*) (289). However, as body size itself is not an indicator of maturity, longitudinal data must be collected regularly (e.g. quarterly measurements) which can be more difficult if young athletes transition between teams and sports. From such data, age at maximum rate of growth (i.e. PHV) can be identified, albeit retrospectively (289).

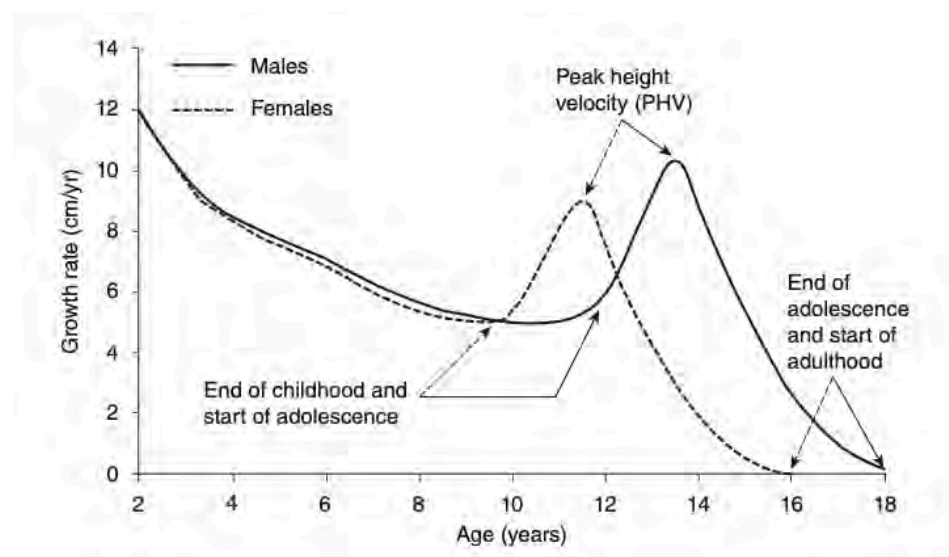


Figure 1. Rate of growth of growth of stature in boys and girls throughout childhood and adolescence, with important events relative to growth identified (289)

Owing to the practical issues surrounding longitudinal data collection, estimating maturity offset (the number of years an individual is before or after PHV) (199) or determining the percentage of predicted adult height (%PAH) attained (136) are more viable alternatives. Both of these methods require the collection of chronological age (years and months) and anthropometric data including body mass, standing and sitting height (136, 199). The maturity offset (199) (*equations 2.1.1 and 2.1.2*) is often used as it allows researchers and practitioners to classify young athletes as pre- or post-PHV (162, 204, 254). By subtracting the maturity offset value from chronological age, the athlete's age at PHV (APHV) can also be identified; allowing athletes to be categorized as either early-, on time-, or late-maturers (68). The maturity offset regression equations for males and females are based on Canadian children who were followed through adolescence and then cross-validated against Canadian and European longitudinal samples (199). However, this method of assessment does have a standard error of approximately six months, which should be considered when interpreting the data (68). For example, researchers have used thresholds to classify individuals using the following criteria; pre-PHV = offset <-1.0; circa-PHV = -0.5 to 0.5; and post-PHV = offset >1.0 (68, 195, 199).

Boys maturity offset (199)

$$= -9.236 + [0.0002708 \times (\text{leg length} \times \text{sitting height})] - [0.001663 \times (\text{age} \times \text{leg length} \text{ interaction})] + [0.007216 \times (\text{age} \times \text{sitting height})] + [0.02292 \times (\text{mass} \div \text{height})]$$

[Equation 2.1.1]

Girls maturity offset (199)

$$= -9.376 + [0.0001882 \times (\text{leg length} \times \text{sitting height})] + [0.0022 \times (\text{age} \times \text{leg length})] + [0.005841 \times (\text{age} \times \text{sitting height})] - [0.002658 \times (\text{age} \times \text{mass})] + [0.07693 \times (\text{mass} \div \text{height})]$$

[Equation 2.1.2]

Moore et al. (210) presented simplified equations for predicting maturity offset and found the equations' accuracy differed between sexes. An equation using standing height yielded the most accurate results in girls (standard error = 0.53 years), while in boys sitting height resulted in the lowest error (standard error = 0.51 years). Modified equations of similar precision were also provided to assist where sitting height had not been collected (210). It should be noted that longitudinal research shows prediction of APHV using both the original and modified maturity offset equations, are biased towards chronological age, influencing their accuracy with early or late maturing youth (143, 175, 176). These studies found that APHV were predicted to be earlier than observed in late maturing individuals and later than observed in early maturing individuals (68, 143, 175, 176). Of note, the degree of error is smallest around the time of PHV, which is also the developmental stage of most interest to practitioners, because it is during this stage that young athletes experience rapid physiological and structural changes (68).

Fransen and colleagues (85) have attempted to remove the bias with early- and late-maturing youth by calculating a 'maturity ratio' (chronological age/APHV). However, the prediction equations used in the new approach were criticised for using chronological age on both sides of the equation, resulting in spuriously high values of R^2 (228). Those opposing this approach have warned that the inflated R^2 values are likely to be misleading or even fundamentally flawed (228). Therefore, when determining youth as either pre-, circa- or post-PHV, practitioners and researchers should apply the standard error thresholds for the maturity offset equation used (68). However, one recent longitudinal study assessed the accuracy of four different prediction equations to estimate APHV (methods by Mirwald et al. (199), Moore et al., (210) and Fransen et al., (85)) in individual elite soccer players and concluded none of the methods provided an accurate prediction, limiting their utility (296). In another recent study, three methods of estimating the timing of PHV (generic age at PHV; maturity offset APHV;

window of %PAH) were compared against observed age at PHV in male soccer players (238). Data showed generic age and predicted APHV correctly predicted observed age at PHV for 14 participants (61%), whilst %PAH window (85-96 %) correctly predicted 22 of the participants (96%) (238).

Overall, the accuracy of maturity offset and APHV has been questioned, with validation studies suggesting that these estimates are more useful when athletes are near the time of actual PHV (49, 172). Therefore, where young athletes are quite a few years away from PHV when they first enter an athletic development program, estimating %PAH attained is deemed a more appropriate measure of somatic maturity. Further, the applicability of using the maturity offset method in sports with biases towards individuals that are early- or late-maturers (e.g. late maturers in gymnastics) (169) should be carefully considered.

Regression equations to estimate eventual adult height and %PAH attained have been developed by Khamis and Roche (136), and require chronological age, body mass, standing height and mid-parental height (mother and father) data to be collected. Specifically, the equations use different age-specific constants for boys and girls from 4.0 to 17.5 years, allowing the individual's height at the time of observation to be expressed as a percentage of their predicted eventual adult height (173). The %PAH value is an indicator of the athletes maturity status at the time of observation and these data can be used to bio-band young athletes into different bands (i.e. <85%, pre-pubertal; 85%-90%, early-pubertal; 90%-95%, mid-pubertal; and >95%, late-pubertal) (48, 49, 173). When comparing individuals of the same chronological age, those who have achieved a greater percentage of their estimated adult height are more mature than individuals with a lower percentage (68). Interestingly, relative maturity differs between sexes, with females (on average) reaching their mature state two years before

males, which indicates girls are more biologically mature than males at each chronological age (68). The error associated with the Khamis and Roche prediction equations should be considered when estimating somatic maturity as these could impact the ‘band’ athletes fall into (173). For example, one study demonstrated that for the average male aged 11-15 years, the 50th and 90th percentile errors translated to ~1.5% and ~3.0%, respectively (173). Other sources of measurement error for this method also merit attention; for example, self-reported parental height measures (i.e. tendencies to overestimate) (173). Of note, researchers have developed corrective equations to adjust for self-reported parental height (63).

In practice, the estimation of somatic maturity is particularly useful in sports where stature influences performance (289). Further, research indicates that periodically utilizing bio-banding in training and competition may provide young athletes with a different but positive training experience (48, 173). For example, in a football setting, players’ perceptions of playing in bio-banded games have been shown to vary according to maturity status (48). Early maturing players found the games more physically challenging, while late maturing individuals benefited from having more opportunity to demonstrate their full capabilities from physical, technical and tactical perspectives (48). It should be noted that these bands are not fixed and can be modified to reflect the intended experience for the athletes (173). In a strength and conditioning context, bio-banding can be used to accommodate individual differences in maturity status by adjusting the young athlete’s training load and training programme prescription (49).

2a.1.2 The influence of growth and maturation on physical performance and training

During childhood research shows boys and girls experience similar rates of biological development and therefore display relatively similar levels of physical fitness and motor skill development (68). Within this period of development, a *preadolescent spurt* has been identified

during the mid-childhood phase (i.e. approximately between the ages of 5 and 9 years old) whereby accelerated gains in muscular strength, speed and power are apparent in boys and girls (309). These improvements have been attributed to rapid developments in the central nervous system (CNS), specifically relating to factors such as greater levels of neuroplasticity and enhanced muscle recruitment and coordination (36, 309). However, developmental trends indicate that the rate of improvement in these physical performance capabilities begins to slow in late-childhood (309). Following the onset of adolescence, both males and females experience positive adaptations in performance, although sex-related differences in physical fitness become apparent (68, 309).

Males experience superior gains in physical performance capabilities, owing to natural reductions in fat-mass, increases in muscle mass and stature, as well as rises in certain hormonal concentrations (e.g. testosterone and growth hormone) (15, 152, 170, 174). Owing to these natural adaptations, it is perhaps unsurprising that research shows early-maturing males consistently outperform average- and late-maturing boys across a range of physical performance measures (170). However, research shows a similar pattern in females does not exist, with maturation enhancing some aspects of physical performance, but not others (170). For example, the natural increases in fat-mass females experience may negatively impact certain motor skills that involve the movement of body mass (170). Interestingly, the timing of these ‘spurts’ in performance vary across different physical fitness components. For example, strength and power gains are aligned more to peak weight velocity (PWV), which occurs slightly after PHV (68, 309), whilst accelerated gains in sprint speed occur around the time of PHV (195). Therefore, it is important for practitioners to have an appreciation and awareness of the non-linear development of physical fitness components that youth experience with growth and maturation.

Understanding the influence of growth and maturation can be particularly useful when discussing young athletes' development with technical coaches, especially in sports in which relative strength and power are important determinants (e.g. gymnastics) (273). Researchers have emphasized the need to develop relative strength from childhood, and to continue targeting this physical quality throughout adolescence, especially for females who will acquire natural gains in fat-mass and may experience reductions in sports that involve moving their body mass (e.g. jump height) (62, 197, 205). As the ability to produce force is a prerequisite to movement proficiency and is essential for all sports (315), increasing levels of muscular strength in young athletes (and in particular female athletes) should be a key priority at all stages of development (156). Research has shown muscular strength is trainable throughout childhood and adolescence (9, 149, 151, 152), with longer training periods (9, 149) and higher training intensities ($> 80\text{-}89\%$ of one repetition maximum (1RM)) of resistance training found to be most effective (149).

Being able to distinguish between training-induced adaptations and those resulting from growth and maturation is a challenge for practitioners working with young athletes. Where possible, practitioners should utilize available data (ideally longitudinal in nature) that has explored the effects of growth, maturation, and training on physical qualities and sport performance measures, to help determine whether their training program has realised adaptations that exceed expected changes from natural development. For example, sprinting research in young males shows stride length increases with maturation, and this is likely due to increased limb lengths and improved relative force production (195). Using linear regression analysis, the study predicted that sprint speed increased by $0.57\text{ m}\cdot\text{s}^{-1}$ for every 10% increase in stride length (195). Practitioners could use this data to monitor changes in performance as

young athletes mature and identify if a meaningful change has occurred as a result of training interventions.

In addition to understanding the potential differences between growth and maturity versus training-induced gains in performance, practitioners should also be aware that the underpinning adaptations from training-induced gains may differ depending on the athlete's stage of maturation (156, 254), which could have important practical implications for young athletes. For example, research has shown that pre-PHV youth were particularly responsive to training modes driven by neural adaptations such as plyometrics; while post-PHV athletes responded most positively to combined strength and plyometric training, which stimulate both neural and structural adaptations (163, 244, 254). During the prepubertal stage of development, heightened levels of neuroplasticity are apparent, which drive notable increases in cognitive functioning and motor coordination (18, 36, 90). The notion of “synergistic adaptation” indicates that training programmes may benefit from ensuring exposure to training stimuli that correspond with those that may be occurring as a result of natural development. Therefore, when programming for young children who are experiencing rapid neural development due to growth and maturation, practitioners should consider incorporating neuromuscular training strategies that target the development of movement coordination, strength, power and speed (49, 220, 315). When working with adolescent athletes, neural adaptations will be ongoing but additional hormonal changes and marked increases in sex androgen concentrations are apparent, leading to structural and architectural changes (156, 170). Consequently, training strategies should complement these naturally occurring adaptations, and emerging evidence exists that supports the use of combined training (i.e. strength and plyometric training) for the development of muscular strength, power and speed, albeit in adolescent youth (163, 270).

Leading position statements from national associations advocate prepubertal athletes should adopt an early ‘sampling’ approach to promote long-term athletic development (LTAD) and develop a broad range of motor skills to increase athleticism and enhance sports performance in later adolescence (146, 151). Research has examined differences in physical fitness and coordination levels of boys who participated in a single sport versus multiple sports, across three age groups (6–8, 8–10, and 10–12 years old) (86). The authors found that the oldest multisport cohort of boys (10-12 years old) outperformed those in the single sport group (86). The authors partly attributed this finding to the multisport athletes’ greater exposure to different physical, cognitive and psycho-social environments, but acknowledged further longitudinal research is needed to provide greater insights (86). This study supports the notion of young athletes spending time developing competence in a breadth of motor skills during childhood, when the CNS matures at an accelerated rate (86, 139, 155). It is during this stage of development that children’s levels of neuroplasticity are heightened, which as a consequence increases their potential to acquire new motor skills (18, 36, 155). Specifically, repeated exposure to a breadth of motor skills is thought to develop children’s decision-making abilities, proprioceptive awareness, and pattern recognition capabilities, due to the strengthening of synaptic pathways and synaptic pruning of motor control strategies (13, 155). Of note, the ability to learn new motor skills becomes more challenging throughout adolescence and adulthood, as research suggests a non-linear decrease in the volume of grey brain matter occurs with age (90, 155).

The CNS continues to develop into the third decade of life, with the development of more complex functions of cognition and emotion apparent (55). Thus, different regions of the brain mature at different rates; importantly, the need for basic sensorimotor control is prioritised (i.e. in childhood) before higher level cognitive functioning or processing (i.e. early adulthood) (55,

129). This can have important performance- and injury-related implications for young athletes participating in sports that demand high levels of cognitive and sensorimotor functioning (55). For example, some research shows anterior cruciate ligament (ACL) injuries occur more readily when an athlete is cognitively distracted (i.e. the CNS failing to anticipate and/or correct high-risk movement patterns) (55, 110). A primary aim of those working with young athletes should therefore be to promote LTAD and foster talent development in a holistic manner (233). Developing a broad range of athletic motor skill competencies (AMSC; *figure 2*) at the earliest stage possible should be prioritised, particularly those movements that the young athlete's sport does not typically involve (206, 224). Exposing athletes to a combination of general and specific strength and conditioning activities that develop AMSC and enhance health and skill-related components of fitness is recommended (66, 219, 224). Training dosages of two sessions of integrated neuromuscular training per week has been shown to enhance measures of isometric force-time characteristics (57), motor skills (e.g. squat jump height (57) and standing long jump distance (66)) and movement competency (209) beyond those in age-matched controls, in pre-pubertal children. These studies show the potential benefits appropriate strength and conditioning programmes can offer pre-pubertal children, with relatively low doses of training exposure. It should be noted that if a young athlete starts to engage in strength and conditioning programmes later during adolescence, practitioners are still encouraged to develop and refine AMSC, owing to their association with athletic performance (155).

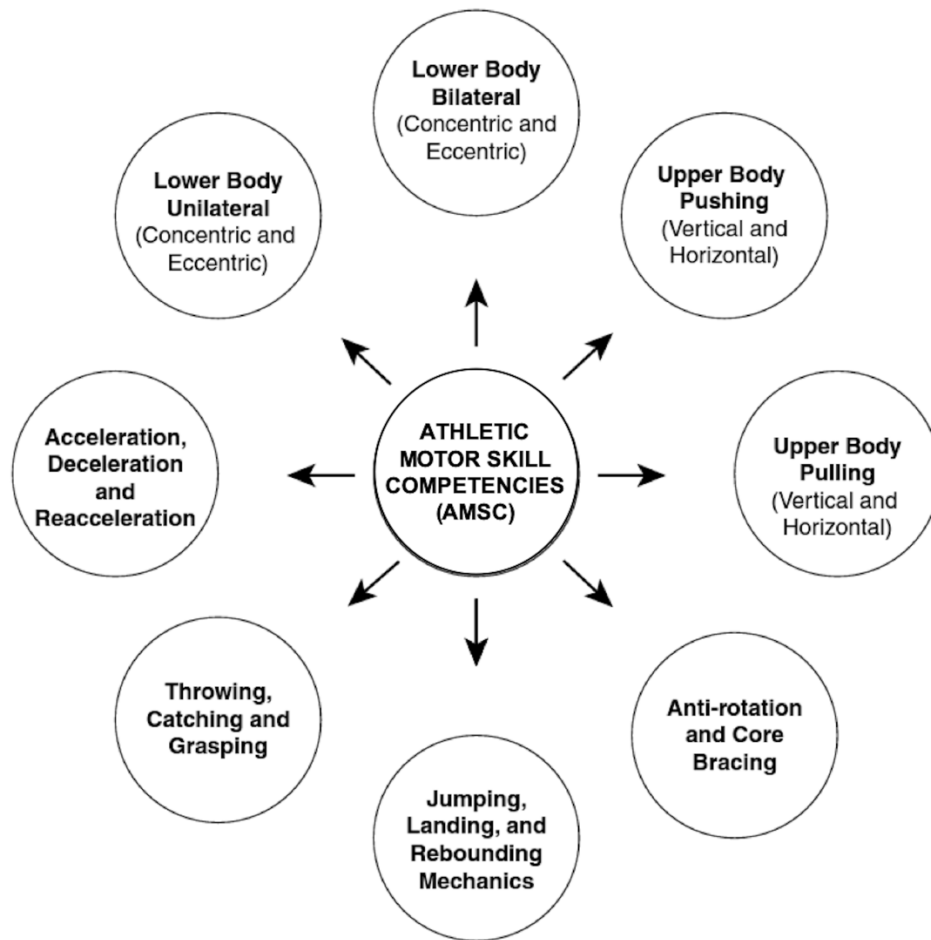


Figure 2. The athletic motor skill competencies (AMSC)

2a.1.3 Understanding growth and maturation and injury risk

A major role of the strength and conditioning practitioner working with young athletes is to reduce injury risk (151). Specific maturity-related changes that occur with PHV (262, 307) and peak PWV (262) have also been associated with greater injury-risk. For example, some young athletes experience rapid growth during the pubertal growth-spurt that temporarily disrupts motor control and results in performance decrements, termed ‘adolescent awkwardness’ (245). Similarly, young athletes need to be prepared to tolerate the additional loading that their connective tissues will experience with the increased body weight resulting from the pubertal growth spurt. For example, an increase of body mass index per month of $\geq 0.3\text{kg/m}^2$ has been shown to be an injury risk factor in male soccer players aged 11-16 years old (135). Recently,

Johnson and colleagues (127) investigated how maturity status and maturity timing influences injury risk in youth soccer players. The results showed maturity status influenced injury risk, with a significant increase in injury incidence (115 %) and injury burden (i.e. the incidence rate multiplied by the mean days missed per injury (225 %)) in circa-PHV players (127). However, maturity timing was not found to significantly impact injury risk after accounting for maturity status, although injury incidence was highest in early and on-time individuals (127).

Injury risk is recognised as a complex phenomenon, with certain risk factors viewed as modifiable or non-modifiable (264). Recently, Read *et al.* (264) proposed a traffic light system (*figure 3*) for those working with young athletes to help them consider the extent to which an injury risk factor is modifiable; red = non-modifiable (e.g. previous injury, rapid growth); yellow = partially modifiable (e.g. fatigue, early specialization); and green = modifiable (e.g. neuromuscular control and training volume). The authors emphasized that attention to all injury risk factors is important; however, more focus should be placed on mitigating the modifiable factors (264). For example, information on non-modifiable factors such as previous injuries and growth and maturation should be collected and tracked. With such data, practitioners can target potential neuromuscular alterations which are modifiable (i.e. neuromuscular recruitment and resultant movement patterns), to minimize the risk of re-injury or new injuries which result from compensatory motor control strategies (264). Such a targeted approach would be particularly useful when working with young athletes involved in sports with a high proportion of high load landing, such as gymnastics.

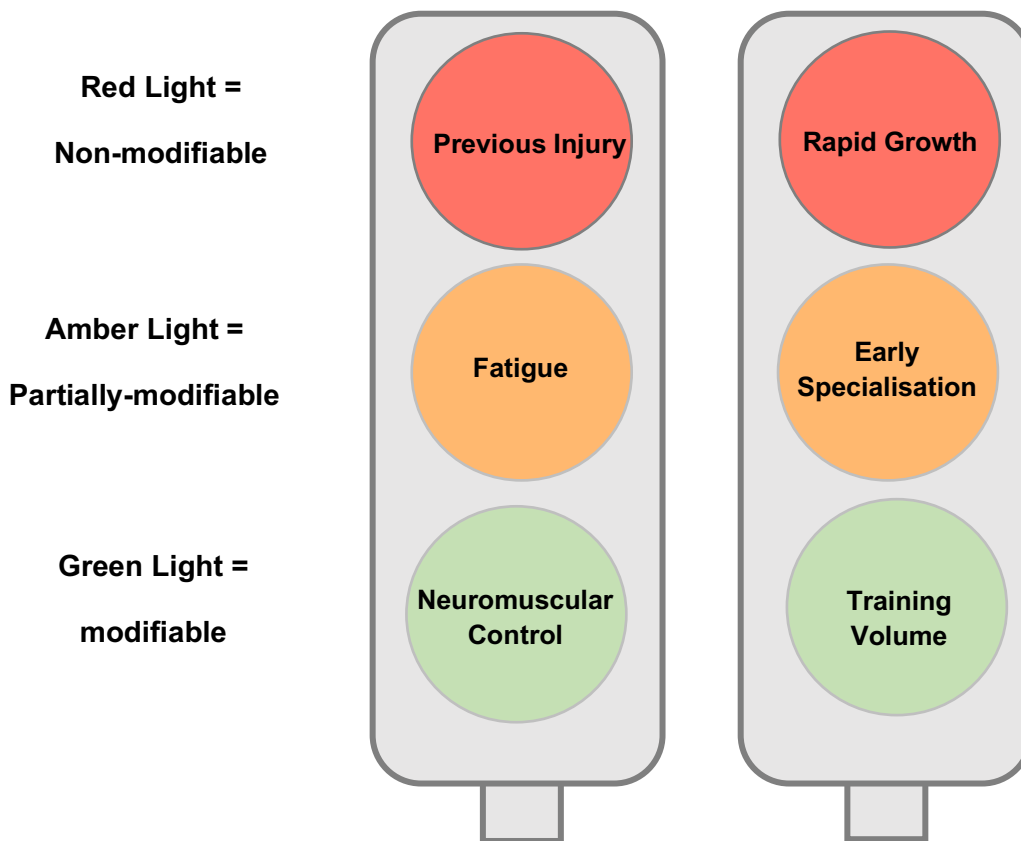


Figure 3. The traffic light system for risk factors: red = non-modifiable (e.g. previous injury, rapid growth); yellow = partially modifiable (e.g. fatigue, early specialization); and green = modifiable (e.g. neuromuscular control and training volume) (264)

Approximately 50% of all paediatric sport-related injuries have been attributed to overuse (305, 313). Causative factors for these types of injuries in youth have been associated with early specialization sports (305), with existing data indicating highly specialised athletes are twice as likely to sustain an overuse musculoskeletal injury compared with athletes with low specialization (10). Injury patterns vary according to the type of sport (239); notably, one study found individual sport specialised athletes experienced a higher proportion of overuse injuries than team-sport specialised athletes (~44% vs. ~32%) (239). The authors attributed this finding to the individual sport-specialised athletes having higher training volumes (hours per week) and being involved in sports that require repetitive loading of the same structures (239). Submaximal loading, repetitive stress, poor technique and insufficient rest are described as

extrinsic factors that may predispose young athletes to overuse injuries (128). Highly prevalent growth-related overuse injuries in young athletes include Little League elbow and Osgood-Schlatter disease, resulting from repetitive microtraumas to the growth cartilage at the epiphysis (growth plate) and musculotendinous insertions, respectively (128). Further, as youth experience growth in limb lengths and stature, their centre of mass increases, which could alter the demands of dynamic joint stabilization and consequently heighten soft-tissue load/stress and injury risk (264).

Maturation has also been linked to certain acute type injuries such as ACL injuries, with incidences heightened around the time of adolescence (251, 253). Sex differences in sport-related, non-contact ACL injuries are evident following the pubertal growth spurt, with females reportedly 4 to 6 times more likely to sustain an ACL injury than males (1). One longitudinal prospective study in a female athlete explored the injury risk factors associated with maturation across a 3-year period, prior to the female athlete sustaining an ACL injury (1). The data showed that during puberty, the athlete experienced increases in body mass, height of the centre of mass and knee abduction loads, without concomitant increases in hip and knee strength, which increased her risk of ACL injury (221). Further, female athletes have been shown to exhibit higher variability in the coordination between sagittal-plane hip and knee motion, as well as frontal-plane motion in the dominant limb during drop jumps (54). The authors suggested that reduced stability in hip- and knee-coordination patterns during landings could lead to less efficient or aberrant mechanics, and increase injury risk in the athletes (54). Thus, there is a clear rationale to target the development of motor coordination by exposing young athletes to a breadth of AMSC and increasing muscular strength levels to enhance their force production and absorption capacities (155). Data also indicate that exposure to such training

earlier in a young athletes' development (i.e. preadolescence) prior to the onset of neuromuscular deficits, can reduce their risk of experiencing an ACL injury (226).

2a.1.4 Using maturity data in practice

When collecting and tracking maturity and performance data, practitioners should aim to provide technical coaches with information about the athletes' development relevant to their maturity status. For example, superior insight can be gained from practitioners producing Z-scores for young athlete's fitness testing data according to their stage of maturity, as opposed to chronological age alone. Recently, Till and colleagues (301) proposed a new method of calculating Z-scores using regression equations and rolling averages according to both chronological age and maturity offset (years from PHV). This method would allow testing data to be analysed more accurately and interpreted individually for early specializing athletes who are at different stages of development (301), while also reducing selection bias (49). For example, in youth tennis players, data indicated that 89% of early maturing males and 27% of early maturing females moved out of the top 10% when 5 m sprint performances were compared with biological age rather than chronological age (218); thus highlighting how technical coaches could be unintentionally bias towards early maturing individuals. Later maturing tennis players could appear to be performing worse than their age-group peers, but when maturity is considered, those players can be equal to, or better than the group average (218). Providing technical coaches with this type of information is important to ensure talent identification processes consider the long-term development of young athletes.

Research indicates that periodically utilizing bio-banding in training and competition may provide young athletes with a different and positive training experience (48, 173). For example, research in a football setting has shown early maturing players found bio-banded games to be

more physically challenging, while later maturing individuals benefited from having more opportunity to demonstrate their full capabilities (48). While certain sports lend themselves to utilizing bio-banding in this manner, strength and conditioning practitioners can use maturity data to inform decision making processes regarding training strategies for young athletes. For example, in the context of ballet and gymnastics, there is a known aesthetic bias towards a later-maturing physique in females (169); however, these individuals may become disadvantaged at a later stage as they reach puberty, when increases in training load coincide with rapid periods of growth, potentially reducing performance (e.g. loss of flexibility) and increasing injury risk (33, 201). In this example, practitioners could use bio-banding to ensure dancers/gymnasts' training prescription is developmentally appropriate (e.g. adjust training loads around puberty, reduce training monotony, target flexibility and mobility) and interpret performance testing data in relation to maturity timing (201). Overall, by considering inter-individual differences in physical performance and injury risk profiles, technical competency, stage of biological and psycho-social maturity, coaches will be better equipped to implement appropriate training strategies for the young athletes (173).

2a.2 SUMMARY

Children and adolescents of similar chronological age can vary considerably in biological maturity, which will influence physical performance, sport-related injury risk and consequently training prescription. Because youth mature at different times and rates, evaluating biological maturation in young athletes is important. Somatic assessments of biological maturity for young athletes are likely to be most appropriate due to their simplicity, accessibility and non-invasive nature. There are many different methods of monitoring and estimating somatic maturity, including longitudinal growth curves, predicting APHV and the use of percentages and predictions of PAH. The most appropriate method(s) for athletes will depend on the

purpose of the assessment (e.g. %PAH is an estimate of maturity status, while predicting APHV is an estimate of maturity timing), feasibility (e.g. difficulties surrounding longitudinal monitoring of growth rates) and the error of measurement. However, as maturity offset may not be valid in prepubertal athletes far away from PHV, the most appropriate method of measuring maturity status in young athletes is likely to be %PAH attained (136). Where possible, regular collection of anthropometric data every three months will allow growth rates to be calculated and meaningful changes in stature to be detected (289). Practitioners working with young athletes should appreciate and understand the influence of maturation on the natural development of physical performance and the potential negative impact on sport-related injury risk. Specifically, being able to estimate young athletes' maturity status provides practitioners with superior insights into training prescription, helps explain fluctuations in physical fitness and motor coordination, and assists in mitigating injury risk.

Chapter 2b:

Practical Strategies for Integrating Strength and Conditioning into early Specialization Athletes

Moeskops, S., Oliver, JL., Read, PJ., Cronin, JB., Myer, GD. and Lloyd, RS. Practical strategies for integrating strength and conditioning into early sport specialization athletes *Strength Cond J.* under review

2b.1 INTRODUCTION

Early sport specialization is characterised as intensive year-round (> 8 months per year) training and/or competition, involving participation in a single sport that typically begins in the pre-pubertal years (146). Early specializing young athletes can be exposed to intensive training schedules (i.e. high volumes and frequencies), with chronic exposure to the same sporting-skills that may limit diversified skill acquisition and reduce long-term participation in sport (146). Notably, these athletes often accumulate weekly training hours which surpass the recommendations of not exceeding the child's chronological age in years (29, 267). Early specializing sports are typically individual in nature and include: gymnastics, figure skating, dance, tennis, and swimming (168, 239, 267). However, the trajectory of youth from other sports choosing to specialize early is growing (29) and overall rates of specialization and the exclusion of multi-sport participation in the developmental years are at an all-time high (224).

In certain *early entry* sports, where peak elite performance tends to occur at a younger age (e.g. women's gymnastics, figure skating), early specialization approaches are more accepted with a view that it is necessary to increase the likelihood of success in the sport (146). However, there is emergent consensus amongst researchers and practitioners opposing this approach,

owing to the associated potential negative effects on children and adolescents' physical and psycho-social well-being (29, 146, 151, 168, 215). Some evidence suggests that young athletes may be at greater risk of developing overuse type injuries (224), experiencing overtraining or burnout syndrome (56), presenting with 'blunted' motor skill development (56) and prematurely withdrawing from their sport (146, 164). Early adolescence has been recommended as the earliest stage of development at which young athletes involved in *early entry* sports, should specialize (119, 224). Additionally, authors of position statements have suggested that those involved in sport, should revisit and reset competitive expectations for young athletes to discourage early specialization (146). For example, greater impact could be achieved if National Governing Bodies share this vision and embed information about the risks of early specialization into their coaching education pathways.

While sport offers multiple benefits to children, data indicate that less than 1% of high-school athletes reach the professional level of sports (27, 229). It is important for children to challenge themselves, to be passionate about their sports, and to pursue their sporting dreams; however, key stakeholders responsible for their development should be realistic about the sporting trajectories of any young athlete. Furthermore, there is no guarantee that specializing early in a particular sport will result in success at an elite-level, and research has shown specializing later could be more advantageous (203). Moesch et al. (203) investigated group differences between elite and near-elite young athletes from sports measured in centimetres, grams, or seconds. The authors indicated that elite athletes specialized at a later age and trained less during childhood, but then started to intensify their training regimes during late adolescence, resulting in a higher number of accumulated training hours compared to near-elite athletes (203). Further, recent reviews of literature have explored the impact of early specialization on

career and task-specific athletic performance, and concluded that sport specialization was not a prerequisite for success at more elite levels (139, 265).

It is our opinion, and those proponents of existing long-term athletic development (LTAD) models and position statements, that young athletes should refrain from specializing in a single sport until later in adolescence (146, 151, 315). While a sea change is required in youth sports to arrest the move towards early specialization, many strength and conditioning practitioners will inevitably find themselves working with young athletes who specialize early. It is important for practitioners working in these circumstances to have an evidence-informed approach to strength and conditioning provision. Children that specialize from an early age will be entering a sporting system prior to the onset of puberty (e.g. gymnastics); therefore, they will experience growth (e.g. increases in size, stature and mass) and maturation (e.g. skeletal, sexual and somatic maturity) processes (68) while also training for, and competing in, their chosen sport.

Young athletes will experience natural fluctuations in physical fitness (153, 195, 257, 289) and injury risk factors (109, 221, 251, 253) at certain stages of maturity, and the manner in which these developmental adaptations interact with training load is complex and may be heightened in single-sport athletes (53, 177, 233, 264). Consequently, having an awareness of how growth, maturation and training interact, and an understanding of the unique demands of implementing strength and conditioning programs for early specializing athletes, is important. Similarly, practitioners may work with these athletes at the beginning of their LTAD journey and hopefully oversee their non-linear development towards young adulthood. Therefore, the purpose of this review is *firstly*, to examine how growth and maturation data can be used to inform programming with early specializing athletes; *secondly*, to provide practitioners with

advice and recommendations on how to integrate strength and conditioning into early specialization sports with a LTAD approach; and *thirdly*, to discuss strategies of monitoring training loads for early specializing athletes.

2b.2 CONSIDERATIONS WHEN WORKING WITH EARLY SPECIALIZING ATHLETES

2b.2.1 Use of growth and maturation data

It is important to recognize that while athletes starting out in early specialization sports will be typically in the prepubertal stage of development, differences in maturation may already exist as the skeleton continually develops throughout childhood and adolescence (68). Consequently, choosing the most appropriate method of assessing maturity status in early specializing athletes is important (157). Owing to the limitations and restrictions associated with skeletal age verification or sexual age estimation, it has been recommended that practitioners utilise somatic assessments to estimate biological maturity (157). Methods by Mirwald et al. (199) which predict maturity offset may not be valid in prepubertal athletes if they are not approaching peak height velocity (PHV) (175, 176). Therefore, the Khamis and Roche method (136) of estimating percent of predicted adult height (%PAH) attained is likely to be the most appropriate method of identifying prepubertal athletes' stage of maturity and has been used within the literature to group athletes into 'bands' (49, 173). For example, Cumming *et al.* (49) indicated how %PAH can be used to bio-band young athletes using the maturity offset method (i.e. < -1, pre-PHV; -1 to +1, circa-PHV; and > +1, post-PHV) or bands for %PAH attained (i.e. <85%, pre-pubertal; 85%-90%, early-pubertal; 90%-95%, mid-pubertal; and >95%, late-pubertal). It should be noted that when using the methods developed by Khamis and Roche (136) to predict %PAH attained, where possible parental height should be measured directly to increase the accuracy of predictions.

The on-going collection of anthropometric data (i.e. body mass, standing and sitting height) every 3-months to allow growth rates to be calculated is also recommended (289) in early specializing athletes and all young athletes. If longitudinal growth rate data are obtained, PHV and peak weight velocity (PWV) can be identified in early specializing athletes around the time of the adolescent growth spurt. PWV tends to occur after PHV and notably, boys and girls reach PWV within different periods of time (i.e. boys = approximately six months, girls = few months up to a year) (170). Coaches can subsequently use growth and maturation data to estimate when early specializing athletes are experiencing rapid periods of growth or are approaching the adolescent growth spurt that may inform training strategies (49, 173).

It should be noted that when early specializing athletes approach the pubertal growth spurt, injury risk may increase concomitantly (221, 253, 263, 264) and individuals might experience a plateau or decrement in some aspects of performance (170, 174). However, PHV and PWV do not necessarily cause injury, rather, the periods of rapid growth are likely to increase the relative risk of injury and specifically the proliferation of risk factors in early specializing athletes (53, 54). Importantly, maturity data should be used by practitioners to help early specializing athletes and technical coaches to understand potential changes in performance or function, and provide objective data that can be considered as part of interdisciplinary conversations regarding optimizing programmes to promote improvements in performance. For example, a young gymnast experiencing rapid growth could find performing habitual skills on the balance-beam more difficult, as a result of increases in the height of their centre of mass making dynamic joint stabilization more challenging (264). During this unique stage of development, coaches may need to consider modifying the athlete's training emphasis (e.g. revisit athletic motor skill competencies (AMSC) and increase relative muscular strength),

incorporate targeted injury prevention exercises, and monitor training loads/volumes closely (173, 224, 264), as opposed to removing athletes from the program.

2b.2.2 Engaging with key personnel

Overuse injuries in early specializing athletes are likely to be more avoidable than acute type injuries, with estimates of ~50% deemed preventable in youth with appropriate training and management (306). Fostering a collective approach to training with technical coaches and parents of early specializing athletes can be challenging. The perceived belief that high amounts of sports-specific training early in childhood will lead to an increased likelihood of sporting success may exist amongst technical coaches and parents (224), whereas the associated increase risk of injury might be less well understood (10, 11). In a recent survey conducted with parents, over 80% had no knowledge of sport volume recommendations regarding hours per week (~84%), months per year (~82%), and only ~43% thought that year-round sport participation may increase the risk of overuse-type injury (11). In sports such as gymnastics, early specializing athletes might also be encouraged to practice at home, which results in the accumulation of even higher and uncontrolled overall workloads. Children are advised not to participate in more hours of sport per week than their chronological age, or greater than a maximum of 16 hours per week (29, 146, 224). However, these training volumes are often exceeded in sports such as gymnastics (178, 267) and year-round training and overscheduling of competitions exist in early specialization sports (27, 118). In an attempt to better manage overall workload stress, it is recommended that strength and conditioning should replace part of the weekly training volumes of those early specializing athletes with high weekly training volumes, rather than merely being viewed as an addition to the programme. However, it is acknowledged that this approach will require effective collaboration and a shared vision amongst the athlete(s), technical coaches and parents.

Developing meaningful and respectful relationships with technical coaches and parents in addition to the young athletes themselves is imperative to build a truly holistic athlete-centred program. In doing so, it is easier to explain and justify the need for a long-term commitment to strength and conditioning programs. Non-scientific language should be used and engaging resources (e.g. infographics) could enhance the understanding of coaches, parents and the athletes themselves of why strength and conditioning is an important element of the program (see *figure 1*). Anecdotally, inviting technical coaches, parents and early specializing athletes to ‘welcome meetings’ at the start of a new competitive year can be extremely useful. Such events enable practitioners to highlight the benefits of strength conditioning, provide insights into what is involved and dispel myths around particular modes of training (e.g. resistance training with young athletes). Having open conversations with all parties and providing them with opportunities to ask questions about the training program is strongly encouraged.

WHY EARLY SPECIALISATION ATHLETES SHOULD ENGAGE IN S&C



Figure 1. Why early specializing athletes should engage in strength and conditioning

2b.2.3 Implementing LTAD-centred strength and conditioning programs

Through high volume periods of sport-specific training, some early specialization athletes may display advanced or even adult-level technical skills at young ages (e.g. golfers who display very advanced technical skills as a result of deliberate practice from a young age) (168). However, the perceived need for these athletes to reach advanced standards ahead of their time is short-sighted and may have negative connotations (168). Therefore, a long-term approach to the physical development of early specializing athletes is needed, with health and wellbeing a central priority (146, 224). Recommendations for practitioners working with early specialization athletes looking to adopt this approach are shown in *Table 1*. Practitioners (and technical coaches) must remember that early specializing athletes are not ‘miniature adults’ and therefore, the training strategies and structure of sessions must be developmentally appropriate (65, 75, 300). For example, elements of non-structured forms of training should be included in all training sessions regardless of training age or stage of development, to encourage movement creativity and exploration (e.g. obstacle courses, playground games) (255). Owing to the high volumes and frequency of sport-specific training sessions in early specialization sports, strength and conditioning practitioners may often be required to deliver sessions ‘on field’ at sports training locations (e.g. tennis court, gymnastics centre). The equipment, time and space available for training is likely to depend upon the nature of the sport, competitive level and culture of the club. Practitioners working within more challenging training situations must therefore be flexible, and consider the most effective and efficient training strategies available to elicit the targeted adaptation. The sequencing of the strength and conditioning provision and the early specialization athlete’s sport-specific training should be considered. For example, a 5-week neuromuscular training program including plyometrics, acceleration/deceleration and COD drills using minimal equipment (medicine balls, boxes etc), implemented before and after a tennis session were evaluated between pre-practice and post

practice in high-level prepubertal male tennis players (80). From the data it was concluded the program that took place prior to tennis-specific sessions was more effective in improving tennis performance-related factors (e.g., sprint, jumping performance, and serve velocity) than the program that took place after tennis-specific sessions (80). These findings highlighted the potential benefits of implementing strength and conditioning programs prior to sport-specific sessions to optimize the training responses, when levels of neuromuscular fatigue are lower. However, in some instances there might be a rationale for arranging strength and conditioning sessions after technical sessions to challenge movement control in a fatigued state; therefore, practitioners must be clear on what the aims of the training sessions are.

Table 1. Recommendations for those working with early-specializing athletes

<i>LTAD and performance</i>	<i>Reducing injury risk</i>	<i>Health and wellbeing</i>
<ul style="list-style-type: none"> • Perform a thorough needs analysis of the early specializing athlete's sport (physiological and biomechanics demands) • Provide a holistic training program which develops a broad range of AMSCs and allows early specializing athletes to explore movements that they are less exposed to • Promote fun and enjoyment during training sessions e.g. integrating obstacle courses, partner-balances, games and challenges into programs • Aim to individualize training where possible and crucially, regress or progress exercises on an individual basis • Adapt and monitor training around athletes' training load and competitive schedule 	<ul style="list-style-type: none"> • Perform an injury analysis of the early specializing athletes sport and identify relevant risk factors • Gather thorough injury history information (acute and overuse type) • Implement strategies to address relevant injury risk factors, considering the early specializing athlete's training age and stage of maturation • Implement integrative neuromuscular training programs • Create supportive and open environments to encourage early specializing athletes to report injuries or concerns 	<ul style="list-style-type: none"> • Monitor early specializing athletes closely for signs of overtraining and burnout syndromes • Educate technical coaches and parents about the risks associated with practicing excessively at home on top of high volumes of training of sports-specific training • Utilise wellness and mood monitoring questionnaires • Present monitoring reports in a child-friendly and engaging way to the early specializing athlete. • Monitor athletes for signs of nutritional deficiency and ensure parent/athlete seek qualified professional nutritional advice where necessary

Another challenge for practitioners is to provide an effective training stimulus that differs to what early specializing athletes typically experience during their sport-specific skill training, in order to induce adaptations above those that they will acquire from their high volumes of technical training and competition (206). This is likely to be more relevant in early specialization sports that involve high amounts of sport-specific physical preparation. For example, combined strength and plyometric training significantly increased elite pre-pubertal gymnasts' drop jump performance, with the authors recommending that a reduction in the time spent on habitual repetitive routines allows time for an alternative and more targeted strength and power training stimuli (178). It should be noted that the nature of early stage strength and conditioning for young athletes will initially focus on the execution of foundational athletic movements (e.g. squatting and hinging) using body weight as a form of resistance; however, to realise ongoing adaptations, and as training-age and technical competency increases, higher intensity resistance training will be required to further enhance strength and power qualities (149). Training will need to be progressively overloaded (164) but also considered in light of the early specializing athlete's overall training load. For example, as a young gymnast approaches a competition mesocycle, they will complete more full routines at higher intensities (e.g. landings/dismounts on to mats instead of foam pits, and tumbling on harder surfaces); consequently, practitioners may benefit from reducing the volume and/or intensity of high-impact plyometrics during this phase to avoid excessive amounts of high-impact landings which could lead to overuse injuries.

When designing training programs to enhance performance and reduce injury risk, conducting a thorough needs analysis of the sport's demands (physiological and biomechanical) (260) and types of activities the early specializing athlete will be frequently exposed to is important. Coaches should consider injury epidemiology within the sport to identify: common overuse

injury sites, areas prone to strength and mobility deficiencies, postural issues and limb asymmetries (260, 264). Because overuse injuries can be prevalent in early specializing athletes (128, 146, 151, 168, 215), practitioners should adopt a philosophy and implement practice that includes a large movement variability, with the aim of providing exposure to a variety of movement patterns to vary the point of force application and co-ordination demands (151). Further, if growth-related injuries are prevalent in the sport, practitioners should also be aware of the underpinning mechanisms, and the signs and symptoms associated with these injuries. Should an early specializing athlete display gradual onset of pain, a symptom indicative of overuse injuries (128), medical advice should be sought and appropriate rehabilitation and management strategies should be integrated into the training program. For example, as lumbar-spine injuries are prevalent in golfers, incorporating anti-rotation exercises to reduce injury risk and aid in spinal motion control could be of benefit (261). It must be stressed that one size will not fit all, as these factors will differ markedly between early specializing athletes from different sports (e.g. differences in high-impact training of gymnasts compared to rowers). For example, young rowers would benefit from training targeting posterior chain strengthening, non-sagittal movement patterns and basic jumping, landing and rebounding mechanics. Conversely, practitioners working with young gymnasts might limit the amounts of jumping and rebounding activities they incorporate into training, particularly during busy periods of competition. Thus, considering which AMSC the early specializing athletes' sport does not address will be important to reduce injury risk and develop well-rounded athletes (255).

2b.2.4 An integrated approach to monitoring workloads for early specializing athletes

Measures of training load are typically categorized as either internal or external (20) and can be used to monitor athletes' responses to training and readiness to train (104). Internal training loads describe the relative biological stressors (physiological and psychological) imposed on an athlete during training or competition and are commonly assessed using: heart rate, blood lactate, oxygen consumption and rate of perceived exertion (RPE) (20). Whereas external training loads are objective measures of the work that an athlete has completed during training or competition (e.g. total distance covered, number of jumps/throws, volume-loads) (20).

A key role for practitioners working with early specializing athletes is to assist with monitoring of internal and external training loads, as well as utilizing screening tools for indicators of overtraining and burnout (fatigue, reduced performance, illness etc.) (224, 264). Researchers have monitored training loads over 41 weeks in young athletes from various sports and reported intensity during the week prior to injury was significantly higher compared to that of the preceding 4-weeks (177). The influence of 'spikes' in training load on injury risk in youth was evaluated in a 2-year study in male youth cricketers, which monitored acute and chronic workloads of bowling sessions and found that 'spikes' in workloads were associated with an increased injury risk (312). Specifically, an increase in acute- and chronic-workloads of more than two standard deviations, resulted in a 4–5 fold increase in injury risk in the subsequent four weeks (312). These type of data can be used to inform the planning of training workloads around different seasons and competition demands to ensure sufficient chronic workloads are maintained, whilst minimizing spikes in workload (312). Indeed, this is likely to be more challenging in certain sports than others; nevertheless with such an approach, acute and chronic training loads could be managed more carefully. Indeed, the organization and monitoring of

weekly training loads is a complex process and can be challenging owing to individual fluctuations in overall training loads (e.g. practicing at home, training camps, competitions, school and club training commitments) as well as, large interindividual variances in responses to load (280, 282). However, integrating monitoring processes will allow training loads and recovery bouts to be modified between training sessions to reduce the risks of maladaptive training responses (e.g. overtraining, burnout, overuse injury) (280).

Notwithstanding the range of available metrics to quantify workload from different training modes (e.g. volume-loads from resistance training, or distances covered during a conditioning session), one viable method of monitoring athletes' internal response to training across a wide range of training modes is the session-rating of perceived exertion (sRPE) (280). Using this approach with early specializing sports requires the young athletes to state an overall RPE for a given training session which is then multiplied by the session duration. Given the likely young ages of early specializing athletes, anecdotal experience has shown that parents and technical coaches are often needed to assist with the monitoring process and that a period of familiarization is required to ensure children can provide meaningful and more accurate subjective responses using the RPE scale. The use of child versions of sRPE after each session is encouraged and has been validated with resistance training in children (74). Valid data can be obtained using online platforms (e.g. web-based questionnaires, spreadsheets) and athletes should be encouraged to report sRPE 30 minutes after training (84), or no longer than 48 hours post-training (79, 280). Coaches' intended training loads do not always align to the athletes' perceived sRPE load, resulting in a mismatch which could lead to a maladaptive training response (30, 280). Should training load exceed the practitioner or technical coach's intended dose of training, external training variables can be manipulated to achieve the desired internal response in the following session (280).

If equipment, human resource and time permit, measures of neuromuscular fatigue can also be collected to assess athletes' responses to training and/or readiness to train using various jumping protocols (e.g. reactive strength index from drop jumps) (104). It should be noted that chronic fatigue could be exacerbated in early specialization athletes involved in sports with traditionally high volumes of training, such as gymnastics and ballet. However, utilising monitoring tools with large numbers of athletes and collecting accurate data across multiple coaches (e.g. school, club, national teams) in practice can be very difficult. Crucially, practitioners are encouraged to observe athletes' demeanour prior to, during, and after training for signs of fatigue (e.g. loss of motivation, lethargy, bad moods) and are encouraged to have reciprocal conversations with them regarding their readiness to train (154). Importantly, training should be adapted accordingly (e.g. reduce session intensity) if the athlete presents signs of accumulated fatigue (154).

Practitioners should work closely with technical coaches to develop ways of monitoring the training loads during sport-specific activities and critically, build in periodic de-load/recovery weeks to facilitate recovery and growth processes. Further, in early specialization sports that do not typically have an 'off-season' or train all year-round (146, 267), practitioners should work closely with technical coaches to periodise a post-season/competition transition phase. Further, de-load weeks could be co-ordinated to align with inter-semester breaks (71). Educating parents and coaches about the benefits of reducing training loads for 2-4 weeks during a transition phase or the inclusion of de-load weeks will be essential. Highlighting the need to reduce training stressors to avoid burnout (28, 56) and allowing early specializing athletes adequate time to recover physically (i.e. dissipate cumulative fatigue) and psychologically from previous training/competition phases is strongly recommended (96). For example, following a competitive phase of training, early specializing athletes could benefit

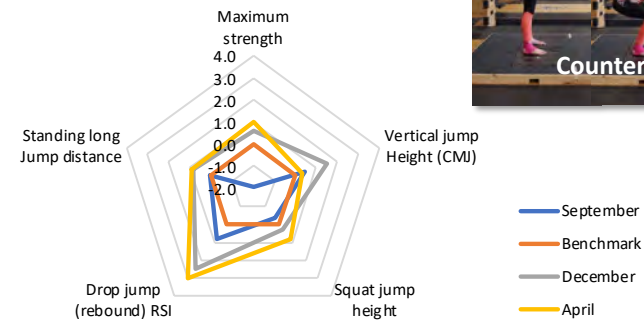
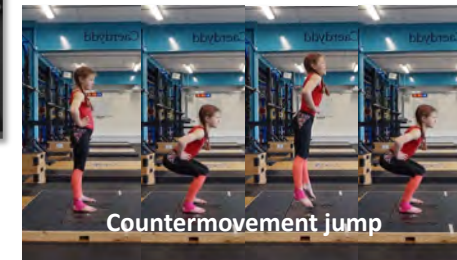
from fun-based ‘challenge weeks,’ which include different types of movement challenges (e.g. sports-acrobatic partner balances) and activities that encourage new skill exploration (e.g. athletes create the obstacle courses) (255). The rationale for this is to reduce the volume of sport-specific skills the early specializing athlete is exposed to, with the aim of reducing overuse-injury risk.

The potential psycho-social implications for athletes specializing from an early age are noteworthy (28). Researchers have indicated that numerous stressors are associated with early specialization such as increased anxiety, competition-related stress, poor sleep quality, social isolation, decreased family time, perfectionism and burnout (28, 29). Therefore, strategies to reduce the risk of early specializing athletes experiencing physical and psycho-social adverse effects should be prioritized (28). For strength and conditioning practitioners working with young athletes, the aim of training sessions should be to incorporate process-oriented goals for motivation purposes. This approach should also help to create a fun, enjoyable and holistic training environment and optimise buy-in to the program (154). Further, practitioners should encourage early specialization athletes to communicate honestly about how they are feeling and utilize other monitoring tools such as wellness/mood questionnaires (e.g. sleep quality, soreness, fatigue, motivation to train etc.) and training diaries. Together, these data can be used to better understand the demands and stressors on these athletes and potentially change training cultures in early specialization sports. As parents, technical coaches and the athletes themselves are key to establishing consistent data that provide insights into workloads, it is important that data is reported back to all parties in a timely manner to effectively ‘close the loop’ on the information sharing process. Reports produced for athletes must be easily understood and presented in an engaging way (e.g. use of visual and audio methods); *figure 2* shows an example report for a young gymnast (104).

PROGRESS REPORT

Date:
Athlete name:
Sport: Gymnastics
Age: 9
Biological age: 75% PAH (pre-pubertal)
S&C training age: 1 year

- The 'benchmark' line in **orange** represents the **average** and has been calculated using data from previous research in gymnasts who are of similar physical maturity to you.
- Scores that are on or **above** the orange line indicate that you have performed **average, or above average** for the test.
- Scores that are **below** the orange line are **areas for improvement**.



*Any questions?
Ask your strength and
conditioning coach*

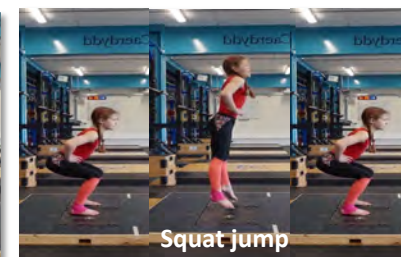
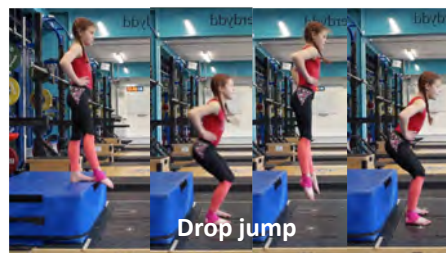


Figure 2. Example progress report for a young gymnast

Coaching insights

Given the young nature of early specializing athletes, coaches should be aware that they could be providing the first experience of strength and conditioning for these children. Consequently, providing a positive, beneficial and engaging training experience should be viewed as a crucial part of the strength and conditioning practitioner's role in promoting LTAD (164). Coaches should aim to develop and maintain authentic coach-athlete relationships (154) and create optimal training environments which are fun and engaging for young athletes to thrive in (i.e. increased autonomy, learning new skills, perceiving self-improvement, increasing intrinsic motivation) (103). It is recommended that all early specializing athletes engage in strength and conditioning and that their programs have an early focus on developing movement competency and force production/absorption and competence in a broad range of athletic motor skill competencies (146, 152, 155, 164, 224).

When structuring the session, aside from the desired targeted adaptations, practitioners need to consider the characteristics of the individuals, and their training experiences and levels of technical competence. Anecdotally, varying the amount of structure during different parts of the same session can be effective. Warm-ups provide an opportune time for less structure, whereby early specializing athletes can explore a variety of movement patterns and challenges (e.g. using obstacle courses, animal shapes and games), develop motor skills, and play games involving movements that the athlete's sport might not address. For example, incorporating games towards the end of the warm-up that involve more chaotic and reactive movement scenarios for a group of young gymnasts will likely provide a novel stimulus compared to the repetitive and consistent nature of gymnastics training. During the main part of the session greater structure and focus could be placed upon improving more specific aspects of performance, while also addressing any aberrant movements that may be associated with

heightened injury risk (155). Again, practitioners should aim to include exercises which address ‘gaps’ in an early specializing athlete’s movement portfolio; for example, a tennis player who is very dominant in upper-body anterior, internal rotation movements may benefit from a greater bias of upper body posterior, external rotation exercises.

Further, practitioners should reinforce simple but important aspects of training that promote good long-term training habits for early specializing athletes. These could include: encouraging and supporting team-mates, completing training logs correctly, reporting any concerns or injuries, and tidying up training areas after use. Apportioning 5 to 10 minutes of less structured training using a game, challenge or competition could be a favourable way to end the session. Anecdotally, highlighting the ‘trainer(s) of the day’ at the end of the session based on effort and application (e.g. improved movement quality) as opposed to performance outcomes (e.g. load lifted) tends to be well-received by early specialization athletes with low training experience (154).

2b.3 SUMMARY

Early specializing athletes are at greater risk of experiencing overuse-type injuries, blunting of motor skill development, burnout syndrome and psycho-social issues. Therefore, strength and conditioning practitioners working with these athletes have an important role in integrating holistic, LTAD training programs as well as monitoring growth, maturation, training load and aspects of wellbeing. Where possible, data should be used to inform training strategies and prescription on an individual basis. It is recommended that early specializing athletes engage in strength and conditioning, and specifically target the development of relative strength and a full breadth of AMSC to improve physical fitness and reduce sports-related injury risk. Whilst overall training load must be considered, integrating strength and conditioning which targets

areas of the early specializing athlete's physical development that their sport does not address is critically important. Coaches should aim to collaborate with technical coaches and parents as well as build authentic relationships with the early specializing athlete to provide developmentally appropriate strength and conditioning programs that are holistic and athlete-centred.

Chapter 2c:

The Physiological Demands of Youth Artistic Gymnastics; Applications to Strength and Conditioning

Moeskops, S., Oliver, JL. Read, PJ. Cronin, JB. Myer, JD. and Lloyd, RS. The physiological demands of youth artistic gymnastics; applications to strength and conditioning. *Strength Cond J.* 2018;41(1):1-13

2c.1 INTRODUCTION

The sport of gymnastics possesses a range of sub-disciplines, including rhythmic, trampolining, tumbling and acrobatic, with an estimated 50 million participating world-wide (81); however, artistic gymnastics is one of the most popular in terms of participation rates among children and adolescents (81, 94). Despite certain similarities, the demands of artistic gymnastics differ for males and females. Women's artistic gymnastics consists of four events (vault, uneven bars, balance beam, and the floor exercise), while men's artistic gymnastics comprises six apparatus (floor, pommel horse, rings, vault, parallel bars, and high bar). The physical abilities necessary to perform successfully on each apparatus vary considerably in the required neuromuscular power, strength, flexibility, speed, co-ordination, balance, and energy system demands (121), and are summarised in *figure 1*. The development of these physical qualities in children and adolescents is non-linear due to interactions of growth, maturation, and training (309). Consequently, the development of physical components in young gymnasts can be complex (156) as the timing, tempo and magnitude of development will differ markedly between individuals of the same age (156). In addition to understanding the science behind the training process, practitioners working with young artistic gymnasts should also consider the key principles surrounding paediatric development to better understand the potential trainability and adaptability of gymnasts at different stages of development.

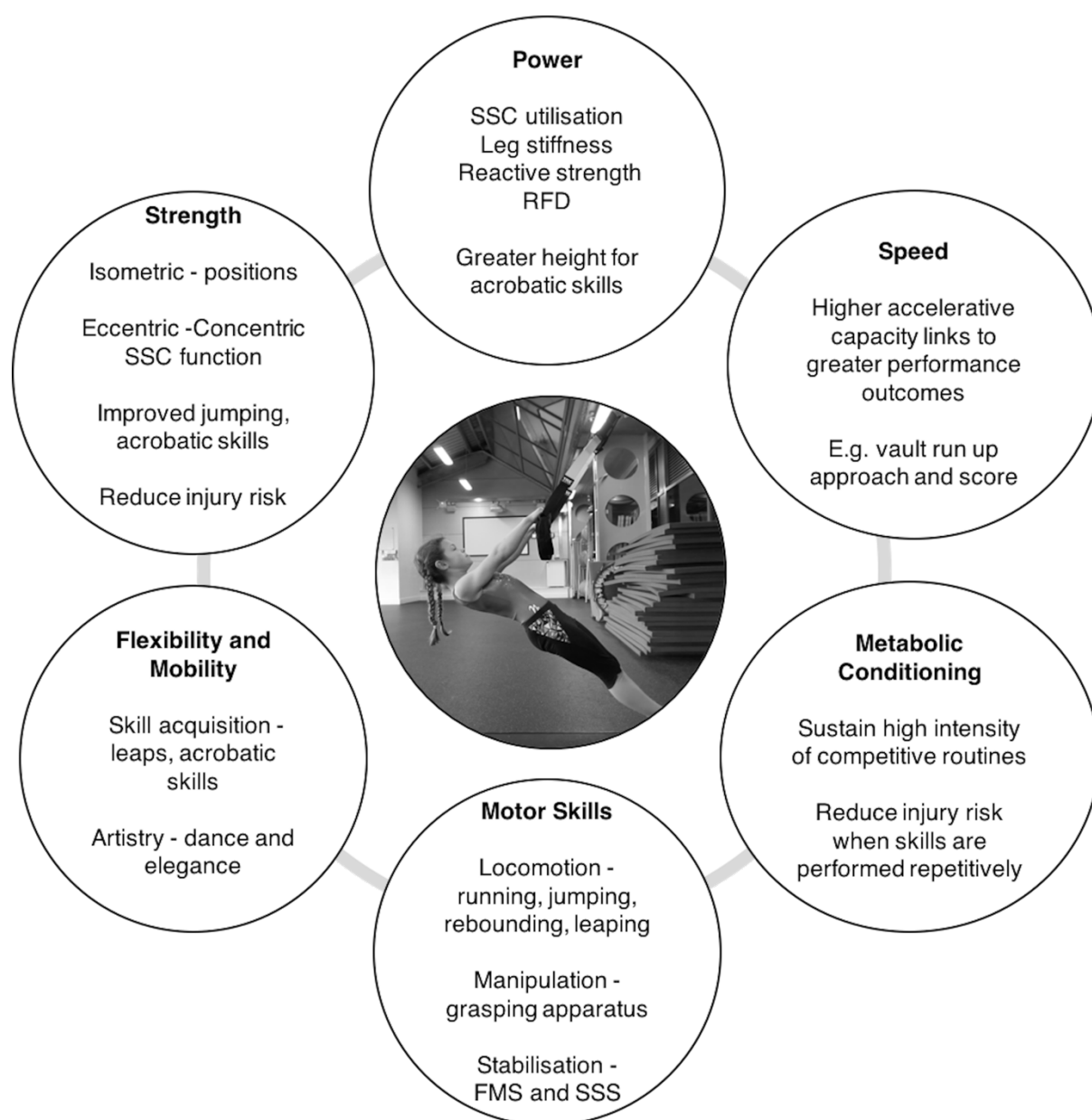


Figure 1. The physical demands of artistic gymnastics

2c.2 PHYSICAL FITNESS REQUIREMENTS FOR ARTISTIC GYMNASTICS

2.c.2.1 Strength, power and speed

Strength. The sport of artistic gymnastics requires high levels of strength and power in the upper and lower limbs to successfully, and safely perform a dynamic and diverse set of movement skills in sequence (94). While these movements will invariably involve a

combination of eccentric and concentric actions, the importance of isometric strength and body tonus should not be underestimated (51) as artistic gymnasts are judged by, and conditioned to, hold a sequence of technical shapes in both dynamic and static conditions (95). Thus, the ability to effectively recruit motor units in order to exert force at variable movement velocities appears to be an important determinant of performance for gymnasts from an early age. For example, during a routine on the floor, gymnasts are required to execute movement patterns that use various segments of the force-velocity curve and involve all types of muscular actions (193, 202).

Take-off characteristics for a double back somersault on the floor have reported mean vertical velocity of centre of mass of $4.2 \pm 0.46 \text{ m.s}^{-1}$ for males, and $3.54 \pm 0.85 \text{ m.s}^{-1}$ for females at take-off (187), while a planche requires high levels of isometric muscular force (133). Furthermore, kinetic analysis of take-off forces during a straight back somersault tumbling series, revealed mean maximal vertical forces and maximal rate of force development were $6874 \pm 1204 \text{ N}$, and $6829 \pm 2651 \text{ N.s}$, respectively (202). Specifically for boys, moving in and out of different positions with control is particularly important on apparatus that is upper body dominant (e.g. the rings, pommel horse) (51). Gymnasts also rely heavily on lower-limb eccentric strength, as they are frequently exposed to landing forces from varying heights, velocities and rotations (89). Researchers have shown that when simulating the impact velocities female gymnasts experience during dismounts from the balance beam and uneven bars (drop landings from 0.69 m 1.25 m and 1.82 m), the gymnasts were required to tolerate vertical peak forces that exceeded nine times their body weight (194). Those able to absorb such forces in an aesthetic manner obtain less deductions, which results in a higher overall score. Therefore, it is evident that gymnasts must manipulate the impulse-momentum

relationship to maximize force production for skill execution and to safely tolerate landing forces to avoid injury.

Power. Similarly, peak power is considered to be an essential component of successful gymnastics performance (121). Gymnasts with higher concentric and eccentric strength and power are able to produce more forceful muscle actions at higher velocities (88), enabling the execution of more challenging acrobatic skills. Researchers have shown that resistance training programs can improve relative power-to-mass ratios in gymnasts through increasing peak power outputs during both countermovement and squat jumps (46% and 43% improvement respectively), and reducing fat mass whilst increasing lean muscle mass. The authors stated that as a result of these adaptations, the gymnasts were able to jump higher, providing increased flight time in which to perform more advanced technical skills, thereby increasing their score potential (88).

The ability to produce high levels of muscular power is salient upon the type of muscular action involved and researchers have shown that when a muscle performs an eccentric action prior to a concentric action, greater power outputs are produced compared to a concentric action in isolation (141). This sequencing of an eccentric contraction followed immediately by a concentric contraction is referred to as the stretch-shortening cycle (SSC) (141). Research has shown that SSC utilization of both upper and lower limbs are key performance indicators for young gymnasts aged 8 to 15 years old (24, 25). For example, research has shown that young gymnasts with an explosive take-off from the board (short repulsive board contact time and high take-off velocity) had increased post-flight times, which resulted in fewer deductions and higher scores in vaulting performance (25). Evidence suggests that during the floor exercise, explosive tumbling involves take-offs with contact times between 115 ± 10 to 125 ± 11 ms

(192), underlining the importance of fast-SSC actions (ground contact times < 250ms) for performance (24). However, recently researchers have found that young elite male gymnasts had unexpectedly poor fast-SSC actions when tested during a 30 cm drop jump protocol (291). The authors suggested that the gymnasts were not effective in their execution of the drop jump due to an over-reliance of sprung surfaces and longer take-off foot contacts during training of tumbling and vaulting performance (291). The findings could also indicate that gymnasts are very proficient at gymnastics skills which require SSC actions, but have not experienced the use of drop jumps in their training on non-sprung surfaces (151).

Speed. The phase of running prior to the point at which an individual reaches their maximum velocity is referred to as the acceleration phase. The ability to accelerate effectively requires the application of high resultant ground reaction forces in a horizontal direction, relative to body weight (214). Maximal velocity usually occurs between 15-30 metres in young athletes (195), and refers to the point at which external forces are no longer changing the velocity. The approach to the vault in gymnastics requires rapid acceleration up to 25 m to facilitate an explosive take-off from the springboard (21). Achieving a high speed during the approach and subsequent power output for the aerial phase is directly associated with improved scores on the vault (24). Elite male gymnasts demonstrate speeds of up to 10.9 m.s^{-1} during competition (5). In young national standard female gymnasts, average speeds of over 18 m were 6.07 m.s^{-1} (8-10 years old), 6.31 m.s^{-1} (11-12 years old) and 6.20 m.s^{-1} (13-14 years old), respectively (24). Interestingly, the results indicate a reduction in sprint speed together with an increase in body mass and height of gymnasts aged from 11-12 to 13-14 years old. As the natural development of speed throughout childhood and adolescence is thought to follow a non-linear process (170), the results could reflect a period of 'adolescent awkwardness' whereby a temporary disruption in motor co-ordination occurs due to growth (14). Furthermore, a fast vault run-up speed and

resultant take-off velocity from the spring board were found to be strong predictors ($r^2 > .64$) of floor tumbling ability (24), demonstrating the importance of developing high running speeds for artistic gymnastics.

2.c.2.2 Balance and stabilization

The aptitude to balance and stabilize the body is a complex process involving sensory information from the vestibular, visual and proprioceptive systems (87), to maintain the body's centre of gravity over the base of support (116, 227). Gymnasts require the ability to balance and maintain postural control via the upper and lower extremity during both static and dynamic movements. Factors that affect young gymnasts' ability to stabilize their bodies during such tasks include; the size of the base of support, height of centre of gravity, and number of limbs in contact with the apparatus (105). Unique to the sport of artistic gymnastics, the equipment's mechanical properties affect the stability of the apparatus which also influences the difficulty of the tasks (47). For example, the handstand is a fundamental skill for male and female gymnasts which has considerably different demands to maintain stability when performed on different apparatus such as the floor, beam, parallel bars, and rings (47, 105). A recent review concluded that when aiming to retain stability during a handstand, the 'wrist strategy' can be adopted to maintain the position, providing the gymnasts body remains in a vertical position (105). The 'wrist strategy' involves increasing the centre of pressure in the fingers or wrists depending on the movement direction of the centre of gravity (287). However, if the area of support is smaller for example on the uneven bars, the "shoulder strategy" may be required to maintain balance (105).

Expectedly, researchers have shown that gymnasts have superior balance ability when compared with controls (4, 35), and various other sports (38, 116). Recent findings from a large

data-set of children aged 5 to 14, found that scores from the balance error scoring system (BESS), significantly improved with increasing age (102). Given the effects of gymnastics-specific training on balance (4, 35, 38, 116), and the natural improvements in balance that manifest during childhood (102), devoting large amounts of time to balance training during young gymnasts' strength and conditioning provision may not be warranted. Instead, warm ups and injury prevention sessions would serve as the opportune time to incorporate exercises that enhance postural/trunk control, stability, and that emphasize high quality (force absorption) landing tasks.

2.c.2.4 Energy demands of gymnastics

The duration of performance within artistic gymnastics varies amongst activities; the vault exercise can last approximately five seconds, while the beam and floor exercises can last up to 90 seconds (121). Both the explosive nature of the sport and short duration of the disciplines dictate that the main supply of adenosine triphosphate (ATP) in gymnastics is via the ATP-PCr and anaerobic glycolytic energy systems. Researchers have shown peak blood lactate concentrations (L_{\max}) above 4 mmol/l for elite males and females on all apparatus, with the exception of the vault (2.4-2.6 mmol/l) (182). Owing to the variety in duration, intensity and tempo of artistic gymnastics activities and the variability of muscle contraction types during competitive routines, gymnasts never reach a "steady state" in performance (121). Therefore, estimating energy costs from the relationship between VO_2 and HR is likely to be invalid when drawn from laboratory testing of the athletes (121).

According to longitudinal data regarding the aerobic capacity of gymnasts, typical maximal oxygen uptake ($VO_{2\max}$) values have remained around 50 ml/kg/min over the last five decades (125). It would appear that aerobic capacity is not a key determinant of performance for artistic

gymnasts. This is perhaps unsurprising considering gymnasts are conditioned to perform short, explosive routines, relying predominantly on anaerobic metabolism. However, this is not to say that possessing some level of aerobic capacity is unnecessary (121), as it has been shown that adolescent female gymnasts attain VO_{2max} profiles as high as 85% (relative to body mass) following competitive routines, such as the floor exercise (182). Additionally, heart rate data of elite gymnasts has been investigated during each apparatus for both males and females (125, 182). Maximal HRs were found to be approximately $>180 \pm 11.33$ beats per minute, with the exception of the vault (and the rings as HR data was not included in the study) (125, 182), demonstrating the high intensity nature of the sport. It would appear from the aforementioned data that during competitive routines, elite gymnasts work close to their metabolic thresholds (120), indicating the need for high-intensity based conditioning programs. Crucially, gymnasts that are able to recover more efficiently between a series of skills or different events, are more likely to sustain a higher level of performance, and reduce their relative risk of injury through fatigue. Therefore, while it may not be a primary training emphasis during the developmental years (156), strength and conditioning programs for youth gymnasts should not eliminate aerobic conditioning as a training stimuli, especially when trying to optimise recovery during repeated bouts of exercise.

Childhood physiology: an increased ability to recover from high-intensity exercise

Balancing fatigue during intense training sessions and technical competency of difficult skills is essential to optimize the safety of young gymnasts (121). Performing highly skilful routines in a fatigued state may increase the risk of injury (271). Thus, it is important that young gymnasts are able to facilitate a fast recovery from high-intensity exercise. Researchers have shown that children recover more quickly from high intensity exercise than adults (6). From a mechanical perspective, children are unable to generate relative power outputs to the same

magnitude as adults (259), which is likely to result in less relative fatigue (6). Similarly, researchers have shown that children's type II muscle fibres are similar or smaller in cross-sectional area than their type I fibres (310), which suggests an extensive underuse of type II motor units during the pre-pubertal years (60). Thus, children's neuromuscular immaturity may impact on their ability to maximally recruit higher-order, type II motor units. This indicates a greater reliance on lower-order type I motor units that facilitates a faster resynthesis of energy substrates, resulting in a faster recovery (6). Additionally, faster PCr resynthesis has been attributed to children's greater reliance on oxidative metabolism and lower dependence on glycolytic metabolism (60). Children also produce lactate at a lower rate than adults during maximal exercise, resulting in reduced lactate accumulation, though their rate of lactate removal appears to be the same (60). Thus, when aiming to develop anaerobic capacity in young gymnasts, practitioners should consider the influence of growth and maturation on the trainability of this system. Furthermore, young gymnasts will require a certain degree of aerobic conditioning to recover from the high-intensity exercise that the sport demands. It is therefore important for coaches to encompass both anaerobic and aerobic conditioning stimuli in artistic gymnasts programming.

2.c.2.5 Flexibility and mobility

Unlike other sports which require optimal ranges of motion for skill acquisition and mechanical advantage (156), artistic gymnastics is an aesthetic sport which demands large ranges of motion to achieve certain positions and techniques for the purpose of scoring (95). For example, following appropriate preparation, male gymnasts perform dislocation elements on the high bar and rings (122), underlining the extreme ranges of motion required by the sport. Furthermore, in women's gymnastics, the Code of Points penalises gymnasts that do not attain 180 degrees of splits during leaps, jumps and acrobatic skills (95). It is essential to note that

while the ability to achieve these limb positions relies heavily on extreme ranges of motion, these movements must be supplemented with appropriate levels of muscle strength throughout the range of motion (51, 122).

2c.3 TRAINING CONSIDERATIONS FOR YOUNG ARTISTIC GYMNASTS

2c.3.1 Growth, maturation and training

Intuitively, gymnastics coaches may favour the selection of late maturing individuals and those that are genetically predetermined to have shorter and slighter statures (particularly in women's gymnastics). However, children develop biologically at different rates, particularly around puberty whereby they experience rapid fluctuations in growth (289). Chronological age is not a valid or reliable indication of maturity status (7). While technical competency will always be a key determinant of training prescription, it is imperative that consideration is given to biological maturation when training young gymnasts within the same competitive age group. Predicting somatic maturity may be a useful and practically viable marker for coaches to monitor gymnasts' growth and maturation (157). For example, owing to the influence of stature on performance and the high representation of later maturing youth (297), practitioners could determine the percentage of predicted adult stature (136), which offers a practical and reasonably accurate measure of estimated maturity for youth populations (136).

With a clear understanding of biological maturation, practitioners working with young gymnasts should be better placed to prescribe and coach developmentally appropriate training strategies that meet the specific needs and goals of the individual (13, 151, 152). For example, by collecting basic anthropometric data on a quarterly basis, practitioners can identify with reasonable accuracy when a gymnast is experiencing a growth spurt, and can tailor training accordingly. From a physical perspective, when working with youth who are undergoing rapid

periods of growth, coaches should spend time addressing any decrements in range of movement (foam rolling soft tissue, unloaded stretches) and balance, due to the changes in the height of centre of gravity (static and dynamic balancing/stabilizing activities). Furthermore, coaches must individualize programmes to target deficits in strength resulting in muscle imbalances (233). There are numerous training strategies available to practitioners to develop the physical performance characteristics of young artistic gymnasts, which can be seen in *figure 2*. The challenge of working with youth who are experiencing a growth spurt is exacerbated when sport-specific training loads are high, which are common in youth gymnastics (239). This scenario can lead to high amounts of accumulated fatigue at a time when young gymnasts are experiencing significant biomechanical alterations (e.g. increased limb length, reduced relative strength) as a result of growth. Data suggest that the growth spurt poses an increased risk of injury in young athletes as a result of musculoskeletal vulnerability (186), especially with respect to overuse (34), and acute traumatic (307) injuries. Due to the heightened injury risk during this stage of development, routine screening of basic anthropometric data, and some form of movement screening (e.g. the tuck jump assessment or drop jump testing for knee valgus during landings) is recommended. Similarly, practitioners are also advised to make use of some form of health and well-being questionnaires to monitor sleep, fatigue, muscle soreness, mood, levels of social interaction, and any onset of pain that could be associated with musculoskeletal injuries (151). Furthermore, coaches must carefully monitor training loads (both volume and intensity) and closely monitor the total loads experienced by young gymnasts. This requires a quantification of training load during strength and conditioning training, sport-specific training, and competitions to reduce the risk of; overuse-type injuries, non-functional overreaching, overtraining syndrome, and burnout (56). Practitioners should adopt an integrated approach to quantify training loads, using a combination of both internal and external load metrics to provide insight into the total stress placed on the athletes (20).



Figure 2. Training strategies for the development of physical characteristic in young artistic gymnasts

2c.3.2 A holistic approach to training

Research from numerous reports in various sports have suggested that children specializing in a single sport prior to puberty may be disadvantaged at a later stage (118, 215, 224). Historically, gymnastics coaches prioritise the implementation of traditional gymnastics-specific conditioning programs from a very early age (12, 247), which often involves circuits of body weight exercises and repetitions of skills. However, while such training programs typically only involve the development of specific physical qualities and movement patterns for gymnastics, it is recognised that well-rounded athleticism should be developed in all youth (151). It is proposed that neuromuscular training (NMT), which uses a combination of general and specific strength and conditioning activities to enhance health and skill-related components of fitness (108) could be an advantageous addition to gymnasts programs to enhance performance and reduce the relative risk of sport-related injury. Crucially, training provision for youth should be programmed in a holistic and integrated manner in order to provide a variety of training stimuli to develop multiple fitness components and overall athleticism (44).

Conventionally, gymnastics coaches' conditioning programs are largely skill driven owing to the specific demands of the sport (126). Training specificity cannot be underestimated in this sport and can be used to prepare gymnasts effectively, providing training is progressively loaded. However, the broader field of strength and conditioning may offer additional benefits to the physical preparation of gymnasts (88, 100, 178, 246). Indeed, the challenge for the strength and conditioning coach working with young gymnasts is to safely provide an effective training stimulus that is different to that which they experience during their sport-specific training, yet is still relevant to their athletic development. Young artistic gymnasts will likely be accustomed to experiencing high ground reaction forces during activities such as tumbling or vaulting (140, 284). For example, pre-pubescent female gymnasts have been shown to endure vertical ground reaction forces of 2-4 times body weight at the wrist, and 3-8 times body weight at the ankle, on the floor apparatus (32). A major role of the strength and conditioning coach is to increase the robustness of the child to repeatedly tolerate these ground reaction forces safely and effectively, in both a fatigued and non-fatigued state. Frequent exposure to specific movement patterns whereby the application of force is not varied may result in chronically overstressing the musculoskeletal system (8, 56).

Strength and conditioning coaches working within early specialization sports should be particularly aware of the benefits that movement variability provide for motor skill development and reducing the risk of overuse injuries (8, 151). The strength and conditioning coach has a role to play in developing general levels of athleticism in the young child that will facilitate their lifelong participation in sports and activities outside of gymnastics. In the event that a young gymnast decides to disengage from the sport, it is important that they are physically prepared for the demands of other sports or physical activities (151), not just

attempting to maximize specific abilities for gymnastics. Finally, coaches should be mindful that strength and conditioning provision with young gymnasts should be fun, challenging, and enjoyable, to optimise athlete buy-in and long-term adherence to programmes.

2c.3.3 Strength and power training

Traditional fears that resistance training induces excessive muscle hypertrophy, resulting in increased body mass has anecdotally discouraged some gymnastics coaches from using this training modality, particularly with young females (88). However, the adaptations from resistance training in youth prior to the onset of puberty are likely to be neuromuscular in nature (91), meaning that large increases in muscle cross-sectional area are unlikely (156). Consequently, increases in strength during this stage of development, especially in the early stages of the training intervention, will be as a result of improved neuromuscular qualities (motor unit recruitment, synchronization & firing frequency) as opposed to hypertrophic adaptations (152). Following the adolescent growth spurt, both neurological and morphological adaptations may also occur as a result of training (156). However, as the goal for most gymnasts would be to develop relative strength, appropriate training prescription (lower repetition ranges, higher intensities, and longer rest periods) should result in myofibrillar hypertrophy and increased functional mass, as opposed to sarcoplasmic hypertrophy and increased non-functional mass (281).

Sex differences in the rate of muscular growth are apparent following the onset of puberty, with males displaying accelerated gains in strength (170) and females a reduction in strength and power production (230). Decrements in neuromuscular strength during this stage of development may increase females' risk of certain injuries, especially those involving the anterior cruciate ligament (ACL) (83, 253), a catastrophic injury which can occur during

landings in gymnastics (111). Gymnasts are required to ‘stick’ landings following certain skills and dismounts to avoid large deductions and to optimize performance (95); therefore, the need to develop eccentric strength to assist in force dissipation strategies is necessary. Programmes which specifically focus on the development of eccentric strength in highly trained athletes improve power, velocity and jump height characteristics, compared to controls that trained without an accentuated eccentric load (285). However, there remains a lack of literature that has specifically examined the effects of eccentric strength development in young athletes. Short term neuromuscular training interventions which focus on ‘soft’ landings with an emphasis on knee and hip flexion, significantly improved adolescent female athletes’ biomechanics during landings (223), which could be a beneficial strategy for gymnasts to adopt for dismounts and ‘sticking’ landings. Given that gymnasts may develop greater activation in their knee extensor muscles due to a gymnastics-training induced adaptation prior to puberty (200), and females are predisposed to deficits in hamstring strength following the onset of puberty (107), integrated NMT programmes (222, 226) targeting hamstring strengthening should be incorporated into pre-pubertal and adolescent young gymnasts’ training programmes.

Irrespective of the stage of development, resistance training for gymnasts with a low training age and low levels of technical competency should begin with exercises that are low to moderate in intensity (e.g. body weight) and technically simple (225). The primary focus should centre on building a base level of muscular strength and developing a broad range of robust movement patterns (151). Over time, gymnasts will become proficient at body weight exercises and will ultimately require a new stimulus to overload the body for further adaptation (276). Intensity (or load) can be increased with minimal or no equipment, by altering the body’s position against gravity. Additional external load in the form of free weights, elastic resistance bands and medicine balls, has been shown to be a safe and effective means of enhancing young

athletes' strength within resistance training programs (151). Unfortunately, very few studies have investigated the effects of resistance training programs with artistic gymnasts. Recently, one study in elite pre-pubertal female gymnasts found that a 16-week training intervention, combining high impact plyometrics with heavy resistance training, was more effective in improving various parameters of drop jumps (e.g. flight time, contact time, flight-contact time ratio, and estimated mechanical power) than habitual skill training (178). As a result, the authors recommended a reduction in time spent on technical routines and repeatedly performing gymnastics movements, and the inclusion of 2-3 intense strength and power workouts per week (178), prescription guidelines that are in line with existing youth resistance training recommendations (67, 152). Furthermore, a recent meta-analysis in well-trained young athletes has concluded that on the premise that technical competency has been suitably developed, the most effective dose-response relationship occurs with; conventional resistance training programmes of periods > 23 weeks, 5 sets per exercise, 6–8 repetitions per set, a training intensity of 80–89% of 1 RM (149). This underlines the need for progressive overload even in youth, in order to ensure ongoing neuromuscular adaptation.

It should also be stressed that when technical proficiency is evident, young gymnasts will likely require exposure to larger external loads, typically elicited through barbell related activities such as squatting, deadlifting, lunging, and weightlifting exercises (including their derivatives) to promote further adaptations. Resistance training should be implemented as an alternative training session to gymnastics training, and not merely as an addition. Regular resistance training should form part of young gymnasts' training programs to develop/maintain levels of muscular strength, avoid detraining of neuromuscular qualities, and to prevent overuse injuries associated with high volumes/intensities of sports-specific training (56, 67, 75, 76, 152, 305). One to three resistance training sessions per week are recommended for young athletes,

providing that adequate time for rest and recovery is integrated into the gymnasts' periodised plan (152).

Gymnastics performance is characterized by powerful muscle actions, and training should acknowledge the principle of specificity for optimal adaptations with the goal of developing high contractile velocities (88). As training age and technical competency increase over time, resistance training exercises and weightlifting movements can be performed more explosively to promote appropriate neuromuscular adaptations (134). French et al. (88) utilised a power-specific resistance training programme in elite female gymnasts, which significantly enhanced whole body muscular power capacities. The training included exercises which focused on applying as much force as possible in the shortest period of time which is an important factor for performance in gymnastics (88). This resulted in an increased level of performance, as demonstrated in their competition scores (especially on the floor), due to improvements in leaping and tumbling (88). Furthermore, a recent study investigated the effects of a 6-week resistance training program on jumping performance in pre-pubertal rhythmic gymnasts using sport specific (three repetitions of ten dynamic exercises wearing a weighted belt that was 6% of body mass) and non-specific (a moderate load/high repetition resistance training program with dumbbells) interventions (246).

While both strength training programs increased lower limb explosive strength by 6-7%, only the non-specific training intervention significantly improved flight time in the hopping test which assessed leg stiffness (246). Drop jumps are a highly complex task for young athletes to develop proficiency in (12), however importantly, they are primarily used as a training tool to target fast or slow SSC function through progressive overload. Cueing shorter contact times during drop jumps typically encourages faster SSC activity, while cueing athletes to prioritize

maximum jump height may result in slower SSC actions (165). An increase in leg stiffness may result in reduced ground contact times, leading to a more efficient utilization of the SSC (2, 141). Shorter contact times with rapid amortization periods have been shown to result in greater reutilization of elastic energy (316). While gymnasts need increased leg stiffness for fast SSC actions, the optimal amount of leg stiffness is task specific (188). Certain skills in gymnastics will require a more compliant system involving longer contact times and slower SSC actions, resulting in greater jump heights (2). Plyometrics have been shown to enhance leg stiffness in young boys (160) as well as promote improvements in rebound jump height, vertical jump performance, running velocity, and rate of force development (153), all of which are highly relevant to gymnastics.

However, as a large proportion of gymnastics training already involves plyometric exercise, prescribing an alternative training stimulus that focuses on different regions of the force-velocity curve may be more beneficial such as, strength training (high force), or weightlifting derivatives (high force-moderate velocities). Cumulatively, existing research would suggest that integrating resistance training with gymnastic-specific strength programs may indeed provide an additional training stimulus to enhance performance and reduce injury risk in young gymnasts. While studies have demonstrated the benefits of resistance training for adult gymnasts (88), the effects of a long-term resistance training intervention in pre-pubertal and adolescent gymnasts is yet to be explored.

2c.3.4 Speed Development

The natural development of speed throughout childhood and adolescence is thought to follow a non-linear process (170), with fluctuating improvements in sprint performance occurring in pre-adolescent and adolescent periods (309). Researchers have indicated that the trainability of

sprint speed is optimal when the prescription matches the natural adaptive processes that occur during maturation, a phenomenon referred to as “synergistic adaptation” (163). For example, when aiming to increase sprint speed in pre-pubertal populations, utilizing plyometrics to elicit neurally-mediated adaptations during this stage of maturation is a favorable form of training (73, 163). For post-pubertal males experiencing other maturity-related changes, such as natural increases in muscle mass and changes in circulating androgens, (170, 302) combined resistance training and plyometrics may be the most optimal training stimulus to improve sprinting velocity (163). It is important to note that coaches should pre-screen athletes individually prior to implementing plyometrics to ensure good technical competency is present during landing tasks (150). This is particularly important for gymnasts if the exercises chosen are not performed on sprung surfaces that the gymnasts are accustomed to. However, as previously stated, gymnasts experience a large amount of plyometric based training within their sport and therefore, strength and conditioning coaches must carefully consider the prescription of such training. Controlling the volume (number of foot contacts) and intensity (via exercise choice) is critical for appropriate periodization of gymnasts’ training.

While integrated NMT programs inclusive of resistance training and plyometrics increase speed (albeit indirectly at times) in young athletes (66, 94, 108, 153, 163, 254), specific speed training may provide additional adaptations in running speed for young gymnasts. The vault run-up approach in gymnastics is up to 25 m, thus technical coaching should focus primarily on developing relevant acceleration mechanics and horizontal force production, as opposed to those associated with maximal running velocity. A recent meta-analysis concluded that prescription of speed training for youth should occur twice a week and comprise of up to 16 sprints of approximately 20 m, with a work-to-rest ratio of 1:25 (211). Furthermore, the underlying ability to run fast towards the take-off board and vaulting table relies on both the

gymnasts' accelerative capacity and the ability to visually control and regulate the approach (21, 24). Gymnasts that achieve high speeds when running but slow down as they approach the vault will limit their performance (21, 24). Therefore, coaches should aim to develop running speed throughout the vaulting or tumbling sequence in young gymnasts to optimise the transfer of this ability to vaulting performance. To facilitate this transfer, researchers have recommended that coaches' implement targeting activities early on with young gymnasts, such as practising simple vaults from different approach distances (21).

2c.3.5 Flexibility and mobility training strategies

It is common practise for gymnastics coaches to utilize the proposed sensitive period prior to puberty (275) for developing optimal levels of flexibility in gymnasts. Following the onset of the pubescent growth spurt, researchers have shown that range of motion plateaus or declines, particularly in males (77). Thus, due to the scoring criteria involved in gymnastics which rewards extreme ranges of motion, coaches should emphasize flexibility training throughout childhood and adolescence to maximize whole body range of motion. However, as a caveat to this, it must be recognised that appropriate levels of muscular strength are required to safeguard the young gymnast when using potentially extreme ranges of motion. Thus, strength and conditioning provision of gymnasts should be directed towards balancing the development of large ranges of motion around joints with appropriate strength and neuromuscular stability to reduce injury risk and enhance skill acquisition potential.

Coaches should be aware that there are a number of training modalities available to develop optimal levels of flexibility and mobility in young artistic gymnasts. For static stretches, durations of 10 to 30 seconds, three times per exercise appear optimal, as longer durations may result in greater gains but a potential weakening of connective tissues (167, 275). Gymnasts

often stretch on a daily basis, as frequency is an important principle of training for maintaining and improving flexibility, and of importance, there are no studies in children that have shown adverse effects to this approach (275). For gymnasts with a greater training age, ballistic stretching can be an effective method to increase ranges of motion, providing they are performed under control (275). Proprioceptive neuromuscular facilitation (PNF) stretching can result in large improvements in range of motion in youth populations (268, 314). While many gymnastics coaches utilize this technique, caution is necessary so that stretching does not exceed the gymnasts' limits and cause injury (275). This highlights the need for appropriate prescription and supervision when choosing methods to develop range of motion in young gymnasts.

Recently, vibration training has been shown to be very effective in enhancing flexibility and range of motion in young gymnasts (191, 277, 278), with acute improvements of up to 400% and chronic adaptations of up to 100% reported (278). Greater benefits from vibration-training may occur in the gymnast's less flexible leg due to the greater potential for improvement in range of motion available (191). While the mechanisms underpinning these large improvements in flexibility from vibration-training are currently unknown, proposed theories include reduced pain (191, 277), inhibited activation of antagonist muscles (50) and increased blood flow resulting in increased tissue temperature (275).

2c.4 SUMMARY

Strength and conditioning coaches working with young gymnasts must provide an effective training stimulus that is different from what they experience during their sport-specific gymnastics training. Due to the demands of the sport, strength, speed, power, flexibility/mobility, and anaerobic power appear to be the key determinants of artistic

gymnastics performance; all of which strength and conditioning can improve with appropriate training prescription. When looking to develop these physical capacities in young gymnasts a number of training strategies can be adopted; however, technical competency must be prioritised at all times. Importantly, when designing training programs, coaches should be aware of the influence of growth and maturation can have on the trainability of physical abilities.

Chapter 3: Prelude

Chapters 2a-c showed that existing literature indicates that growth and maturation influence the natural development of physical qualities (i.e. muscular strength, power and speed) and motor skills. As the ability to produce force is a prerequisite to movement proficiency and is essential for all sports, assessing muscular strength in young athletes is important. Whilst numerous variables from the isometric mid-thigh pull (IMTP) test have been shown to be highly reliable in adult populations, minimal data exists in youth populations, especially in children. Prior to the empirical studies examining the development of isometric force-time variables and their associations with vaulting performance later in the thesis, the first study sought to determine the reliability of the IMTP in a cohort of pre- and post-PHV female athletes.

Chapter 3:

Within- and Between-Session Reliability of the Isometric Mid-thigh Pull in Young Female Athletes

Moeskops, S., Oliver, JL. Read, PJ. Cronin, JB. Myer, JD. Haff, GH. and Lloyd, RS. Within- and between-session reliability of the isometric mid-thigh pull in young female athletes. *J Strength Con Res.* 2018;32(7):1892–1901

3.1 INTRODUCTION

There is now a recognised consensus regarding the importance of prioritizing the training of muscular strength in children and adolescents (149, 152). Support for this approach is based on empirical evidence showing that enhancing muscular strength in young athletes can improve proxies of physical performance (149), reduce sports-related injury risk (226), and positively affect various aspects of health and well-being (152). From a performance perspective, muscular strength underpins the ability to proficiently develop fundamental movement skills, and is critical to the acquisition of all other fitness components (9).

Valid methods of assessing maximal muscular strength include; repetition maximum tests, predictive tests, isometric assessments, and eccentric protocols (185). Using tests that can differentiate between growth-related and training-induced adaptations in strength and power is critical in younger populations, as these fitness qualities are likely to increase due to growth and maturation (15). Current methods of assessing young athletes' maximal force-producing capacities have included 1 repetition maximum (1RM) tests (72). Researchers have demonstrated that 1RM testing is safe and appropriate in healthy children and adolescents,

providing the athletes are technically competent and closely supervised by qualified professionals (72). For youth with a low training age, or those who cannot consistently perform exercise techniques correctly, implementing multi-repetition RM protocols to evaluate muscular strength may be viewed as an alternative approach (152). The use of a higher number of repetitions (e.g. 10 RM) performed with sub-maximal loads to fatigue has allowed researchers to predict 1RM values in youth (67). However, these tests are less accurate for evaluating maximal strength (67), and increase the likelihood of accumulating large amounts of fatigue which could result in the breakdown of exercise technique and increased injury risk (152).

The isometric mid-thigh pull (IMTP) is a force-time diagnostic tool and is the most frequently implemented isometric strength test in the adult based literature (98, 130). Although the test itself is isometric, it has been significantly correlated to dynamic and athletic tasks in adults such as; vertical jump performance (130), sprint speed (298), agility (298), weightlifting movements (97), 1RM squat (130), and 1RM deadlift (52). However, further research is needed to examine the relationship between the IMTP and athletic tasks in children and adolescents. Kinetic measures including peak force (PF) and rate of force development (RFD) at different time sampling epochs are regularly reported (97, 98, 298), and have been established as highly reliable in adult populations (52, 58), albeit with greater variability shown for time dependent variables (166).

Very few studies have examined the reliability of force-time characteristics using IMTP protocols in youths. Dos'Santos et al. (59) found that PF and time-specific force values (30-250 ms) were highly reliable between and within-sessions in adolescent male soccer players. However, the potential effects of maturation on the reliability of IMTP performance remains

unclear, as does the reliability of the protocol in young female athletes. Therefore, the purpose of this study was to examine the within- and between-session reliability of the IMTP in pre- and post-peak height velocity (PHV) female athletes.

3.2 METHOD

3.2.1 Experimental Approach to the Problem

This study used a within-subject repeated-measures design, to quantify the reliability of force-time characteristics of the IMTP in youth female athletes. Participants were grouped according to their maturational status (pre-PHV and post-PHV), and each sub-group followed the same testing procedures. Following a familiarization, each participant attended three different testing days (that were at least 24 hours apart), and performed three trials on each session.

3.2.2 Subjects

Thirty-eight female athletes ($n = 19$ pre-PHV, $n = 19$ post-PHV) aged 6–17 years agreed to participate in the study. PHV refers to the age at which a young athlete experiences maximum rate of growth during the adolescent growth spurt (170), and is commonly used as a measure of somatic growth (157). Standing height (m), sitting height (m), and body mass (kg) were used to determine participants' maturity status using years pre- and post-PHV as outlined in the original research (199), as well as the percentage of predicted adult height (PAH) (136) as shown in *table 1*. While there is an error of approximately 6 months associated with the maturity offset, the significant differences in body mass, leg length, standing height between the two groups (*table 1*), combined with the additional maturity assessment using percentage of predicted adult height indicates that the determination of participants' maturation were relatively homogenous and accurate. Participants reported no injuries at the time of testing, were all regularly participating in sport, had a training age of less than 12 months, and no prior

experience of the IMTP procedure. Participants were instructed to wear the same clothing and footwear to each testing session, and to refrain from strenuous activity 24 hours before testing. Parental consent and participant assent were obtained following ethical approval from the institutional research ethics committee (ethics code: 17/1/02R).

Table 1. Mean (\pm SD) values for descriptive details of each groups' anthropometric data

Group	<i>N</i>	Age (yrs)	Standing height (m)	Sitting height (m)	Leg length (m)	Body mass (kg)	Maturity offset (yrs from PHV)	Predicted % adult height
Pre PHV	19	8.0 \pm 2.0	1.246 \pm 0.117	0.676 \pm 0.06	0.579 \pm 0.077	26.1 \pm 7.0	-3.2 \pm 1.6	71.0
Post PHV	19	14.6 \pm 1.5*	1.649 \pm 0.078*	0.865 \pm 0.035*	0.783 \pm 0.054*	57.7 \pm 8.3*	2.2 \pm 1.1	95.3

Note: PHV = Peak height velocity; * = Significantly greater than pre-PHV

3.2.3 Procedures

Familiarization

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). All participants familiarized themselves with the IMTP testing protocol, which took place at the beginning of the first testing session. This involved each individual practicing the IMTP protocol until the lead researcher was satisfied with the athlete's technical competency. The force traces of the practice trials were observed for asymmetry and a stable weighing period prior to the pulling phase of the protocol.

All testing sessions took place in a laboratory using a custom built IMTP testing device (see figure 1) and two force plates sampling at a frequency of 1000 Hz (type 9287BA, Kistler Instruments AG, Winterthur, Switzerland). The athletes' second pull position for the power clean was then identified individually to optimize the production of maximal force and rate of force development (288). In line with previous research, the athletes adopted an IMTP set up position where; feet were hip-width apart, the bar was positioned at mid-thigh, the torso was upright with a neutral spine, and knee and hip angles were between $140 \pm 5^\circ$ and $135 \pm 5^\circ$, respectively (52, 97, 98). The customized IMTP rig allowed for incremental bar height adjustments of 1 cm to accommodate athletes of different statures. All participants were instructed to stand bilaterally with one foot on each force plate, and once the athlete adopted the correct IMTP position, their hip and knee angles were verified and recorded using a handheld goniometer (plastic 12 inch, 66fit). Bar height was recorded using the measurement markings on the custom-made rig. Foot position was determined using a customized 2-figure grid reference system for each participant's heel and forefoot position to standardize foot

position between testing sessions. Grip width was also established for standardization purposes and was measured using the difference between each index finger. Lifting straps were used to secure the athlete to the bar to reduce the likelihood of grip strength being a limiting factor for performance (98). Adhesive markers were placed on the grid references and bar for each young athlete to aid the setup process for each trial.

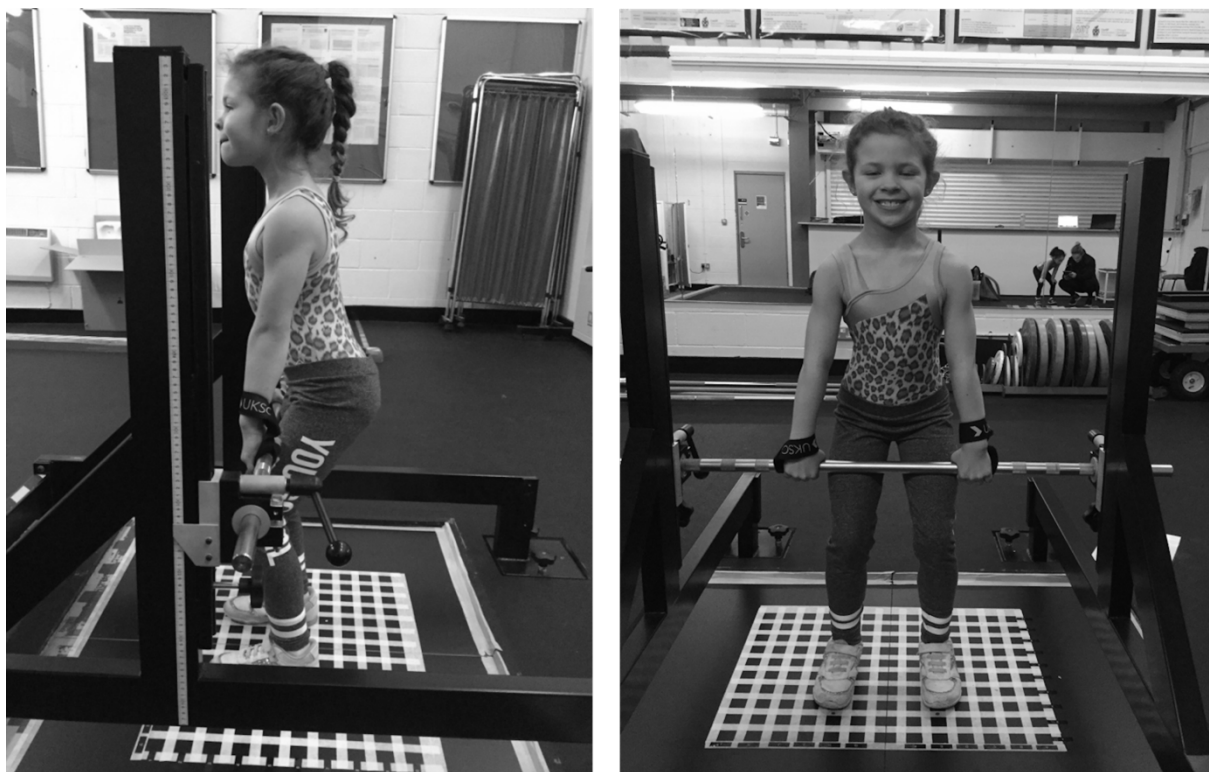


Figure 1. Isometric mid-thigh pull set up position lateral and anterior view

Testing session

All participants performed a standardized 10-minute dynamic warm up before each testing session commenced, which included relevant activation and mobilization exercises, before advancing to 3 sets of 3 squat jumps, countermovement jumps and pogo hops. Each participants' specific measurements were replicated for each testing sessions to reduce the risk of measurement error associated with changes in athletes' posture (58). Once set up in their

individualized IMTP position, participants were afforded one practice of the IMTP protocol sub-maximally and maximally, separated by two minutes rest time. The participants were then asked to step off of the force plates for zeroing purposes. Following a minimum of a 60 second rest period, the children were then ready to commence testing. Child friendly cues such as “*stand still like a statue*” were used to optimize the stabilization of body weight during the first second of each test, prior to initiating the pull. All subjects received the standardized instruction previously used for the IMTP protocol, “*pull as hard and as fast as possible until I say stop,*” (58, 97, 98) and were instructed to pull equally with both hands. After a countdown of “3, 2, 1 pull,” participants worked maximally for the five second period of data collection. All participants completed three trials of the protocol and standardized verbal encouragement was provided throughout each trial. A minimum of two minutes of passive rest was given between trials to ensure sufficient recovery (99). Trials were discounted and repeated if the following occurred: the participant lost grip, a visible countermovement was present, or if the trial was not considered as maximal. In adult populations, a difference of > 250 N has resulted in the trial being repeated (98). Given the inherent variability in coordination for child populations (161), a difference greater than 15% of their peak force resulted in an additional trial being performed.

Variables

All isometric force-time curves were analyzed by the same researcher using custom built Labview (LVRTE2014SP1; National Instruments) analysis software, previously used in adult IMTP literature (98). For time-dependent variables, initiation of the pull was determined using the visual onset method, recommended in previous research (166). From the force-time data, the following variables were processed:

- *Absolute peak force (PF)*: The maximum force (N) generated during the 5-second protocol.

- *Relative peak force (N/Kg)*: The maximum force (N) generated during the 5-second protocol divided by the athlete's body mass (kg).
- *Force at 30, 50, 90, 150, 200, and 250 milliseconds*: The force (N) produced at each time sampling interval calculated from the initiation of the pull.
- *Rate of force development (RFD)*: The rate at which force is developed during a maximal contraction ($\text{N}\cdot\text{s}^{-1}$). RFD was calculated from the slope of the force-time curve during predetermined time bands; 0–50, 0–90, 0–150, 0–200, and 0–250 milliseconds (98).
- *Peak rate of force development (pRFD)*: The pRFD is the highest RFD during a specific time sampling window (98). The 20-millisecond timeframe (pRFD20) was chosen for analysis owing to its superior reliability when compared to other sampling windows. (98)
- *Time to peak force (TPF)*: The total time (milliseconds) taken to reach the absolute peak force.
- *Time to peak rate of force development (TPRFD)*: The total time (milliseconds) taken to reach the peak rate of force development.

3.2.4 Statistical analyses

Descriptive statistics (means \pm standard deviations) were calculated for all force-time variables for each group. The assumption of normality was assessed via the Shapiro-Wilk test. The change in the mean and a repeated-measures analysis of variance (ANOVA) was conducted to determine if there was any systematic bias between-session (session 1, 2 and 3) and within-session (trials 1, 2 and 3) for each group. Sphericity was assessed via Mauchley's Test and where violated, Greenhouse-Geisser was implemented. A Bonferroni post hoc test was used to identify pairwise differences. Between- and within-session random variability was determined using mean coefficients of variation (CV%) and intraclass correlation coefficients (ICC) to determine both absolute and relative reliability. Acceptable thresholds were determined using

a CV of <10% (44). Ninety-five percent confidence intervals (95% CI) were calculated for all variables. Magnitudes of ICC were classified according to the following thresholds: >0.9 nearly perfect; 0.7-0.9 very large; 0.5-0.7 large; 0.3-0.5 moderate; 0.1-0.3 small (112). Noise:signal ratios were calculated for each variable using the typical error (noise) and the smallest worthwhile change (signal), with the smallest worthwhile change a factor of 0.2 of the between-participant standard deviation from consecutive trials, or across all trials to provide a mean ratio. Descriptive statistics and repeated-measures ANOVAs were computed using SPSS Statistics v.22, with statistical significance set at an alpha level of $p < 0.05$. ICC and CV% were calculated using an online spreadsheet run through Microsoft Excel for Mac version 15.35 (114).

3.3 RESULTS

Within-session descriptive statistics for each variable and associated reliability measures for pre- and post-PHV cohorts are presented in *table 2 and figure 2*. There was no systematic bias for any variables, and the random variation in absolute and relative peak force was slightly more reliable in post-PHV participants (CV = 5-6%, ICC = 0.91-0.96) compared to pre-PHV participants (CV = 8-10%, ICC = 0.87-0.97). Force measured at different time sampling intervals showed moderate reliability in the post-PHV cohort (CV% = 7.9-16.8%; ICC \geq 0.77) but greater variation was evident in the pre-PHV group (CV% = 22.3-32.3%; ICC \geq 0.78;). All time-related variables (RFD at various sampling intervals, pRFD, TPF and TPRFD) showed a greater range of ICC (0.29-0.9) and much larger variation across trials (CV% = 25.2-125.7%).

Between-session descriptive statistics for each variable and associated reliability measures for pre- and post-PHV cohorts are displayed in *table 3 and figure 3*. Between-session typical error of absolute and relative peak force was slightly more reliable in post-PHV (CV = 6.2-6.3; ICC

≥ 0.85) compared to pre-PHV (CV= 9.7-9.8%; ICC ≥ 0.71), while pre-PHV also demonstrated significant improvements in performance from trial 1 to 2, indicating the presence of systematic bias. Force measured at each time sampling interval showed moderate reliability in the post-PHV cohort (ICC = 0.75-0.78; CV% = 11.7-22.2%) but greater variation was evident in the pre-PHV group (ICC = 0.83-0.86; CV% = 20.5-25.6%). All time-related variables (RFD at various sampling intervals, pRFD, TPF and TPRFD) showed a greater range of ICC (0.10-0.76) and much larger variation across trials (CV% = 31.6-143.1%).

The noise:signal ratio data presented in *table 4* show that the majority of testing variables achieved a ratio of between 1.93-2.65, however, measures of absolute peak force achieved ratios of ≤ 1.33 in both pre- and post-PHV.

Table 2. Within-session reliability for IMTP kinetic variables in pre- and post-PHV female athletes

Variable	Mean results (\pm SD)			Change in mean (%)		CV (95% CI)		ICC (95% CI)	
	Trial 1	Trial 2	Trial 3	Trial 2-1	Trial 3-2	Trial 2-1	Trial 3-2	Trial 2-1	Trial 3-2
Pre-PHV female athletes									
Absolute PF (N)	704.83 \pm 243.85	695.22 \pm 247.99	710.57 \pm 257.18	-1.8	2.6	7.0 (5.3 - 10.6)	7.5 (5.6 - 11.3)	0.97 (0.91 - 0.99)	0.97 (0.92 - 0.99)
Relative PF (N/kg)	26.84 \pm 5.26	26.3 \pm 4.58	26.97 \pm 4.81	-1.8	2.6	7.0 (5.3 - 10.6)	7.5 (5.6 - 11.3)	0.87 (0.68 - 0.95)	0.87 (0.69 - 0.95)
Peak RFD (N·s ⁻¹)	2380.98 \pm 2333.70	2486.21 \pm 1473.61	2401.86 \pm 1804.87	8.8	-9.1	32.2 (23.5 - 51.1)	36.5 (26.5 - 58.5)	0.63 (0.27 - 0.84)	0.78 (0.51 - 0.91)
Time to PF (ms)	4624.79 \pm 1485.07	4023.63 \pm 1387.15	4058.95 \pm 1687.98	-13.3	-3.9	44.4 (32.0 - 72.1)	41.0 (29.6 - 66.2)	0.04 (-0.41 - 0.15)	0.32 (-0.15 - 0.67)
Time to pRFD (ms)	269.26 \pm 148.95	259.32 \pm 127.87	375.42 \pm 257.43	4.1	37.3	81.0 (56.6 - 140.5)	60.2 (42.8 - 100.8)	0.41 (-0.37 - 0.72)	0.29 (-0.17 - 0.65)
Post-PHV female athletes									
Absolute PF (N)	1565.39 \pm 316.36	1538.79 \pm 338.01	1514.13 \pm 302.19	-0.2	-1.4	4.9 (3.7 - 7.4)	6.2 (4.6 - 9.3)	0.96 (0.89 - 0.98)	0.95 (0.88 - 0.98)
Relative PF (N/kg)	27.11 \pm 3.90	26.72 \pm 4.87	26.84 \pm 3.90	-0.2	1.0	4.9 (3.7 - 7.4)	5.8 (4.3 - 8.7)	0.93 (0.83 - 0.97)	0.91 (0.77 - 0.96)
Peak RFD (N·s ⁻¹)	4320.71 \pm 1881.72	3752.18 \pm 1751.22	4189.00 \pm 1905.04	-14.3	10.4	22.0 (16.2 - 34.2)	28.3 (20.7 - 44.6)	0.86 (0.67 - 0.94)	0.68 (0.34 - 0.86)
Time to PF (ms)	3568.63 \pm 1684.74	4227.47 \pm 1707.11	4030.63 \pm 1577.73	19.5	-3.1	42.6 (30.7 - 68.9)	44.3 (32.0 - 72.1)	0.38 (-0.08 - 0.70)	0.40 (-0.05 - 0.72)
Time to pRFD (ms)	205.16 \pm 115.93	200.47 \pm 83.05	213.74 \pm 149.03	1.4	-5.9	47.6 (34.2 - 77.8)	55.1 (39.3 - 91.4)	0.30 (-0.17 - 0.65)	0.36 (-0.11 - 0.69)

Notes: PHV = Peak height velocity; SD = Standard deviation; CV = Coefficient of Variation; ICC = Intraclass Correlation Coefficient; CI = Confidence Interval; PF = Peak Force; RFD = Rate of Force Development; pRFD = Peak Rate of Force Development;

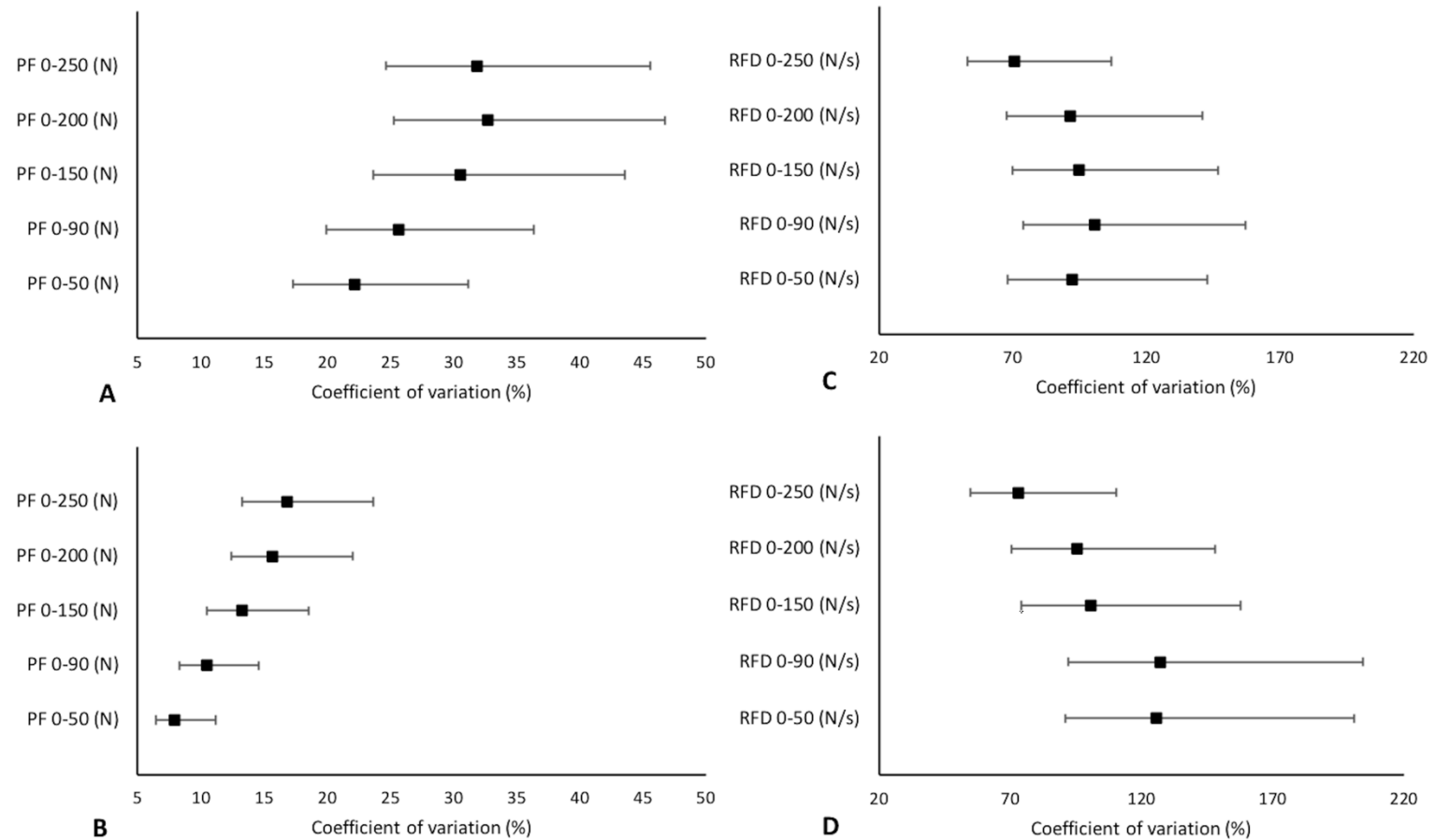


Figure 2: Forest plots displaying coefficients of variation for within-session reliability: (A) pre-PHV athletes force at different time-sampling intervals (B) post-PHV athletes force at different time-sampling intervals (C) pre-PHV athletes force at different RFD epochs, and (D) post-PHV athletes force at different RFD epochs. Error bars indicate 95% confidence limits of the mean difference between trials.

Table 3. Between-session reliability for IMTP kinetic variables in pre- and post-PHV female athletes

Variable	Mean results (\pm SD)			Change in mean (%)		CV (95% CI)		ICC (95% CI)	
	Session 1	Session 2	Session 3	Session 2-1	Session 3-2	Session 2-1	Session 3-2	Session 2-1	Session 3-2
Pre-PHV female athletes									
Absolute PF (N)	672.46 \pm 276.78	749.03 \pm 258.63*	734.44 \pm 258.40	13.5	-2.3	10.2 (7.6 - 15.5)	9.3 (7.0 - 14.1)	0.95 (0.83 - 0.98)	0.95 (0.86 - 0.98)
Relative PF (N/kg)	25.27 \pm 5.46	28.38 \pm 4.93*	27.71 \pm 3.99	13.2	-2.0	10.1 (7.5 - 15.3)	9.4 (7.0 - 14.2)	0.81 (0.58 - 0.92)	0.71 (0.39 - 0.88)
Peak RFD (N·s ⁻¹)	2383.52 \pm 1477.41	2539.36 \pm 1589.52	2445.49 \pm 1929.18	9.9	-7.3	44.7 (32.2 - 72.8)	38.9 (28.2 - 62.5)	0.61 (0.23 - 0.83)	0.67 (0.32 - 0.86)
Time to PF (ms)	3813.47 \pm 1494.85	4682.95 \pm 1598.52	3533.05 \pm 1543.31	24.2	-26.3	51.3 (36.8 - 84.5)	50.8 (36.4 - 83.5)	-0.06 (-0.49 - 0.36)	-0.18 (-0.56 - 0.29)
Time to pRFD (ms)	339.42 \pm 209.31	303.26 \pm 125.57	377.68 \pm 235.66	-6.1	7.6	54.2 (38.7 - 89.8)	59.5 (42.3 - 99.5)	0.05 (-0.41 - 0.48)	0.43 (-0.02 - 0.73)
Post-PHV female athletes									
Absolute PF (N)	1619.93 \pm 331.69	1603.05 \pm 317.82	1574.95 \pm 329.83	-0.9	-2.1	6.7 (5.0 - 10.0)	5.8 (4.3 - 8.6)	0.92 (0.80 - 0.97)	0.95 (0.88 - 0.98)
Relative PF (N/kg)	27.85 \pm 4.27	27.75 \pm 4.18	27.84 \pm 3.83	-0.3	0.5	7.3 (5.5 - 11.0)	5.3 (4.0 - 7.9)	0.81 (0.57 - 0.92)	0.89 (0.75 - 0.96)
Peak RFD (N·s ⁻¹)	4880.70 \pm 2300.49	4127.46 \pm 1702.78	4553.50 \pm 1743.76	-13.0	12.0	30.7 (22.4 - 48.5)	27.8 (20.3 - 43.7)	0.70 (0.38 - 0.87)	0.68 (0.33 - 0.86)
Time to PF (ms)	4408.58 \pm 1611.46	3894.79 \pm 1699.34	4178.84 \pm 1571.84	-13.5	10.2	36.2 (26.3 - 58.0)	27.0 (19.8 - 42.3)	0.58 (0.18 - 0.81)	0.74 (0.44 - 0.89)
Time to pRFD (ms)	468.11 \pm 1190.10	226.74 \pm 166.80	492.16 \pm 1454.20	-15.8	-5.4	116.1 (79.1 - 212.6)	136.6 (91.7 - 257.3)	0.06 (-0.39 - 0.49)	0.04 (-0.41 - 0.48)

Notes: PHV = Peak height velocity; SD = Standard deviation; CV = Coefficient of Variation; ICC = Intraclass Correlation Coefficient; CI = Confidence Interval; PF = Peak Force; RFD = Rate of Force Development; pRFD = Peak Rate of Force Development; * = Significantly greater than session 1

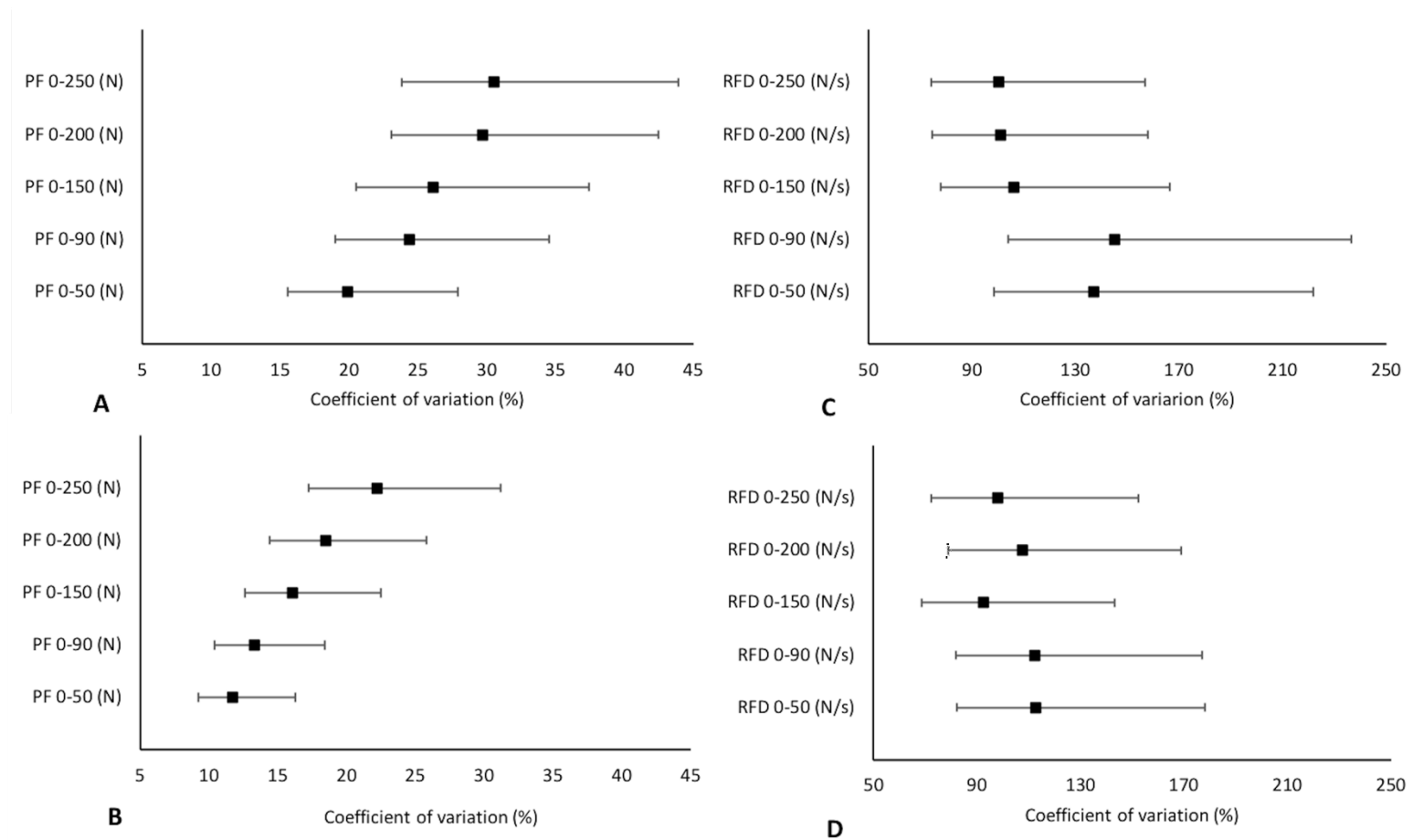


Figure 3: Forest plots displaying coefficients of variation for between-session reliability: (A) pre-PHV athletes force at different time-sampling intervals (B) post-PHV athletes force at different time-sampling intervals (C) pre-PHV athletes force at different RFD epochs, and (D) post-PHV athletes force at different RFD epochs. Error bars indicate 95% confidence limits of the mean difference between trials.

Table 4. Noise: signal ratios from between-session IMTP kinetic variables in pre- and post-PHV female athletes

Noise/Signal Ratio				Noise/Signal Ratio			
Variable	Session 2-1	Session 3-2	Overall	Variable	Session 2-1	Session 3-2	Overall
Pre-PHV female athletes							
Absolute PF (N)	1.11	1.24	1.19	Time to pRFD (ms)	5.32	5.31	5.32
Relative PF (N/kg)	2.20	2.53	2.53	Time to PF (ms)	4.03	5.79	4.13
Force at 50 ms (N)	1.93	2.06	1.98	0-50 RFD (N·s ⁻¹)	11.59	2.43	4.33
Force at 90 ms (N)	2.94	1.71	2.18	0-90 RFD (N·s ⁻¹)	7.98	2.56	4.26
Force at 150 ms (N)	2.67	1.70	2.03	0-150 RFD (N·s ⁻¹)	3.87	2.67	2.98
Force at 200 ms (N)	2.74	1.99	2.12	0-200 RFD (N·s ⁻¹)	3.75	2.31	2.56
Force at 250 ms (N)	2.51	1.69	1.93	0-250 RFD (N·s ⁻¹)	3.48	2.00	2.38
				Peak RFD (N·s ⁻¹)	3.51	3.56	3.26
Post-PHV female athletes							
Absolute PF (N)	1.47	1.20	1.33	Time to pRFD (ms)	3.52	2.88	3.24
Relative PF (N/kg)	2.22	1.68	2.02	Time to PF (ms)	3.65	31.62	5.13
Force at 50 ms (N)	2.43	2.51	2.42	0-50 RFD (N·s ⁻¹)	4.18	3.26	3.55
Force at 90 ms (N)	2.40	2.63	2.50	0-90 RFD (N·s ⁻¹)	2.88	3.04	2.92
Force at 150 ms (N)	2.05	2.73	2.44	0-150 RFD (N·s ⁻¹)	2.01	2.99	2.40
Force at 200 ms (N)	2.11	2.59	2.42	0-200 RFD (N·s ⁻¹)	1.99	2.80	2.47
Force at 250 ms (N)	2.63	2.49	2.65	0-250 RFD (N·s ⁻¹)	2.62	2.64	2.76
				Peak RFD (N·s ⁻¹)	2.85	3.13	3.10

Notes: PHV = Peak height velocity; SD = Standard deviation; PF = Peak Force; RFD = Rate of Force Development; pRFD = Peak Rate of Force Development;

3.4 DISCUSSION

The aim of this study was to determine the within- and between-session reliability of force-time variables during the IMTP in pre- and post-PHV female athletes. Absolute and relative peak force were found to be reliable for both within- and between-sessions for both maturity groups. However, systematic bias was evident in the pre-PHV cohort between the first two testing sessions, which highlights the need for additional familiarization with younger and less mature female athletes. All other kinetic variables showed moderate to low reliability. Cumulatively, these findings confirm the reproducibility of the IMTP protocol for assessing maximal force production, and offer practitioners a viable option to assess maximal strength capabilities in female athletes pre- and post-PHV.

Non-significant changes in means, high ICCs and low CVs indicated strong within-session reliability for measures of absolute and relative peak force for both pre- and post-PHV athletes. While the means of all other variables did not change significantly within session, they did show much higher typical errors, especially RFD and pRFD and those variables that were time-dependent (TPF and TPRFD). This finding is commensurate with previous literature that has shown within-session RFD and RFD sampled at different time intervals to be less reliable than peak forces measured in the IMTP in 16-year old males (58). These findings would suggest that providing young athletes are afforded appropriate opportunity to familiarize themselves with the IMTP protocol, practitioners could use peak force data from a single trial. However, owing to the ease of administration and minimal time requirements for the IMTP, practitioners may wish to take a mean across multiple trials to reduce the level of noise, whereby random variation can be reduced by a factor of $1/\sqrt{\text{number of trials}}$ (250).

Reliable testing protocols are required in order to confidently detect meaningful changes in performance. The current study reported strong between-session reliability for absolute and relative peak force as evidenced by high reproducibility and low variation for both absolute and relative measures of peak force in pre- (ICC = 0.71-0.95; CV = 9.2-9.7%) and post-PHV (ICC = 0.94-0.85; CV = 6.2-6.3%) female athletes. Similar to the within-session reliability, pre-PHV youth showed a higher degree of typical error in both absolute and relative measures of peak force across the three testing sessions in comparison to post-PHV athletes. Other researchers have reported slightly greater between-session reliability for measures of absolute peak force during the IMTP protocol in male adolescent soccer players (CV = 4.6% (58)) and in recreationally active males (CV = 3.1% (117)). Thus, it appears that between-session reliability measures of peak force improve with age, maturation and training history, especially those with greater experience of maximal lifts.

Considering maturation in the design of reliability studies is an important and often over-looked phenomenon. In the current study, pre-PHV showed greater variability in absolute and relative peak force than post-PHV athletes. Also, significant differences in mean peak force between the first two test sessions were evident, suggesting the presence of systematic bias within the less mature cohort. These data indicate that immature female athletes produce slightly less consistent peak force values during the IMTP, and require a greater amount of familiarization prior to testing. The greater degree of movement variability in less mature children has previously been shown in youth during jumping protocols (82), and is likely due to lower levels of coordination and immature prefrontal motor cortex activation resulting in more variable task execution.

Pre-PHV females had higher variability ($CV = 19.3\text{-}36.3\%$) in force values at different sampling intervals than post-PHV athletes ($CV = 10.2\text{-}23.2\%$), which supports the maturity-related trend shown for absolute and relative peak force. Both groups were less consistent and more variable at producing force across different sampling intervals compared to measures of absolute peak force which is consistent with previous IMTP research in adolescents (58), and adults (52, 98, 117). This suggests the ability to reproduce time-specific force values is naturally more variable, and could be due to vagaries in neuromuscular factors such as motor unit recruitment and discharge rates (166). Therefore, force at different sampling intervals should be used with caution, particularly in pre-PHV athletes.

Examining noise:signal ratios can increase practitioners' confidence that true changes in performance will be detected (113). Although none of the time-specific force values achieved a noise value lower than the signal, all variables obtained overall noise:signal ratios of less than 2.2 and 2.7, in pre- and post-PHV athletes, respectively. Absolute peak force was found to have the lowest noise:signal ratios for both pre- (1.19) and post-PHV (1.33) groups, and became slightly higher for relative peak force measures (pre-PHV = 2.02 and post-PHV = 2.53). Consequently, a greater magnitude of change is required to exceed the typical error in these measures, and to accurately monitor changes in different force sampling intervals (113). Given the potential for large improvements in strength that youth can experience from growth, maturation and training (152), it is likely that changes observed in youth populations would surpass the smallest worthwhile change and exceed the random variation in these measures. For example, in the current study, a change in absolute peak force in excess of ~ 65 N in post-PHV female athletes would infer that a meaningful change has occurred as a result of training and/or maturation; changes of these magnitudes have been demonstrated previously in youth-based training studies (217). When choosing to use noise:signal ratios for force at different

time sampling intervals, practitioners should consider the typical error of the variable to ensure the measure is sensitive enough to monitor changes in maturation or training. While this study is the first to report noise:signal ratios for IMTP variables in young females, the values are comparable to existing youth data on spatiotemporal measures obtained during maximal speed in boys (overall noise: signal ratios between 1.92-4.44) (196).

Finally, the between-session results from both group's time-dependent variables (RFD at various sampling intervals, pRFD, TPF and TPRFD) were deemed unreliable due to a large range in ICC (0.10-0.76) and high CV% (CV% = 31.6-143.1%). Similar findings have been reported in active children and adolescents for countermovement jumps (82). It has been documented that RFD measures are inherently less reliable, particularly in multi-joint tasks due to more degrees of freedom and movement options available in the musculoskeletal system (166). While previous studies have reported high levels of reliability for time-dependent force measures in trained adult athletes (97, 98), the low reliability data from this study indicates that these variables are more unstable in youth.

3.5 PRACTICAL APPLICATIONS

There are a number of test protocols available to assess muscular strength capacity in youth; however, such protocols require a suitably robust level of technical competency for youth to safely perform them. As peak force measures from the IMTP have been validated against 1RM squat performance (130), the IMTP protocol offers practitioners a viable alternative for assessing maximal strength capacities in youth with lower levels of experience. Interestingly, while both absolute and relative peak force were found to be reliable, noise:signal values suggest these measures could be useful to practitioners in different ways. Absolute peak force was able to detect changes in maturation, due to the large differences observed in the measure

from pre- to post-PHV. However, relative peak force values remained around 27 N/kg, suggesting this measure is less sensitive to changes in maturation but could be used to assess young female athletes' innate ability (e.g. talent identification or responses to training). Owing to the systematic bias in peak force shown by the pre-PHV group between the first two test sessions, additional familiarization is recommended for younger children to optimize between-session reliability. The IMTP protocol is deemed a highly reliable method of quantifying peak force capability in children and adolescents, and offers practitioners a safe and time efficient means of assessing maximal isometric strength capacities in young females.

Chapter 4: Prelude

Chapter 3 provided empirical evidence that indicated that the IMTP was a reliable method of assessing absolute and relative peak force in child and adolescent females with appropriate amounts of familiarisation. With the addition of this novel data, and considering the non-linear development of paediatric populations, it was deemed important to understand how these key force-time variables differ according to maturity status and competitive level in young female gymnasts. Practitioners could use these data as a reference point for expected differences throughout normal growth and maturation, for the purposes of benchmarking children and adolescents against maturity-related or competitive level normative data, and used to indirectly compare against training-induced adaptations to determine the effectiveness of training programmes. In addition, whilst some research has identified determinants of gymnastics vaulting performance using dynamic protocols, *chapter 4* sought to examine the relationship between isometric force-time variables and vertical take-off velocity. The information acquired could help practitioners target and develop physical qualities that are important to young female gymnasts' vaulting performance.

Chapter 4:

The Influence of Biological Maturity and Competitive Level on Isometric Force-Time Curve Variables and Vaulting Performance in Young Female Gymnasts

Moeskops, S. Oliver, JL. Read, PJ. Cronin, JB. Myer, JD. Haff, GH. and Lloyd, RS. The influence of biological maturity and competitive level on isometric force-time curve variables and vaulting performance in young female gymnasts. *J Strength Con Res.* 2020;34(8) 2136–2145.

4.1 INTRODUCTION

Young artistic gymnasts who develop high levels of muscular strength can enhance performance and reduce the risk of gymnastics-related injury (22, 88, 178, 206, 273, 276). Many complex gymnastic skills are underpinned by the ability to jump, rebound, accelerate, and decelerate (206). Young gymnasts therefore require the capacity to produce and rapidly absorb high forces to proficiently and safely perform dynamic actions (193, 206), especially in light of higher anterior cruciate ligament (ACL) injury rates of competitive female gymnasts compared with other sports (22, 32, 111).

Elite or competitive female gymnastics is recognised as an early specialization sport. Evidence suggests that coaches intuitively select later-maturing individuals who are typically shorter in stature for their chronological age (169). Further, muscular strength assessments are often included in talent identification testing batteries for elite-orientated, competitive, pre-pubescent gymnasts (122, 308). While gymnastics training itself provides a stimulus that enhances

muscular strength (31, 178), natural improvements in strength also occur during childhood and adolescence due to growth and maturation (152, 170) which can be attributed to increases in muscle size, changes in muscle architecture, and improvements in motor unit recruitment (152, 257). Thus, accounting for biological maturity when testing and monitoring young athletes seems warranted.

Previous researchers studying young female gymnasts have reported increases in lower limb muscular strength and power that occur with advancing chronological age and/or competitive level (24, 61, 286). 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 (170), analyzing how physical qualities develop from a maturity perspective seems warranted (152, 157, 162). 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) (61, 286, 308) or report numbers of repetitions completed for an exercise (e.g., leg lifts to the bar) (286), 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 (213). 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 (88, 206). 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 (88). 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 (283). 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 (24, 290), 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 (42, 98, 99, 130). 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 (42, 97). 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 (58, 204, 283). Furthermore, the IMTP test has been significantly correlated with a range of dynamic athletic tasks including; sprint speed (298), vertical jump performance and 1RM squats (130), 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 (24), 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.

4.2 METHODS

4.2.1 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.

4.2.2 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) (136): <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 institutional ethics committee (ethics code: 17/1/02R). 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.

4.2.3 Procedures

Before testing commenced, all participants performed a standardized 10-minute dynamic warm-up led by the principal 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 (136). Descriptive data for each maturity group are presented in *Table 2*.

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

Table 2. Descriptive statistics for all anthropometric variables (mean \pm SD)

Group	<i>n</i>	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 \pm 1.1	124.5 \pm 8.8	66.9 \pm 3.8	57.7 \pm 5.5	25.2 \pm 4.5	70.1 \pm 4.0	11.3 \pm 5.2
Late pre-pubertal	47	10.7 \pm 0.8 ^a	139.8 \pm 6.8 ^a	73.9 \pm 4.1 ^a	65.9 \pm 3.9 ^a	33.8 \pm 6.4 ^a	79.8 \pm 2.8 ^a	11.1 \pm 5.3
Pubertal	19	12.8 \pm 0.8 ^b	150.4 \pm 5.6 ^b	78.2 \pm 2.7 ^b	72.3 \pm 2.7 ^b	45.1 \pm 9.5 ^b	89.2 \pm 3.2 ^b	11.0 \pm 6.1
Recreational	21	9.6 \pm 2.6	134.8 \pm 14.4	71.1 \pm 6.1	63.7 \pm 8.6	33.5 \pm 11.6	76.2 \pm 9.3	4.4 \pm 1.8
Regional	48	9.8 \pm 1.8	135.4 \pm 11.3	72.2 \pm 5.5	63.1 \pm 6.4	32.3 \pm 9.7	77.1 \pm 6.9	9.8 \pm 3.1 [^]
National	41	10.0 \pm 2.2	135.5 \pm 13.0	71.5 \pm 6.1	64.0 \pm 7.3	31.2 \pm 8.3	78.0 \pm 8.3	14.4 \pm 4.1 [^]
Elite	10	8.6 \pm 1.5	127.3 \pm 9.9	68.1 \pm 3.9	59.2 \pm 6.2	27.2 \pm 6.0	72.8 \pm 5.1	18.9 \pm 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; [^] = 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 (204). 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 $135^{\circ} \pm 5^{\circ}$, and hip angle of $140^{\circ} \pm 5^{\circ}$ (204). Lifting straps were used to secure the gymnast to the bar to reduce likelihood of grip strength being a limiting factor for performance (98). 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 (204). All gymnasts received the standardized instruction of “*pull as hard and as fast as possible until I say stop*” (98) 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 (99). All isometric force-time curves were analyzed by the same researcher using custom-built Labview (LVRTE2014SP1, National Instruments, Austin, TX, USA) analysis software (98). Initiation of the pull was determined using the visual onset method, which has been previously recommended (166). The following variables were processed for which reliability data has previously been reported (204):

- *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, 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, 0–150, 0–200, and 0–250 ms (98)
- *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, 0–150, 0–200, and 0–250 ms
- *Peak rate of force development ($pRFD_{abs}$)*: highest RFD during a 20-ms time sampling window (98)
- *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 (204). Acceptable reliability was reported for PF_{abs} and PF_{rel} ($CV \leq 7.5\%$), while analyses of force at specific time epochs revealed CVs between ($CV = 22\text{--}33\%$). Greater variability was reported for RFD-related variables ($CV \geq 32\%$); therefore, results for these variables should be interpreted with an understanding of the heightened noise (204).

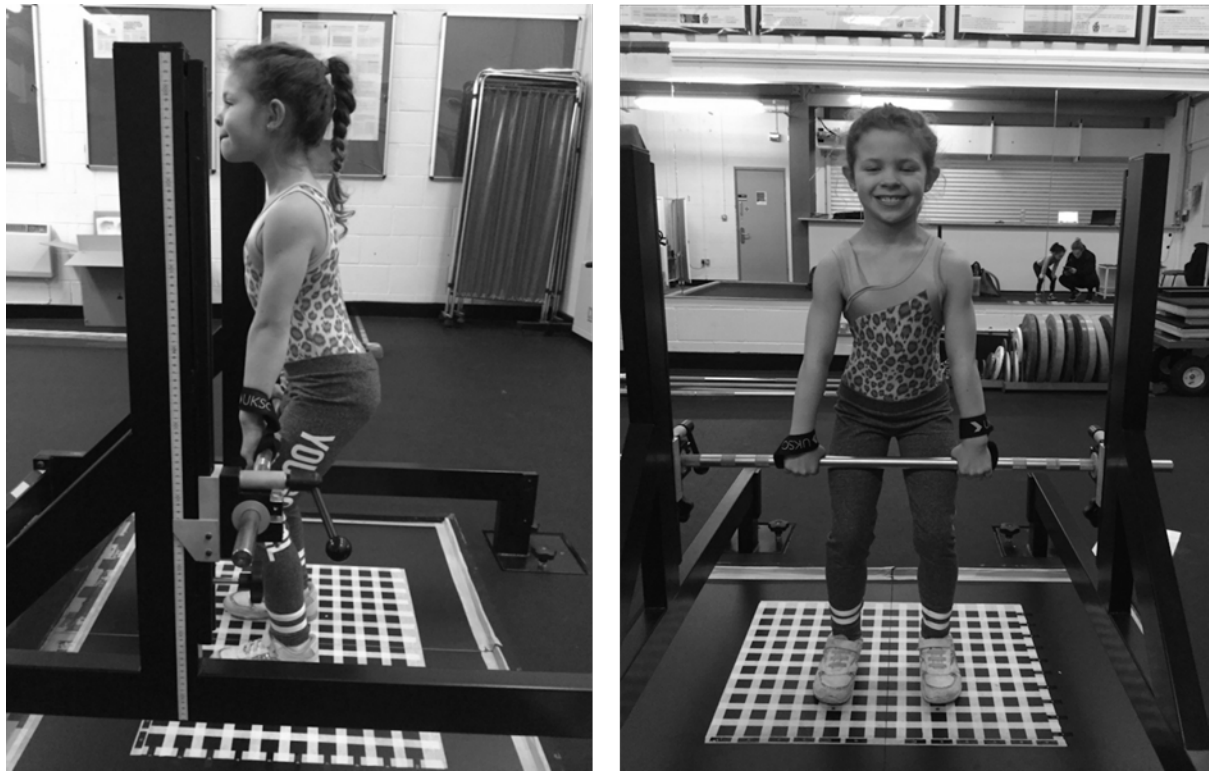


Figure 1. Lateral and anterior view of the isometric midhigh pull setup position

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 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 (317), the most appropriate cut-off frequency was 10 Hz. Vertical take-off velocity from the springboard was calculated using the central difference method (317). The best vault was determined as the highest straight jump and was used for further analyses.

4.2.4 Statistical Analyses

Descriptive statistics (mean values \pm 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. Multi-collinearity was tested using variance inflation factor and tolerance diagnostics (0.2 tolerance cut-off). 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 (115). 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 (232): <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 multicollinearity 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.

4.3 RESULTS

4.3.1 Grouped by maturity status

IMTP variables for early and late pre-pubertal and pubertal groups are displayed in *Figure 2 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 ($d = 0.05\text{--}0.15$).

Absolute force measured at different time epochs showed significant, moderate to large increases between early pre-pubertal and pubertal groups for all time intervals ($p < 0.05$; $d = 0.7\text{--}1.4$). 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 ($d = 0.4\text{--}0.5$). 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 ($d = 0.36\text{--}0.7$). No significant 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 ($d = 0.02\text{--}0.4$). 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 ($p < 0.05$; $d = 0.47\text{--}0.57$) and significantly greater than the pubertal group at 0–150 and 0–200 N/s epochs ($p < 0.05$; $d = 0.25\text{--}0.58$). 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-pubertal group ($d = 0.01$). No significant differences were evident between late pre-pubertal and pubertal groups for any IMTP or vaulting variables.

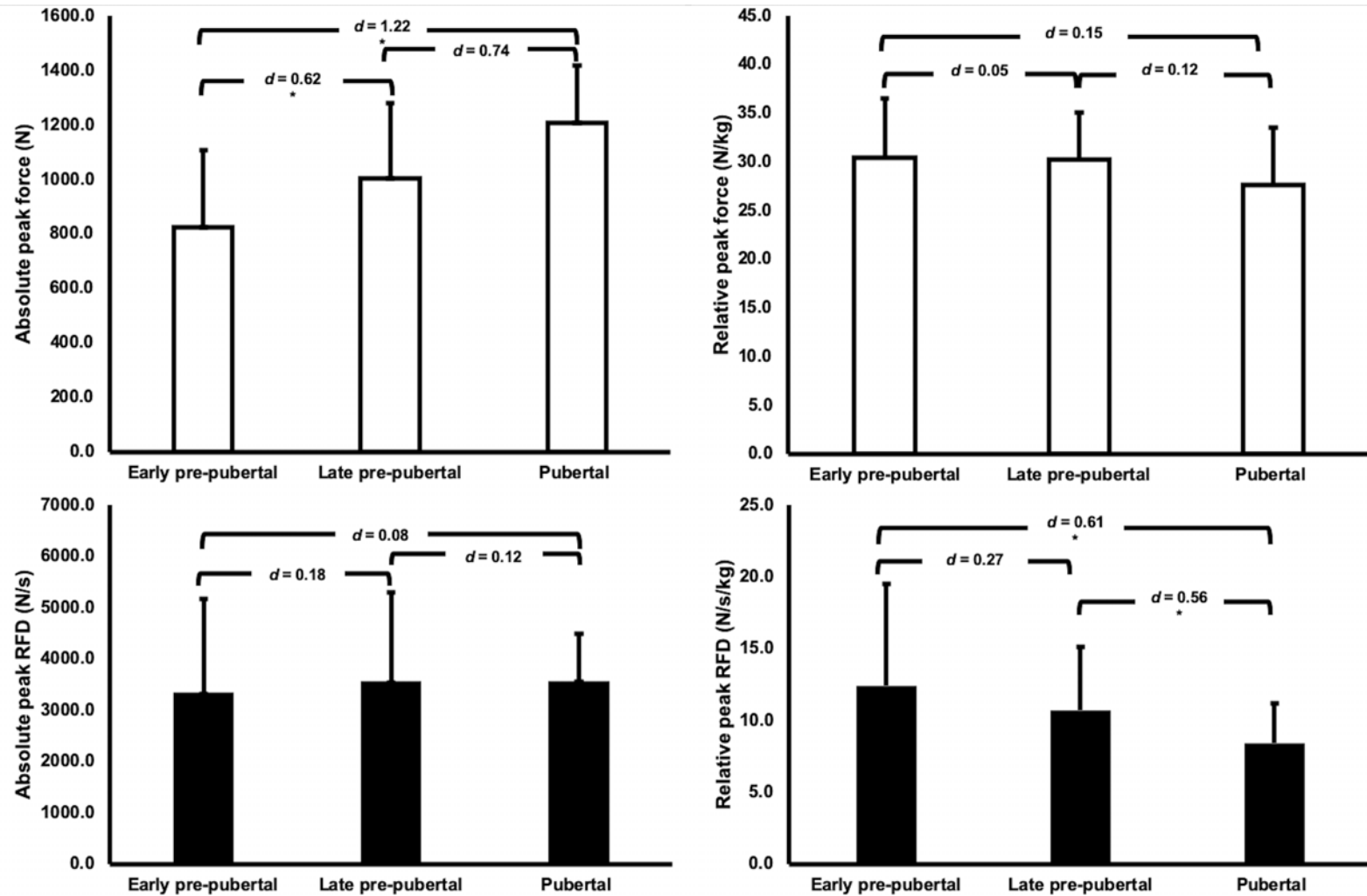


Figure 2. Maturity group analysis for absolute peak force, relative peak force, absolute peak RFD and relative peak RFD

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

Group	PF _{abs} (N)	Absolute force at 50 ms (N)	Absolute force at 90 ms (N)	Absolute force at 150 ms (N)	Absolute force at 200 ms (N)	Absolute force at 250 ms (N)
Early pre-pubertal	825.7 \pm 282.2	241.4 \pm 78.1	275.9 \pm 97.3	338.0 \pm 143.0	405.8 \pm 189.6	469.5 \pm 227.2
Late pre-pubertal	1005.1 \pm 273.0 ^a	311.7 \pm 94.1 ^a	338.0 \pm 97.9 ^a	409.2 \pm 131.7	479.6 \pm 162.4	551.0 \pm 183.7
Pubertal	1206.9 \pm 210.2 ^a	380.5 \pm 90.1 ^a	404.8 \pm 98.2 ^a	465.0 \pm 109.0 ^a	535.6 \pm 130.2 ^a	632.5 \pm 166.9 ^a
	PF _{rel} (N/kg)	Relative force at 50 ms (N/kg)	Relative force at 90 ms (N/kg)	Relative force at 150 ms (N/kg)	Relative force at 200 ms (N/kg)	Relative force at 250 ms (N/kg)
Early pre-pubertal	30.47 \pm 6.07	9.01 \pm 2.10	10.34 \pm 3.02	12.60 \pm 4.50	15.07 \pm 6.10	17.42 \pm 7.51
Late pre-pubertal	30.20 \pm 4.91	9.35 \pm 2.03	10.19 \pm 2.26	12.39 \pm 3.44	14.60 \pm 4.71	16.86 \pm 5.59
Pubertal	29.59 \pm 5.96	9.26 \pm 1.91	9.86 \pm 2.17	11.36 \pm 2.72	13.16 \pm 3.55	15.61 \pm 4.73
	pRFD _{abs} (N/s)	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	3220.8 \pm 1843.7	433.2 \pm 479.9	623.8 \pm 683.5	788.4 \pm 727.0	930.4 \pm 772.9	998.9 \pm 769.6
Late pre-pubertal	3537.0 \pm 1760.9	242.0 \pm 200.8	427.0 \pm 389.7	730.8 \pm 633.7	900.5 \pm 686.1	1005.7 \pm 657.6
Pubertal	3351.3 \pm 944.7	268.8 \pm 204.8	419.5 \pm 379.7	652.8 \pm 482.5	842.5 \pm 530.7	1061.6 \pm 604.0
	pRFD _{rel} (N/s)	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	12.4 \pm 7.1 ^b	1.7 \pm 2.0 ^c	2.4 \pm 2.8 ^c	3.0 \pm 2.7 ^b	3.5 \pm 2.9 ^b	3.8 \pm 2.9
Late pre-pubertal	10.7 \pm 4.4 ^b	0.8 \pm 0.7	1.4 \pm 1.3	2.3 \pm 2.0	2.9 \pm 2.2	3.2 \pm 2.1
Pubertal	8.4 \pm 2.8	0.7 \pm 0.5	1.1 \pm 1.0	1.7 \pm 1.3	2.2 \pm 1.4	2.7 \pm 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 ($p < 0.05$).

PF_{abs} = absolute peak force; PF_{rel} = relative peak force; RFD_{abs} = absolute rate of force development; pRFD_{abs} = absolute peak rate of force development; RFD_{rel} = relative rate of force development; pRFD_{rel} = relative peak rate of force development

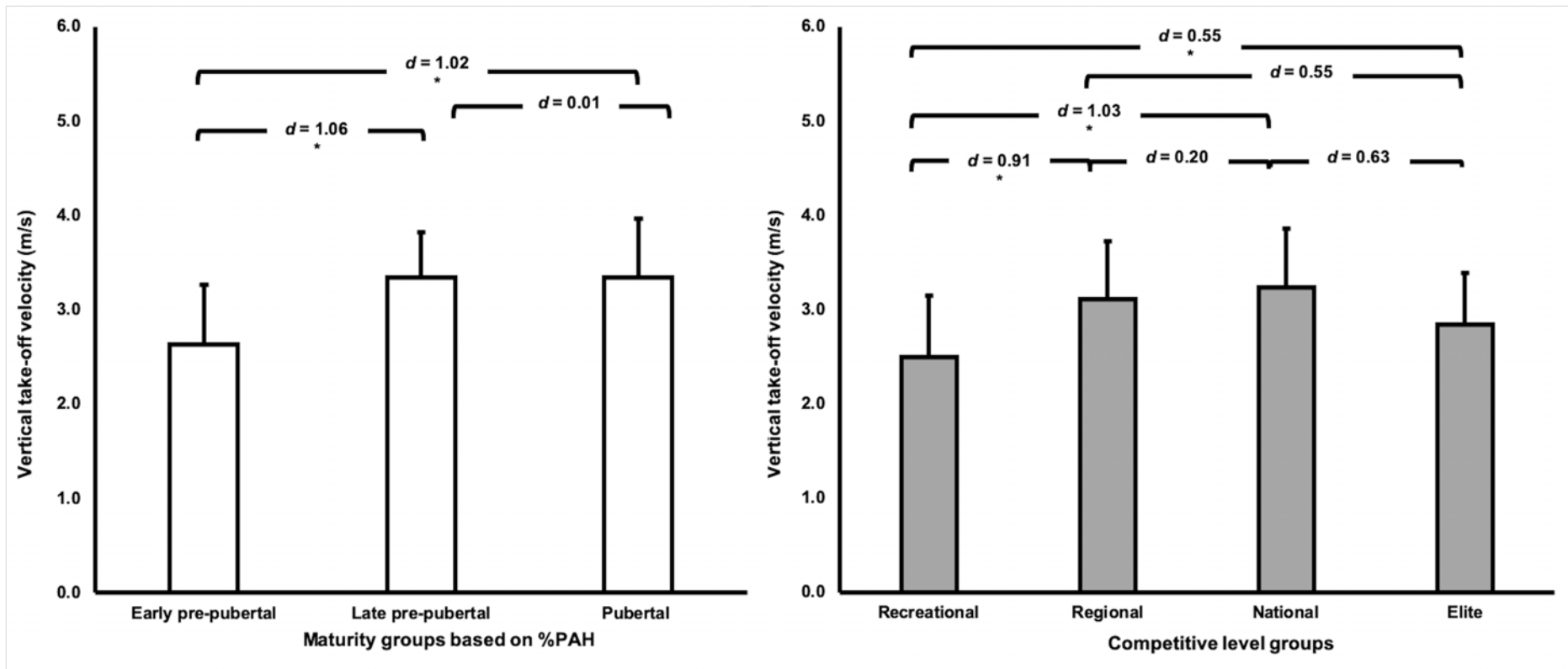


Figure 3a and 3b. Maturity and competitive level group analysis for vertical take-off velocity from the spring-board during vaulting performance

4.3.2 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).

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*.

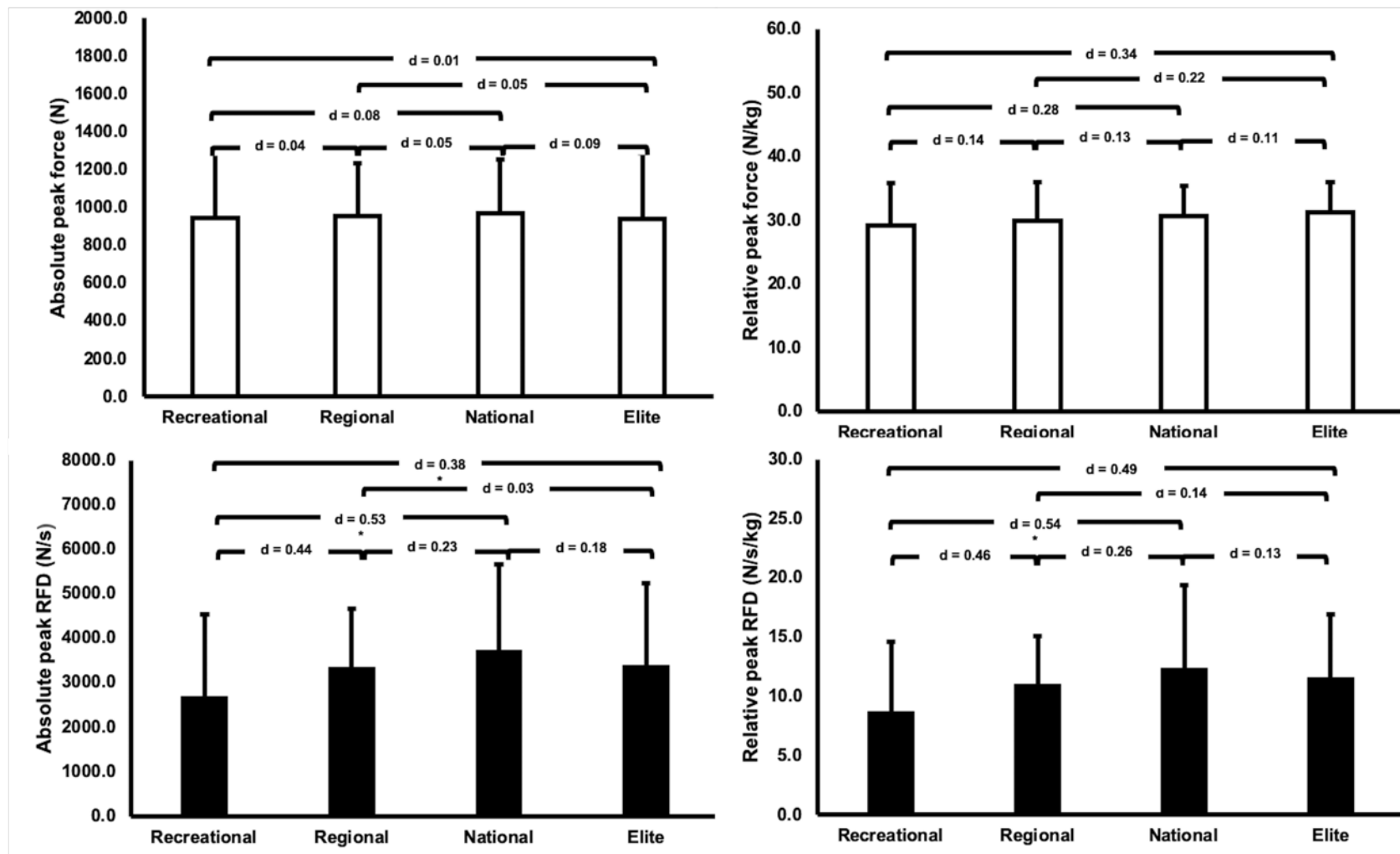


Figure 4. Competitive level group analysis for absolute peak force, relative peak force, absolute peak RFD and relative peak RFD

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

Group	PF _{abs} (N)	Absolute force at 50 ms (N)	Absolute force at 90 ms (N)	Absolute force at 150 ms (N)	Absolute force at 200 ms (N)	Absolute force at 250 ms (N)
Recreational	943.9 \pm 367.0	291.3 \pm 105.6	317.1 \pm 119.9	354.8 \pm 138.4	407.2 \pm 165.7	646.2 \pm 545.5
Regional	955.0 \pm 278.1	292.8 \pm 110.7	321.2 \pm 115.3	383.0 \pm 354.8	448.0 \pm 174.6	521.6 \pm 196.7
National	967.9 \pm 284.8	295.1 \pm 87.9	325.0 \pm 94.5	400.2 \pm 135.3	477.0 \pm 172.5	543.8 \pm 207.1
Elite	941.5 \pm 346.9	246.4 \pm 85.8	308.0 \pm 105.4	407.3 \pm 174.0	502.0 \pm 221.8	599.2 \pm 277.0
	PF _{rel} (N/kg)	Relative force at 50 ms (N/kg)	Relative force at 90 ms (N/kg)	Relative force at 150 ms (N/kg)	Relative force at 200 ms (N/kg)	Relative force at 250 ms (N/kg)
Recreational	29.2 \pm 6.7	9.1 \pm 1.9	10.0 \pm 2.9	11.2 \pm 3.5	12.9 \pm 4.8	15.1 \pm 6.4
Regional	30.0 \pm 6.0	9.1 \pm 2.1	10.0 \pm 2.5	12.0 \pm 3.7	14.2 \pm 5.1	16.5 \pm 6.0
National	30.7 \pm 4.7	9.4 \pm 2.1	10.5 \pm 2.6	12.9 \pm 3.9	15.3 \pm 5.0	17.4 \pm 6.1
Elite	31.3 \pm 4.73	9.0 \pm 1.9	10.5 \pm 2.9	13.9 \pm 5.1	15.1 \pm 6.1	20.3 \pm 8.8
	pRFD _{abs} (N/s)	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	2692.0 \pm 1830.8	266.6 \pm 306.8	434.0 \pm 632.8	512.3 \pm 498.9	646.2 \pm 545.5	782.3 \pm 628.0
Regional	3350.0 \pm 1302.0	303.4 \pm 344.9	483.1 \pm 526.6	702.5 \pm 660.8	851.8 \pm 722.4	975.5 \pm 678.4
National	3722.9 \pm 1930.1 ^a	399.4 \pm 462.2	554.2 \pm 542.6	834.3 \pm 662.3	1009.4 \pm 690.5	1074.8 \pm 690.0
Elite	3388.2 \pm 1852.1 ^a	333.4 \pm 216.4	669.8 \pm 495.5	1064.1 \pm 769.2 ^a	1271.2 \pm 790.0 ^a	1405.9 \pm 850.0 ^b
	pRFD _{rel} (N/s)	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	8.7 \pm 5.9	0.9 \pm 1.2	1.3 \pm 0.7	1.7 \pm 2.0	2.2 \pm 2.2	2.7 \pm 2.4
Regional	11.0 \pm 4.1	1.0 \pm 1.2	1.6 \pm 1.0	2.4 \pm 2.3	2.8 \pm 2.5	3.2 \pm 2.4
National	12.4 \pm 7.0 ^a	1.5 \pm 2.0	1.6 \pm 0.9	2.8 \pm 2.3	3.4 \pm 2.3	3.6 \pm 2.3
Elite	11.6 \pm 5.3	1.2 \pm 0.8	2.0 \pm 0.7	3.7 \pm 2.6	4.4 \pm 2.7 ^a	4.9 \pm 3.0 ^a

^a = significantly greater than the recreational group ($p < 0.05$); ^b = significantly greater than recreational and regional groups ($p < 0.05$).

PF_{abs} = absolute peak force; PF_{rel} = relative peak force; RFD_{abs} = absolute rate of force development; pRFD_{abs} = absolute peak rate of force development; RFD_{rel} = relative rate of force development; pRFD_{rel} = relative peak rate of force development

4.3.3 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 the total variance.

4.4 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 (170). Specifically, growth- and maturity-related increases in muscle size and therefore muscle cross-sectional area enhance force-producing capabilities in youth (170, 257).

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 female athletes (204). 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 across pre-, circa-, and post-peak height velocity groups (62). As artistic gymnastics demands high relative power-to-mass ratios for acrobatic skills (88), 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 (231), fascicle length (3), muscle activation rate (78), and ability to recruit high-threshold type II motor units (78). 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 ($CV = 45\text{--}145\%$) in young females (204); 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 (88). 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 (204). 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 $pRFD_{abs}$ (204).

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) (299), and 5-m acceleration and pro agility time (311). 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 (24) 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 (24). Together, these variables explained 80% of common variance, and squat jump force had a strong significant relationship with vaulting

ability ($r = 0.72$) (24). However, maturity 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 paediatric 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).

4.5 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 aim 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 programme. Crucially, programmes 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. Using 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; therefore, should a gymnast report as a low percentile, training should then be directed to improving relative strength.

Chapter 5: Prelude

Chapter 4 identified the differences in IMTP force-time variables between gymnasts grouped by biological maturity status and competitive level. This study also determined that IMTP force-time variables failed to explain high proportions of variance in vaulting vertical take-off velocity. Jumping and rebounding are recognised as important prerequisites for high impact loading gymnastics skills and are fundamental motor skills that all young athletes should be able to perform competently. Whilst some mechanistic age-related data exist comparing the jumping abilities of female gymnasts, examining how dynamic force-time variables from jumping protocols differ according to maturity status was yet to be explored. This information would enable practitioners to use this data as a reference point for expected differences throughout normal growth and maturation and could also be used for benchmarking purposes with gymnasts. Additionally, minimal research at present has explored the determinants of gymnastics vaulting take-off velocity in young females. *Chapter 5* therefore aimed to determine the relationship between dynamic force-time variables and vertical take-off velocity.

Chapter 5:

The Influence of Biological Maturity on Dynamic Force-Time Variables and Vaulting Performance in Young Female Gymnasts

Moeskops, S., Oliver, JL. Read, PJ. Cronin, JB. Myer, JD. Haff, GH. Moore, IS. and Lloyd, RS. The influence of biological maturity on dynamic force-time time variables and vaulting performance in young female gymnasts. *J Sci Sport Ex.* 2020;1-11

5.1 INTRODUCTION

Jumping and rebounding are important prerequisites that underpin the high impact loading gymnastics skills (e.g. acrobatic series, tumbling etc.) (290). 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) (206). Consequently, rebounding and jumping performance of artistic gymnasts are commonly assessed to identify key determinants of the sport (51, 179, 181, 290), determine physical profiles (247, 308) and evaluate the efficacy of training interventions (41, 100, 178, 209).

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 (159) as well as the athlete's ability to perform efficient SSC mechanics (304). 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 (16, 304).

Researchers have emphasized the importance of measuring different expressions of SSC function in gymnasts as gymnastics skills involve both slow- and fast-SSC (209, 290). Protocols that examine fast-SSC function include drop jumps, repeated-hopping tasks and sprinting (161, 242), whereas slow-SSC tests typically involve countermovement jumps (CMJ) and standing long jumps (159). Further, concentric only jumps which do not involve SSC function are frequently used as part of jumping test batteries (i.e. squat jump (SJ)) (24, 162, 290). Comparisons of jump height or flight time between CMJ and SJ tests enable researchers to evaluate how effective gymnasts are at utilizing the contribution of the elastic energy during the braking phase (24, 179, 290). 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 (248). 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 (24). 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 the large inter-individual variation in maturity status within a given age group (69). Research shows maturation influences the development of physical qualities and motor skills in youth, particularly following the pubertal growth spurt (170). For example, significant differences in absolute isometric peak force (204), vertical jump height (162) and sprint speed (197) have been reported between pre- and post-pubertal young athletes. As the timing and tempo of biological maturation differs between individuals of the same

chronological age (170), analyzing testing data in young athletes according to maturity status has been recommended (157).

Existing gymnastics literature has often examined jump performance using field-based equipment such as contact mats (179, 183, 248) or methods which solely report performance outcomes such as jump height (286, 308). 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 (213). 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 (24, 205) and age-related jumping and rebounding data in young female gymnasts exists (24, 248), 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 vaulting take-off velocity 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.

5.2 METHODS

5.2.1 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) (136): <75%PAH, early pre-pubertal (early_{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 (ethics code: 17/1/02R).

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

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

5.2.2 Study Design

This study used a cross-sectional design to examine jumping force-time variables 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 (136).

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 (290). 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 (317), 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 (242). 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*.

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 (148).
Peak velocity	V_{peak}	$\text{m}\cdot\text{s}^{-1}$	The fastest vertical speed of the centre of mass during the propulsive phase.
Relative vertical net impulse	$\text{Impulse}_{\text{rel}}$	$\text{m}\cdot\text{s}^{-1}$	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 (138).
Absolute peak force	PF_{abs}	N	The largest force generated before take-off.
Relative peak force	PF_{rel}	$\text{N}\cdot\text{kg}^{-1}$	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}	$\text{W}\cdot\text{kg}^{-1}$	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}	$\text{N}\cdot\text{s}^{-1}$	The change in absolute force divided by the change in time during the propulsive phase.
Relative rate of force development	RFD_{rel}	$\text{N}\cdot\text{kg}^{-1}$	The absolute rate of force development divided by the athlete's body mass.
Absolute peak rate of force development	pRFD_{abs}	$\text{N}\cdot\text{s}^{-1}$	The highest rate of force development during a 20-ms time sampling window.
Relative peak rate of force development	pRFD_{rel}	$\text{N}\cdot\text{s}^{-1}\cdot\text{kg}^{-1}$	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 (39).
Absolute peak force	PF _{abs}	N	The largest net force generated before take-off in the concentric phase.
Relative peak force	PF _{rel}	N·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 braking phase (from the end of the unweighting phase to the end of the breaking phase).
Braking phase duration	Time _{Brake}	s	Time of braking 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·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 braking 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 (148).
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	N/A	$\text{m}\cdot\text{s}^{-1}$	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	$\text{Power}_{\text{brake}}$	W	The average power between initial ground contact and the timing of the maximal displacement of the centre of mass.
Propulsive average power	$\text{Power}_{\text{Prop}}$	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	$\text{Work}_{\text{Brake}}$	J	The average work done between initial ground contact and the timing of the maximal displacement of the centre of mass.
Propulsive average work	$\text{Work}_{\text{Prop}}$	J	The average work between the lowest point of the centre of mass and the point of take-off.
Relative vertical stiffness	$\text{Stiffness}_{\text{rel}}$	$\text{BW}\cdot\text{m}^{-1}$	The ratio of relative peak vertical ground reaction force (BW) to maximal vertical displacement of the centre of mass (m) (189). 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.

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) (163, 290). 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 five standard deviations (*sd*) was then used to identify the initiation of the jump (59). Variables calculated included: jump height (JH), peak velocity (V_{peak}), relative vertical impulse ($\text{Impulse}_{\text{rel}}$), 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 (290). Trials were discounted and repeated if the gymnasts' 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 (39). 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

(39). 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 (39, 237). 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 (39). 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 (39). Further, the propulsive phase occurs immediately after the braking phase and ends at the point of take-off, with the athlete's velocity typically peaking just before 'flight' (39).

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 (242). Participants were cued to *"step out off of the box and rebound as high and as fast as possible"* (242). 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, braking average power ($Power_{brake}$), propulsive

average power ($\text{Power}_{\text{prop}}$), braking average work ($\text{Work}_{\text{brake}}$) and propulsive average work ($\text{Work}_{\text{prop}}$).

Vaulting

Two-dimensional video analysis was used to determine the gymnasts' vertical take-off velocity ($\text{m}\cdot\text{s}^{-1}$) 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 (317), 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 (317). The best vault was determined as the highest straight jump (using the hip marker position) which was used for further analyses.

5.2.3 Statistical Analyses

Descriptive statistics (mean values \pm *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. Multi-collinearity was tested using variance inflation factor and tolerance diagnostics (0.2 tolerance cut-off). 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 (40) 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 (115). 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 (232). For each jump test, stepwise multiple regression analyses were employed separately to establish the contribution of jump force-time 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.

5.3 RESULTS

5.3.1 Squat jump

Data showed small to moderate, non-significant between-group differences for JH ($p > 0.05$; *figure 1*). Results for all other SJ variables are presented in *table 2*. Small to moderate significant increases in V_{peak} , $\text{Impulse}_{\text{rel}}$, PP_{abs} and PP_{rel} between the $\text{early}_{\text{pre}}$ and pubertal groups and between the $\text{early}_{\text{pre}}$ and late_{pre} groups were observed ($p < 0.05$). For PF_{abs} , there was a moderate significant increase between the $\text{early}_{\text{pre}}$ 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 $\text{early}_{\text{pre}}$ 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.

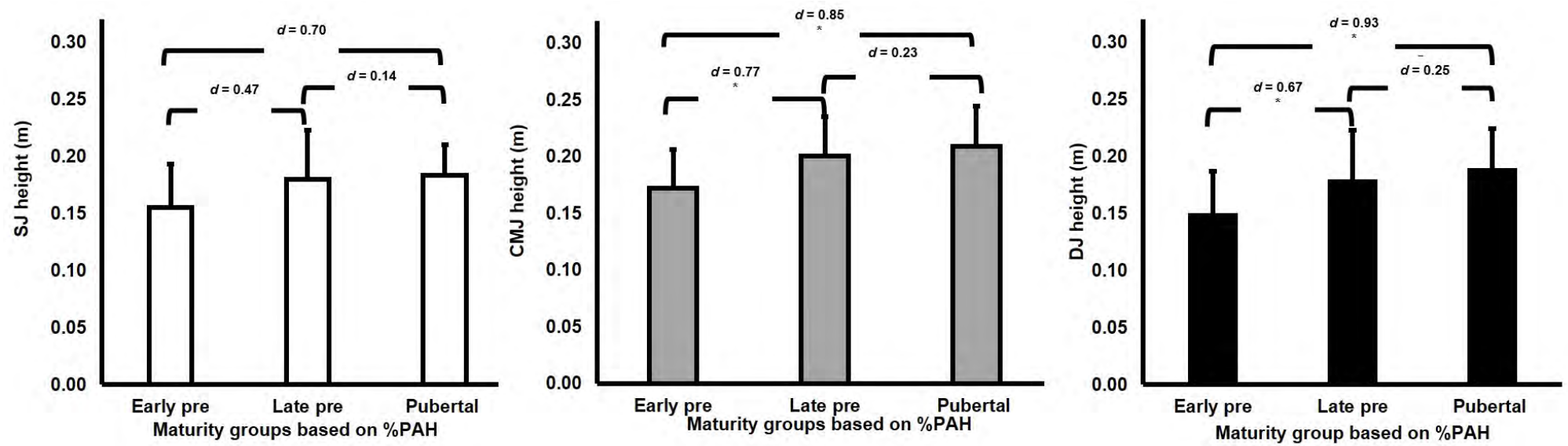


Figure. 1 Maturity group analysis of jump height (m) from the squat jump, countermovement jump and drop jump tests respectively (mean \pm sd)

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

Test Variable	Early _{pre}	Late _{pre}	Pubertal	Between group effect size (<i>d</i>)		
				Early _{pre} - Late _{pre}	Late _{pre} - Pubertal	Early _{pre} - Pubertal
V _{peak} (m·s ⁻¹)	1.97 \pm 0.21	2.12 \pm 0.17 ^a	2.14 \pm 0.12 ^a	0.53	0.05	0.55
Impulse _{rel} (m·s ⁻¹)	1.72 \pm 0.27	1.85 \pm 0.34 ^a	1.98 \pm 0.15 ^a	0.37	0.34	0.75
PF _{abs} (N)	591.14 \pm 206.91	756.25 \pm 174.99 ^a	793.18 \pm 208.40 ^a	0.76	0.18	0.84
PF _{rel} (N·kg ⁻¹)	21.77 \pm 3.41	21.54 \pm 2.42	21.74 \pm 1.40	0.06	0.06	0.02
PP _{abs} (W)	933.37 \pm 1302.96	1302.96 \pm 387.24 ^a	1360.64 \pm 479.61 ^a	0.89	0.09	0.91
PP _{rel} (W·kg ⁻¹)	33.39 \pm 5.71	36.65 \pm 4.42 ^a	37.44 \pm 3.24 ^a	0.48	0.13	0.60
RFD _{abs} (N·s ⁻¹)	1160.20 \pm 499.91	1457.19 \pm 518.07 ^a	1571.72 \pm 549.38 ^a	0.55	0.21	0.68
RFD _{rel} (N·kg ⁻¹ ·s ⁻¹)	43.81 \pm 18.09	42.14 \pm 14.05	43.51 \pm 13.11	0.10	0.09	0.05
pRFD _{abs} (N·s ⁻¹)	3691.94 \pm 4264.53	4069.38 \pm 4303.35	3710.09 \pm 1905.21	0.09	0.10	0.02
pRFD _{rel} (N·kg ⁻¹ ·s ⁻¹)	135.56 \pm 132.10	119.41 \pm 138.07	102.98 \pm 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)

5.3.2 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} ($p > 0.05$).

5.3.3 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 Δ COM, 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 take-off velocity 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.

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

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

Test Variable	Early _{pre}	Late _{pre}	Pubertal	Between group effect size (<i>d</i>)		
				Early _{pre} - Late _{pre}	Late _{pre} - Pubertal	Early _{pre} - Pubertal
GCT (s)	0.193 \pm 0.049	0.191 \pm 0.340	0.214 \pm 0.077	0.10	0.32	0.29
RSI	0.80 \pm 0.26	0.95 \pm 0.29	0.96 \pm 0.32	0.43	0.10	0.58
PF (N)	1549.00 \pm 382.65	2070.72 \pm 472.30 ^a	1918.52 \pm 629.35	1.04	0.29	0.78
Δ COM (cm)	9.91 \pm 2.67	11.34 \pm 2.58 ^a	12.11 \pm 5.40 ^a	0.59	0.01	0.53
Stiffness _{rel} (BW·m ⁻¹)	14.72 \pm 4.58	17.54 \pm 5.16	24.27 \pm 18.27 ^a	0.18	0.62	0.72
SLC	-0.92 \pm 0.05	-0.94 \pm 0.05	-0.94 \pm 0.05	0.27	0.14	0.27
Take-off velocity (m·s ⁻¹)	1.91 \pm 0.19	2.00 \pm 0.17	1.84 \pm 0.37	0.24	0.66	0.25
Power _{brake} (W)	-901.10 \pm 199.90	-1278.17 \pm 285.17 ^a	-1402.65 \pm 372.30 ^a	0.91	0.43	1.21
Power _{prop} (W)	749.40 \pm 176.02	1116.34 \pm 259.12 ^a	1252.18 \pm 266.50 ^a	1.12	0.49	1.45
Work _{brake} (J)	66.35 \pm 17.42	103.60 \pm 29.83 ^a	125.59 \pm 38.23 ^a	1.14	0.50	1.51
Work _{prop} (J)	46.35 \pm 16.45	79.63 \pm 29.20 ^a	102.00 \pm 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 groupGCT = ground contact time; RSI = reactive strength index; Δ COM = centre of mass displacement; SLC = spring-like correlation; 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)

5.3.4 Vaulting

Moderate, significant increases in vaulting vertical take-off velocity were found between the early_{pre} and late_{pre} groups ($p < 0.05$) and between the early_{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.

5.3.5 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 Δ COM (4%).

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	<i>p</i> 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

5.4 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 impulse_{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 (162). In contrast, SJ height was significantly greater between under-16s (post-PHV) and both less mature groups of boys (162). 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 (170).

The observed increases in jump height can be explained by the significant increases in $\text{Impulse}_{\text{rel}}$ and V_{peak} young gymnasts experience with maturity. $\text{Impulse}_{\text{rel}}$ provides insight into athletes' velocity capacity, which directly influences vertical jumping performance (138, 303). 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 (257). However, when normalized to body mass, only $\text{Impulse}_{\text{rel}}$ and PP_{rel} significantly increased with maturity between the $\text{early}_{\text{pre}}$ 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 (24). 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) (3, 257).

Small to moderate significant increases in CMJ height between successive maturity groups were found in this study. These results support previous researchers who have shown CMJ height increases with advancing age and maturity throughout childhood and adolescence (101, 150, 158, 170). 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} , $\text{Impulse}_{\text{brake}}$, $\text{Impulse}_{\text{prop}}$, PP_{abs} , $\text{Power}_{\text{brake}}$ and $\text{Power}_{\text{prop}}$) between successive groups. It is therefore likely that the significantly greater impulse more mature gymnasts

produced resulted in higher jump heights than their less mature counterparts. This is further evidenced by the moderate to large significant increases in $\text{Impulse}_{\text{brake}}$ and $\text{Impulse}_{\text{prop}}$ 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 in the CMJ, 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 IMTP protocol (205). 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 $\text{early}_{\text{pre}}$ group and both late_{pre} and pubertal cohorts of gymnasts. The significantly greater amount of PF, work, power and $\text{stiffness}_{\text{rel}}$ 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 $\text{GCT} < 250 \text{ ms}$ for fast-SSC function which is noteworthy, and may reflect selection and/or a 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 (19, 142, 153, 257). Thus, maturity-related increases in kinetic variables in this study are likely attributed to structural and neural adaptations (257). Specifically, natural increases in tendon CSA and

stiffness (144, 231), increases in preactivation (147, 236) and reduced co-contraction ratios (147) 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 (242). 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 (241). 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.

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 the 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 (216, 242). 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 corroborate this study's findings. While the authors recognise this limitation, the current study makes a significant and novel contribution to the paediatric (and gymnastics) literature by examining differences in jump kinetics during jumping and vaulting, which can be used to help inform training prescription.

5.5 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, there were 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 (178, 198). Providing technical competency is maintained, long-term training programmes should aim to provide gymnasts with an effective training stimulus that differs to their sport-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 Δ COM 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 that enhance gymnasts' overall athleticism and reduce the relative risk of gymnastics-related injuries.

Chapter 6: Prelude

Chapter 5 identified the differences in dynamic force-time variables between gymnasts of different biological maturity status using a range of jumping tests. This study also showed that across all jumping tests, the DJ was found to have the highest predictive ability of vaulting vertical take-off velocity. Existing research indicates that faster run-up speeds are important for gymnastics vaulting performance. Whilst some age-related data exists comparing the sprint speed of female gymnasts, examining how sprint speed variables and horizontal jumping performance differ according to maturity status was deemed important. Much like the *Chapters 4* and *5*, these data would enable practitioners to identify expected magnitudes of change throughout normal growth and maturation, which could also be used for benchmarking purposes with gymnasts. Additionally, the ability of sprint-related variables and standing long jump distance (both of which representing horizontal force producing ability) on vertical take-off velocity was unknown. *Chapter 6* therefore aimed to determine how sprint-related variables and standing long jump distance differed between gymnasts of different maturity status and how such variables influenced vertical take-off velocity. Cumulatively, these data could be used to inform training provision and evaluate the effectiveness of training interventions in young female gymnasts.

Chapter 6:

The Influence of Biological Maturity on Sprint Speed, Standing Long Jump, and Vaulting Performance in Young Female Gymnasts

Moeskops, S., Oliver, JL. Read, PJ. JB. Myer, JD. Haff, GH. and Lloyd, RS. (in press) The influence of biological maturity on sprint speed, standing long jump and vaulting performance in young female gymnasts. *Int J Sport Physiol*.

6.1 INTRODUCTION

Within artistic gymnastics, the vault is one of the highest scoring disciplines for all-around female gymnasts (64). To be successful on this apparatus, gymnasts will aim to achieve the highest difficulty value possible, while minimizing deductions on skills to result in greater execution scores (131). The ability to increase height or flight time is determined by vertical take-off velocity (249) and this directly influences both aspects of the scoring system; where longer flight times will enable more complex skills to be performed (23). Faster run-up speeds and take-off velocities from the springboard are needed to generate the required kinetics to elicit longer flight times (21, 25). Senior female gymnasts attain significantly faster maximal speeds during the vault run-up than their junior counterparts (272) and outperform them on the vault and floor apparatus; with higher difficulty value, execution score and overall mean scores reported (64).

Previous literature in gymnasts has used sprint speed or sprint times (247, 286, 308) and standing long jump (SLJ) distance (308) as surrogate measures of performance. These field-based tests are often included in testing batteries for young gymnasts as they are relatively low

cost and produce instantaneous data (308). Age-related research in male youth gymnasts found a constant increase in run-up velocity for the vault with age in men's junior gymnastics (≤ 18 years), followed by a plateau in senior age gymnasts (19-25 years) (26). While the authors subdivided the gymnasts into age-ranges and referred to stages of motor development, the maturity status of individuals was not directly estimated (26). Given its association with vaulting, a small number of studies have used the SLJ protocol to identify key determinants of the sport or for profiling purposes (308); however, age-related comparisons for SLJ performance are limited, with no maturity-related data currently available.

While research exploring age-group differences in speed and jumping performance of gymnasts is of some value, the timing and tempo of biological maturation between individuals of the same chronological age may differ (170). Consequently, the need to analyze the influence of growth and maturation on physical qualities and motor skills in youth has been well documented (195, 257), with non-linear developments in strength (170), power (257) and speed (195) shown across various stages of development. For example, one study in young males reported no significant differences in sprint speed pre-peak height velocity (PHV), while periods of accelerated development occurred circa- and post-PHV (195). Unfortunately, limited research exists that has examined differences in sprint speed and SLJ performance in young female gymnasts when grouped by maturity status. Superior insight into speed and SLJ development of gymnasts could be acquired if performance testing data is considered alongside biological maturity. These data could be used to inform training provision and evaluate the effectiveness of training interventions. For example, the momentum of a gymnast when sprinting towards the vault will be influenced by mass and velocity; therefore, data which explores how these qualities differ between maturity groups could be used to compare and help

determine whether meaningful adaptations have occurred as a result of training or natural development.

In light of the requirements of the sport and the limitations within the existing literature, research investigating sprinting and horizontal jump performance in gymnasts grouped by maturity status seems warranted. Furthermore, the contribution of maturity status, speed, and SLJ variables to vertical take-off velocity during vaulting performance is yet to be explored and could help assist practitioners when prescribing training. Therefore, the aims of this study were to (1) examine how speed, SLJ and vaulting variables differ across young female gymnasts of different maturity status, and (2) determine to what extent these variables influence vaulting take-off velocity.

6.2 METHODS

6.2.1 Subjects

One-hundred and twenty female artistic gymnasts aged 5–14 years participated in the study. All participants had >1 year of gymnastics experience and were training 2–6 times per week, totaling 2–24 hours per week. None of the gymnasts had formalized strength and conditioning experience. Gymnastics training sessions were comprised of standard conditioning activities and time allocated to all disciplines; vault, bars, balance beam and the floor exercise. Participants reported no current 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 Institutional Ethics Board (ethics code: 17/1/02R) and parental informed consent and child assent documents were collected prior to testing.

Table 1. Descriptive statistics for maturity groups' anthropometric variables (Mean \pm SD)

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

Early_{pre} = early pre-pubertal; Late_{pre} = late pre-pubertal

Significant at the level of $p < 0.05$

^a = significantly greater than the Early_{pre} group; ^b = significantly greater than the Early_{pre} and Late_{pre} groups

6.2.2 Design

This study employed a cross-sectional design to examine between-group differences in speed, SLJ and vaulting performance in young artistic female gymnasts of different maturity status. In addition, regression analyses were performed to determine the predictive ability of biological maturity, speed, and SLJ variables on vaulting vertical take-off velocity. Participants attended one testing session in which all data were collected.

6.2.3 Protocols

Prior to testing, all participants performed a standardized 10-minute dynamic warm-up led by the principal researcher, which included 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. Participants were afforded one practice sprint trial and were instructed to sprint as fast as possible over the entire distance. For the SLJ and vaulting, the researcher provided a demonstration of the tests and gave standardized, child-friendly coaching cues.

Anthropometric and maturity measures

Standing height (cm), body mass (kg), chronological age, and parental height were used to determine participants' biological maturity status using %PAH (136); with participants then grouped according to the following bands: <75%PAH, early pre-pubertal (early_{pre}; n = 54); 76%–85%PAH, late pre-pubertal (late_{pre}; n = 47); and 86%–95%PAH, pubertal; n = 19). Previous researchers have suggested 85-90%PAH and 90-95%PAH bands may identify the early pubertal period and mid-pubertal stages in males, respectively (49). Further, a <85%PAH band was also used to group young athletes as pre-pubertal who were approximately 8-12 years old (49). Given that this study included participants who were as young as five years-old, an

additional pre-pubertal band ($\text{early}_{\text{pre}}$) was included. It should be noted that all anthropometric measures of the participants were measured directly, but mid-parental height (136) was self-reported by the parents. Descriptive data for each maturity group are presented in Table 1.

20 m sprint

The sprinting protocol required each gymnast to perform a maximal sprint over a 20 m distance on an indoor track using wireless timing gates (Smart Speed; Fusion Sport, Brisbane, Australia) placed at 0 m, 5 m, 10 m, 15 m, and 20 m. The sprinting distance chosen reflects the specific demands of artistic gymnastics (247) and research has shown maximal sprint speed is typically achieved in youth between 15-30 m (197). Participants were given the instructions “*when you are ready, go*” and verbal encouragement was given throughout the test to encourage maximal effort. Trials were repeated if the researcher perceived the participant had inadvertently reduced their speed prior to the final timing gate. Participants completed three trials, with the fastest used for further analyses. A minimum of two minutes of passive rest was provided to ensure participants were sufficiently recovered. Sprinting data were instantaneously collected via the Smartspeed app using an iPad (iPad mini 2, Apple). Reliability of over-ground sprinting in youth populations has previously been reported with mean coefficients of variation (CV) between 0.83–2.07% (269). The following variables were calculated and used for further analyses:

- Speed ($\text{m}\cdot\text{s}^{-1}$) was calculated by dividing the interval distance (5 m) by the split time (s) between 0-5, 5-10, 10-15 and 15-20.
- Peak speed ($\text{m}\cdot\text{s}^{-1}$) was determined by the highest speed interval.
- Peak momentum ($\text{kg}\cdot\text{m}\cdot\text{s}^{-1}$) was calculated by multiplying body mass (kg) by peak speed ($\text{m}\cdot\text{s}^{-1}$).

Standing long jump

The SLJ protocol required each gymnast to stand with their feet hip width apart behind a marked take-off line and jump forwards maximally (37). In-line with previous youth-based research, participants were permitted to use an arm swing (212) and were cued to *'jump as far as possible and stick the landing'* in each trial. Trials were discounted and repeated if the gymnast did not land without falling or stepping backwards or forwards. The distance from the take-off line to the back of the participant's rearmost heel was recorded to the nearest 0.1 cm using a tape measure (37). SLJ distances were also normalized to leg length (LL) for each participant. Previous research has reported high reliability for SLJ distance jumped in female youth, with a mean CV of 3.4% (212).

Vaulting

Two-dimensional video analysis was used to determine gymnasts' vertical and horizontal take-off velocity from the springboard and jump height of the straight vault. During vaulting trials, one stationary high-speed 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. All gymnasts performed three straight jump vaults from a springboard onto a landing mat. The straight vault is the most basic vaulting exercise and was chosen to ensure all gymnasts were capable of performing the skill regardless of experience or maturity status. All gymnasts received a standardized instruction to *"perform your highest straight jump."* 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 coordinate data were filtered (MATLAB, R2018a) using a low-pass, 4th-order recursive Butterworth filter. Based on residual analysis (317), the most appropriate cut-off frequency was 10 Hz. The best vault was determined as the highest straight jump and was used for further analyses. The following variables were calculated:

- Vertical take-off velocity ($\text{m}\cdot\text{s}^{-1}$) from the springboard was calculated using the central difference method (317).
- $\text{Ratio}_{\text{vert-horiz}}$ was calculated by dividing vertical take-off velocity from the springboard by horizontal take-off velocity. This variable was incorporated to assess gymnasts' technical ability to transfer linear speed from the approach run-up into vertical take-off velocity during the take-off.

6.2.3 Statistical Analyses

Descriptive statistics (mean values \pm SD) were calculated for speed, SLJ distance, vaulting variables for each maturity group. Between-group differences for each variable 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. 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 (115). Pearson correlation coefficients were used to determine the strength of relationships between all variables and vertical take-off velocity for the whole sample. The strength of these relationships was classified based on previous recommendations (232): <0.2 , no relationship;

0.2–0.45, weak; 0.45–0.7, moderate; >0.7, strong. Simple linear regression analyses were used to model the relationship between vaulting vertical take-off velocity and the following variables: maturity status (%PAH), peak speed, peak momentum and SLJ distance. Stepwise multiple regression analyses were then used to establish the contribution of maturity status and all performance variables (speed, peak momentum, SLJ, normalized SLJ and Ratio_{vert-hozi}) 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, while multi-collinearity was tested using variance inflation factor and tolerance diagnostics (0.2 tolerance cut-off). All significance values were accepted at $p < 0.05$, while all statistical procedures were conducted using SPSS v.24 for Macintosh.

6.3 RESULTS

Mean (\pm *sd*) results for speed, SLJ distance, vaulting variables for early_{pre}, late_{pre} and pubertal groups are shown in *table 2*. Moderate differences were shown in all speed intervals, peak speed, SLJ distance, vault vertical take-off velocity between the early_{pre} and late_{pre} ($p < 0.001$; $d = 0.65$ -1.10) and early_{pre} and pubertal ($p = 0.00$; $d = 0.75$ -1.00) groups. Large differences in peak momentum were found between each successive group ($p < 0.001$; $d = 1.23$ -1.85). However, no differences were observed between groups for Ratio_{vert-hozi} and effect sizes were trivial to small ($d = 0.14$ -0.40). Similarly, differences between the late_{pre} and pubertal groups for all variables were non-significant and trivial to small ($d = 0.01$ -0.55), with the exception of peak momentum. SLJ normalized to LL in the pubertal group was less than the early_{pre} group ($p = 0.006$; $d = 0.59$).

Table 2. Maturity group analysis of variables for average speed, SLJ and vaulting (Mean \pm SD)

Test	Variable	Early _{pre}	Late _{pre}	Pubertal	Between group effect size (<i>d</i>) and confidence intervals		
					Early _{pre} -Late _{pre}	Late _{pre} - Pubertal	Early _{pre} - Pubertal
<i>Sprint speed</i>	0-5 (m·s ⁻¹)	3.71 \pm 0.31	4.00 \pm 0.35 ^a	4.23 \pm 0.29 ^a	0.65 (0.16-0.96)	0.56 (0.02-1.10)	0.89 (0.35-1.43)
	5-10 (m·s ⁻¹)	5.15 \pm 0.37	5.60 \pm 0.33 ^a	5.71 \pm 0.29 ^a	0.66 (0.25-1.06)	0.35 (-0.19-0.89)	0.75 (0.21-1.29)
	10-15 (m·s ⁻¹)	5.50 \pm 0.47	6.13 \pm 0.38 ^a	6.30 \pm 0.37 ^a	0.81 (0.40-1.22)	0.45 (-0.09-0.99)	0.92 (0.38-1.46)
	15-20 (m·s ⁻¹)	5.47 \pm 0.54	6.11 \pm 0.42 ^a	6.35 \pm 0.41 ^a	0.78 (0.37-1.19)	0.55 (0.01-1.09)	0.95 (0.40-1.50)
	Peak speed (m·s ⁻¹)	5.56 \pm 0.51	6.22 \pm 0.38 ^a	6.43 \pm 0.38 ^a	0.83 (0.42-1.24)	0.54 (0.00-1.08)	0.96 (0.41-1.51)
	Peak momentum (kg· m·s ⁻¹)	141.1 \pm 34.2	211.5 \pm 49.3 ^a	289.4 \pm 61.9 ^b	1.25 (0.81-1.68)	1.23 (0.66-1.80)	1.85 (1.25-2.45)
<i>SLJ</i>	Distance (cm)	146.6 \pm 18.52	162.8 \pm 22.67 ^a	166.5 \pm 16.40 ^a	0.61 (0.21-1.01)	0.18 (-0.35-0.71)	0.75 (0.21-1.29)
	SLJ normalized to LL	2.55 \pm 0.27	2.47 \pm 0.31	2.31 \pm 0.26 ^c	0.20 (-0.19-0.59)	0.53 (-0.01-1.07)	0.59 (0.06-1.12)
<i>Vaulting</i>	Vertical take-off velocity from board (m·s ⁻¹)	2.64 \pm 0.65	3.34 \pm 0.48 ^a	3.34 \pm 0.62 ^a	1.10 (0.67-1.52)	0.01 (-0.52-0.54)	1.00 (0.45-1.55)
	Ratio _{vert-hozi}	1.18 \pm 0.41	1.30 \pm 0.27	1.34 \pm 0.30	0.32 (-0.08-0.71)	0.16 (-0.37-0.69)	0.40 (-0.13-0.93)

Early_{pre} = early pre-pubertal; Late_{pre} = late pre-pubertal; SLJ = standing long jump; LL = leg length; Ratio_{vert-hozi} = vertical to horizontal take-off velocity ratio
Significant at the level of $p < 0.05$; ^a = significantly greater than the Early_{pre} group; ^b = significantly greater than the Early_{pre} and Late_{pre} groups; ^c = significantly less than the Early_{pre} group

Small effect size (0.20-0.59); Moderate effect size (0.60-1.19); Large effect size (1.20-1.99)

Relationships between vertical take-off velocity and all variables across the whole sample are shown in *table 3*. Moderate significant relationships were indicated between vaulting vertical take-off velocity and maturity (%PAH), SLJ distance, 0-5 speed, peak momentum and Ratio_{vert-hozi} ($r = 0.48\text{--}0.65$; $p < 0.01$). The remaining speed intervals (5-10, 10-15 and 15-20 $\text{m}\cdot\text{s}^{-1}$) and peak speed showed strong significant associations with vaulting vertical take-off velocity ($r = 0.74\text{--}0.76$; $p < 0.001$). Of note, the peak speed interval for each participant occurred in either the 10-15 or 15-20 m split intervals and the common variance between peak speed and the speed intervals 5-10, 10-15 and 15-20 m were very high (i.e. $>80\%$). No relationships were found between vaulting vertical take-off velocity and SLJ normalized to LL ($r = 0.02$).

Table 3. Relationships between vertical take-off velocity during vaulting and all variables across the whole sample

Test	Variable	Vertical take-off velocity from board ($\text{m}\cdot\text{s}^{-1}$)
<i>Biological maturity</i>	%PAH	0.64 ^{*#}
<i>Sprint speed</i>	0-5 ($\text{m}\cdot\text{s}^{-1}$)	0.48 ^{*#}
	5-10 ($\text{m}\cdot\text{s}^{-1}$)	0.74 ^{*†}
	10-15 ($\text{m}\cdot\text{s}^{-1}$)	0.76 ^{*†}
	15-20 ($\text{m}\cdot\text{s}^{-1}$)	0.75 ^{*†}
	Peak speed ($\text{m}\cdot\text{s}^{-1}$)	0.77 ^{*†}
	Peak momentum ($\text{kg}\cdot\text{m}\cdot\text{s}^{-1}$)	0.57 ^{*#}
<i>SLJ</i>	Distance (cm)	0.53 ^{*#}
	SLJ normalized to LL	0.02 [^]
<i>Vaulting</i>	Ratio _{vert-hozi}	0.65 ^{*#}

%PAH = percent of predicted adult height attained; SLJ = standing long jump; LL = leg length; Ratio_{vert-hozi} = vertical to horizontal take-off velocity ratio

* = significant at the level of $p < 0.01$

[^] = <0.2 , no relationship; [#] = $0.45\text{--}0.7$, moderate; [†] = >0.7 , strong

Figure 1a-d shows the equations from the simple linear regression analysis for vaulting vertical take-off velocity across the whole sample for; maturity (a), peak speed (b), peak momentum (c) and SLJ distance (d). The strongest relationship with vaulting take-off velocity was provided by peak speed (59%) followed by maturity (41%), peak momentum (33%) and SLJ distance (28%). Multiple stepwise regression analysis across the whole sample showed that variation in vaulting vertical take-off velocity was best explained by peak speed (58%) and Ratiovert-hozi (13%), accounting for 71% of the total variance. The remaining variables were unable to predict or further explain the variance in the model.

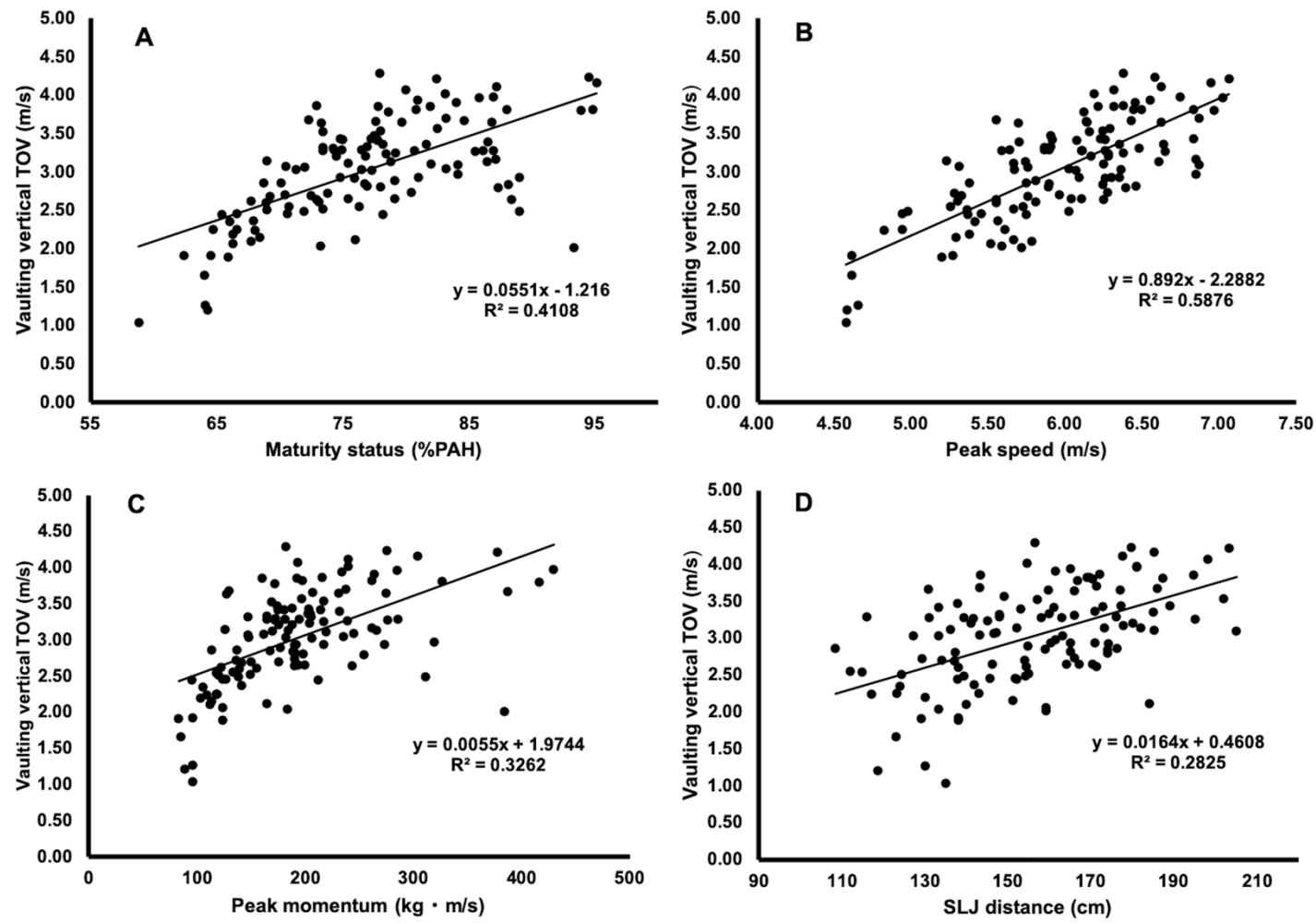


Figure 1. Regression line and equations between vault vertical take-off velocity and maturity status (A), peak speed (B), peak momentum (C) and standing long jump distance (D)

6.4 DISCUSSION

The aims of this study were to examine how speed, SLJ and vaulting variables differ across young female gymnasts of different maturity status, and to determine which variables influence vaulting take-off velocity. The main findings of the current study were that speed, SLJ and vaulting variables (vertical take-off velocity) were moderately greater in the more mature groups, particularly between the Early_{pre} and Late_{pre} groups of young gymnasts. Large differences in peak momentum were evident between each successive maturity group. Peak speed had the strongest relationship ($r = 0.76$) and was found to be the best linear predictor (59%) of vertical take-off velocity during vaulting. Separate simple linear regression analyses revealed biological maturation (41%), peak momentum (33%) and SLJ distance (28%) appear to moderately influence vertical take-off velocity. Multiple regression analyses revealed that peak speed and Ratio_{vert-hozi} explained 71% of the total variance in vaulting vertical take-off velocity, which underlines the importance of a combined fast approach speed and take-off technique for vaulting performance in young female gymnasts.

Findings from this study indicate that maturity status influences linear speed in young female gymnasts. Specifically, both the late_{pre} and pubertal groups were found to be significantly faster in terms of peak speed and at all speed intervals compared to the least mature group. However, no significant differences between the late_{pre} and pubertal gymnasts were identified for these variables. Our findings corroborate existing research which has shown sprint speed develops in a non-linear fashion throughout childhood and adolescence (195, 309). Data indicate specific periods of accelerated development in sprint speed may occur prior to puberty, between the ages of 5-9 years (309) and again post-puberty, but only in males (195, 234, 309). While the present study did not include a post-pubertal group of female gymnasts, our data indicate a similar trend as speed appears to plateau between the late pre-pubertal and pubertal years. Of

note, peak momentum was significantly greater during this stage and as speed remained unchanged, this is likely due to the significant differences in body mass between the groups.

Previous research in young female athletes reported no significant differences in 20 m sprint time between pre- and post-menarcheal 13-year-olds (174). Of the available gymnastics-based research, one study in competitive male gymnasts reported speed increased on average by 0.2 m/s each year between the ages of 12-18 (26). Therefore, the development of sprint speed at different stages of growth and maturation appears to differ between sexes (171, 234). Improvements in speed could be attributed to neuromuscular adaptations, metabolic and hormonal changes, as well as biomechanical and co-ordination factors (234). Further, sex-related differences in speed following the onset of puberty could be influenced by changes in body composition; with females experiencing natural increases in fat-mass and reduced gains in muscle mass than males (170, 195, 234). Based on the developmental period examined in the present study, the maturity-associated improvements in speed are likely due to changes in force production capabilities driven by the natural development of the neuromuscular system (e.g. motor-coordination and unit recruitment), as well as significant increases in leg length that accompany childhood and the start of adolescence (234).

The results indicate that maturation appears to enhance a young gymnasts' ability to jump greater horizontal distances, as evidenced by the more mature gymnasts jumping significantly further than their immature counterparts. However, when normalized to leg length, SLJ was greater in the early_{pre} than the pubertal group indicating the potential implications of anthropometric changes on horizontal jumping performance. Although speculative, these findings may indicate more mature gymnasts possess greater absolute lower-limb strength and power as a result of growth- and maturity-related increases in muscle size and cross-sectional

area (170). However, no significant differences were found between the two most mature groups for SLJ distance or normalized SLJ distance, suggesting SLJ performance may stabilize during this period of development. Previous age-related data has shown that amongst girls of the same height, greater body mass negatively influenced SLJ distance in females aged 11-13 years (174). Therefore, the significant difference in body mass between gymnasts from late_{pre} to pubertal groups in this study could partially explain the plateau in SLJ performance.

Findings from this study show peak speed most strongly influences vertical take-off velocity from the springboard during vaulting, explaining ~58% of variance across all test variables. Moderate significant correlations were demonstrated between vaulting vertical take-off velocity and SLJ distance as well as speed over 0-5 m·s⁻¹; however, neither of these variables were found to be predictors of vaulting vertical take-off velocity. Ratio_{vert-hozi} was the only other predictor identified from the multiple regression analysis that influenced vertical take-off velocity (~12%). Together with peak speed, these variables explained ~70% of variance in vertical take-off velocity, highlighting the importance of a fast approach run-up speed to elicit a greater resultant take-off velocity from the springboard (24, 25). Further, the influence of Ratio_{vert-hozi} on vertical take-off velocity highlights the technical requirements of successful vaulting. For example, gymnasts with high running speeds but poor springboard take-off technique (i.e. torso leaning forwards) are likely to produce too much resultant horizontal velocity, causing negative effects to the straight jump vaults (i.e. longer distances and lower heights). Further, research by Bradshaw and colleagues (21, 25) has shown the ability to maintain a high velocity during the visual control phase (i.e. where gymnasts control their approach and make foot adjustments prior to the springboard) increases post-flight time and vaulting score. Therefore, data from this study emphasizes the importance of enhancing running speed while maintaining technical execution to transfer speed gains to vaulting

performance (25). Of note, as gymnasts experience growth and maturation, their moment of inertia and momentum increases (i.e. greater body mass and taller stature) which may have implications for vaulting and airborne skills. For example, the ability to perform vaults involving rotation will require vertical and angular momentum, and less mature, smaller gymnasts are able to increase their angular velocity to a greater extent than more mature gymnasts with greater inertia. Consequently, gymnasts must generate high running speeds to execute take-offs with appropriate amounts of vertical and angular momentum and importantly, develop the required ability to safely absorb forces upon landing (249).

One limitation of this study is that differences in average sprint speed and SLJ variables between maturity groups were deduced from a cross-sectional data set. The authors acknowledge that future research would benefit from longitudinal assessments that track the natural development of youth female gymnasts across a longer timeframe to further validate this study's findings. Further, the use of average sprint speed produces less information about how the gymnasts' speed is changing within the 5 m intervals examined. Therefore, other methodologies to calculate velocity with higher sampling rates (e.g. radar gun, video analysis) could provide better insight into the sprint abilities of young gymnasts (124). While somatic assessments of maturity status are not invasive for youth, the error of prediction with the equations used in this study is on average 2 cm (136). Further, as the parents of the participants self-reported standing height, greater accuracy could have been achieved if this was measured directly. Despite these limitations, the current study makes a novel and significant contribution to the gymnastics and paediatric literature that can be used to assist the design of long-term athletic development programs.

6.5 PRACTICAL APPLICATIONS

The present study demonstrated that speed, SLJ distance and vaulting performance were significantly greater in more mature gymnasts compared to less mature gymnasts. However, practitioners should be aware that speed and SLJ performance may plateau around the Late_{pre} to pubertal years as no differences were found between these groups. Therefore, training to enhance performance in females during this period is likely to be important. While competitive gymnastics training typically involves high training volumes and intensities of bodyweight exercises from an early age (145), providing an alternative training stimuli (e.g. resistance training, weightlifting) could further improve levels of relative muscular strength and power which may enhance running speed (206, 276). Cumulatively, these data potentially highlight the importance of prioritizing the long-term development of relative muscular strength in female gymnasts throughout childhood and early adolescence.

As our results show that peak speed had the highest predictive ability for vertical take-off velocity during vaulting followed by Ratio_{vert-hozi}, strength and conditioning practitioners should work closely with technical coaches to enhance the physical qualities that underpin vaulting skills (e.g. relative strength and power). While different methods of training are available to enhance sprint speed, the specifics of programming will be dependent on a number of factors including the individual's technical competency, and strength and power characteristics. Interestingly, this study revealed that maturity status (%PAH) was not a predictor for vertical take-off velocity during vaulting. However, when simple linear regression was used to model the relationship between maturity and vertical take-off velocity, the regression equation predicts vertical take-off velocity will increase by 0.55 m·s⁻¹ for every 10% increase in %PAH. These data could provide coaches with a superior insight in an applied setting from both a developmental and talent identification perspective. For example, having an awareness of how much vertical take-off velocity naturally develops in gymnasts as they

mature, will enable practitioners to monitor and detect training-induced changes in performance that are above what is expected from biological maturity alone.

6.6 CONCLUSION

The results from this study support the need to account for biological maturity when testing and monitoring young gymnasts throughout childhood and early adolescence. This study shows that speed, SLJ distance and vaulting performance are greater in more mature young female gymnasts than less mature cohorts. However, speed and horizontal jump distance may plateau around the Late_{pre} to pubertal years. Peak speed had the highest predictive ability and strongest relationship with vertical take-off velocity during vaulting. Further, Ratio_{vert-hozi} was also found to be a predictor of vertical take-off velocity highlighting, the importance of possessing the technical ability to transfer linear speed into vertical take-off velocity for vaulting performance.

Chapter 7: Prelude

Previous chapters identified the differences in isometric and dynamic force-time variables, SLJ distance and sprint speed between gymnasts of different maturity status, as well as the relationship between these measures and vaulting vertical take-off velocity. Across all of the cross-sectional studies it was noted how research was needed that examined the effects of training on these athletic qualities. Neuromuscular training (NMT) is a training method which involves resistance training, plyometrics, speed, dynamic balance/stabilization and postural control, and has been shown to improve measures of physical performance in youth. However, the effectiveness of NMT on the development of strength, power and speed, in female gymnasts (a population already exposed to high volumes of sport-specific training) remains a very under-researched topic. Furthermore, very few studies in youth have examined training responses to longer-term training interventions, with most studies lasting < 16 weeks in duration. Therefore, *Chapter 7* investigated the effects of a 10-month NMT programme on isometric and dynamic force-time characteristics, SLJ distance, speed and vaulting take-off velocity in young female gymnasts. The information acquired can be used to inform practitioners about the efficacy of NMT for gymnasts and provide an insight into the potential efficacy of implementing longer-term training programmes during childhood for young female athletes.

Chapter 7:

The Effects of a 10-Month Neuromuscular Training Program on Isometric and Dynamic Force-Time Characteristics, Speed and Vaulting Take-off Velocity in Young Female Gymnasts

7.1 INTRODUCTION

Female artistic gymnastics is a sport that relies on the ability to express force in a skilful manner across four different disciplines (vault, bars, balance beam and floor) (206, 273). Many dynamic gymnastics skills require explosive lower-limb capabilities and high take-off velocities (24, 25, 179, 249). For example, research has emphasized the importance of high running speeds, explosive springboard take-off and technical execution to optimize vaulting performance (21, 25, 208). The sport also demands high levels of muscular strength to maximize the execution of skills, hold positions isometrically (133), and to safely tolerate large landing forces (206). Therefore, the ability to effectively express and absorb high forces at variable movement velocities appears to be important to gymnastics performance (206).

Leading organisations have recommended that all young athletes engage in neuromuscular training (NMT) in the pre-pubertal years (151, 156, 219, 225). Supplementing technical sports training with NMT has been shown to reduce athletes' sport-related injury-risk, improve movement skill proficiency and enhance physical qualities associated with athletic performance (66, 223, 226). This approach to training aims to elicit adaptations through combining a range of training modes such as resistance training, plyometrics, speed, dynamic balance/stabilization and postural control (66, 223). Despite a growing body of evidence showing the efficacy of NMT in general youth populations (57, 66, 223, 240), whether similar improvements in fitness can be realised in young athletes that participate in high training

volume sports such as gymnastics, remains unclear. One study in pre-pubertal female gymnasts revealed that 8-weeks of NMT significantly improved levels of movement competency and trunk endurance (209); however, the authors concluded that higher intensities and longer training durations could be required to realize adaptations in leg stiffness and reactive strength qualities (209). Previous longer-term data showed a combination of heavy resistance training and high impact plyometric training was more effective for improving drop jump parameters (e.g. flight-contact time ratio, estimated mechanical power) than habitual gymnastics-training alone (178). Furthermore, meta-analysis data in youth has shown resistance training can positively effect vertical jump performance and linear sprint speed (149), which are significant predictors of vaulting take-off velocity (207, 208).

The physical preparation of female gymnasts has traditionally involved a skill-repetition approach, whereby high volumes of technical skills are performed using bodyweight as the primary source of resistance to increase relative muscular strength (276). Whilst this type of training satisfies the principle of specificity, bodyweight training alone is unlikely to provide the necessary overload stimulus required for young gymnasts to continue improving relative strength levels (206, 276). These data support the findings of a meta-analysis which reported training periods of >23 weeks and resistance training intensities of 80–89% of 1RM were most effective for improving muscular strength in youth athletes (149). Furthermore, young female gymnasts cannot rely on natural development alone to promote further gains in strength and power (178, 205, 207, 208). For example, recent data across numerous strength and power tests indicate that both isometric and dynamic measures of relative peak force do not appear to naturally increase with biological maturity in young female gymnasts (205, 207). Additionally, research has shown that pre-pubertal gymnasts were not able to maintain gains in jump performance attained from a strength and power training intervention, experiencing detraining

during subsequent competitive and transition periods (178). These data highlight the importance of young female gymnasts consistently engaging in long-term, periodised, strength and power training programs to enhance athleticism that will transfer to gymnastics performance.

Comprehensively evaluating gymnasts' responses to lower-limb strength and power training, requires the assessment of neuromuscular function across a range of protocols that target different regions of the force-velocity curve (57, 185). Existing youth gymnastics literature has predominantly relied upon vertical jump assessments to evaluate the effectiveness of training programs, including drop jumps (DJ; (17, 178, 209)), countermovement jumps (CMJ) and squat jumps (SJ; (17, 88, 100, 198)). Existing training studies have shown that using a combination of plyometrics and resistance training (180, 198), or resistance training alone (88, 246), can significantly enhance jumping performance in female gymnasts. However, a limitation of current gymnastics literature is that these studies have solely used vertical jumping protocols to evaluate the efficacy of the training; therefore, it remains unclear how NMT can influence maximal force producing capabilities (i.e. isometric or dynamic measures), horizontal force production (e.g. horizontal jumping or sprinting), and whether NMT can elicit positive adaptations in gymnastics-specific measures (e.g. vaulting take-off velocity). One study determined that 6-weeks of plyometric training significantly improved aspects of vaulting performance (e.g. take-off velocity, run up velocity; (100)); however, this short-term study did not report maturity status and therefore, the interaction effects between training and maturation over longer training durations remains unclear.

Another limitation of existing studies in youth gymnastics is the over-reliance on performance-based outcome variables (i.e. jump height and distance). While such measures can establish the

efficacy of NMT, they fail to provide insight into the mechanistic changes that gymnasts might experience from the training stimuli. Kinetic analysis of strength and power performance provides a more granular understanding of training adaptations and ultimately enables more targeted and individualized programming. Some available kinetic data in collegiate female gymnasts has shown significant resistance training-induced gains in peak power output and reductions in time to peak power in CMJ and SJ jump protocols (88). However, kinetic data from long-term training interventions in younger gymnasts is very sparse.

To date, research has yet to establish the interaction effects of training and maturation on various measures of strength, power and speed and gymnastics performance in response to longitudinal NMT in young female gymnasts. Consequently, using a multi-group, repeated-measures approach, the current study compared the effects of 10-months of NMT in addition to gymnastics training on kinetic determinants of strength and power, SLJ distance, sprint speed and vaulting take-off velocity in young female gymnasts. These data were compared to both gymnastics only training and a maturity-matched control group. The hypothesis was that young female gymnasts who participated in supplementary NMT in addition to their gymnastics training would experience significantly greater improvements in kinetic determinants of strength and power, SLJ distance, sprint speed and vaulting take-off velocity than either gymnastics only training or maturity-matched control groups.

7.2 METHODS

7.2.1 Subjects

Forty-three female girls aged 6-13 years agreed to participate in this study, thirty-one were artistic gymnasts and twelve were not involved in the sport. Participants were sub-divided into one of three groups: gymnastics + NMT (GYM+NMT; $n = 16$), gymnastics only (GYM; $n =$

15) and a maturity-matched control (CON; $n = 12$). Both groups of gymnasts were from various clubs in the local area, had > 1 year of artistic gymnastics experience and were participating in competitive gymnastics training 2–5 times per week, for on average ~ 11 training hours per week. The mean ratio of hours of gymnastics training per week, per chronological age was also calculated for each group (*table 1*); the ratio for both groups was ~ 1.2 indicating that on average the gymnasts were participating in more hours of gymnastics than their age. The CON group were physically active but did not participate in formal gymnastics training. The maturity status of all participants was established as either pre-pubertal or pubertal, using percentage of predicted adult height (%PAH) (49, 136, 205). Descriptive data for each group is shown in *table 1*. Anthropometric data and maturity status were not significantly different between the three groups. In addition to their gymnastics training, the GYM+NMT group followed a 10-month NMT program, consisting of 2 x 1-hr sessions/week. The GYM group followed their gymnastics program, but did not receive the NMT; while the CON group did not participate in either formal gymnastics or neuromuscular training. Weekly gymnastics training volumes were not significantly different between the GYM+NMT and GYM groups. None of the participants had previously engaged in formalized strength and conditioning programs and no injuries were reported at the time of testing. Written informed parental consent and participant assent were obtained after ethical approval was granted by the Cardiff Metropolitan University Research Ethics Committee (ethics code 18/40/2R).

Table 1. Descriptive statistics for each groups' anthropometric variables (Mean \pm SD) at baseline

Group	<i>N</i>	Age (years)	Standing height (cm)	Sitting height (cm)	Body mass (Kg)	Predicted % adult height	Training hours per week	Ratio GT/Age
GYM+NMT	16	9.4 \pm 1.8	131.65 \pm 10.22	68.83 \pm 4.34	29.24 \pm 5.94	75.47 \pm 6.59	11.6 \pm 4.5	1.26 \pm 0.53
GYM	15	9.9 \pm 1.8	133.95 \pm 11.66	71.41 \pm 5.53	30.15 \pm 6.67	77.02 \pm 6.66	11.3 \pm 4.0	1.20 \pm 0.39
CON	12	8.7 \pm 1.6	131.11 \pm 12.62	70.10 \pm 6.53	30.23 \pm 6.86	73.58 \pm 5.96	\leq 1.0	N/A

GYM+NMT = Gymnastics + neuromuscular training group; GYM = Gymnastics only group; CON = Control; GT = gymnastics-training

7.2.2 Procedures

This study used a repeated measures design to examine the effects of a 10-month NMT program on kinetics during an IMTP, CMJ and DJ, SLJ distance, sprint speed and vertical take-off velocity during vaulting in young artistic female gymnasts. Physical performance testing and anthropometric data were measured at baseline and thereafter at 4-, 7-, and 10-months. 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 single sets of three dynamic exercises (i.e. 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 technique was deemed competent by the principal researcher.

Anthropometrics

Standing and sitting height were obtained 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 mid-parental height were used to determine participants' biological maturity status, using %PAH (136). All anthropometric data for participants were measured directly, but mid-parental height was self-reported by parents. Using previously determined %PAH bands (205), all participants in this study were estimated to be prepubertal (PAH < 85%) or pubertal (PAH = 86-95%).

Isometric mid-thigh pull

IMTP data were collected in a laboratory using a custom-built IMTP testing device with twin force plates sampling at a frequency of 1000 Hz (9287BA, Kistler Instruments AG, Winterthur, Switzerland). Methods by Moeskops *et al.* (204, 205) were followed for the IMTP testing procedures including: individual set-up position, standardized instructions for participants and inclusion/discounting of trials, and a minimum of two minutes of passive rest was provided between each trial to ensure sufficient recovery (99). Three trials were analyzed for each participant using custom-built LabView (LVRTE2014SP1, National Instruments, Austin, TX) analysis software (97, 204). Initiation of the pull was determined using the visual onset method (166) and the following force variables were processed: absolute peak force (PF_{abs}) and relative peak force (PF_{rel}) scaled to body mass. The best trial was determined by the highest PF_{abs} value and this was used for further analysis. Further information on the variables calculated is provided in *Supplementary Table 1*. Acceptable within- and between-session reliability has previously been reported for PF_{abs} and PF_{rel} in young females (coefficient of variation (CV) \leq 9.4%, intraclass correlation coefficients \geq 0.87) (204).

Countermovement jump, drop jump and standing long jump

All CMJ and DJ trials were collected in a laboratory setting using twin force plates sampling at a frequency of 1000 Hz (PASCO, 2 Axis force platforms, Roseville, CA 95747, USA). In line with previous research, participants were instructed to keep their hands on their hips throughout and their legs extended during the flight phase of each jump (207). To optimize the stabilization of body weight during the first second of the CMJ test, participants were instructed to “*stay as still as a statue*”, before being given a countdown of “3, 2, 1 go”. For the DJ protocol, a 30 cm platform was used and the participants were cued to “*step out and off of the box and rebound as high and as fast as possible.*” For further detail on the testing procedures,

readers are referred to our previous works (207) and *Supplementary Table 1* for additional information on the calculation method for each variable. Force-time data were filtered (MATLAB, R2018a or Labview LVRTE2014SP1; National Instruments) using a low-pass 4th order recursive Butterworth filter. Based on residual analysis (317), the most appropriate cut-off frequency was 13 Hz (207). For the SLJ protocol, gymnasts were instructed to stand with their feet hip width apart behind a marked take-off line, jump forwards maximally and ‘stick’ their landing (37). Participants were permitted to use an arm swing (212) and were cued to *‘jump as far as possible and stick the landing’* in each trial. The distance from the take-off line to the back of the participant’s rearmost heel was recorded to the nearest 0.1 cm using a tape measure (37).

Participants performed three trials of each jump test and were afforded a minimum of 60 seconds passive rest to ensure sufficient recovery between trials (290). The best trial selected for further analysis was determined by jump height for the CMJ, highest spring-like behaviour correlation (i.e. a perfect inverse relationship is indicated, $r = -1.0$) for the DJ (242) and furthest distance jumped for the SLJ (208). Coefficients of variation for these jumping tests in young females has previously been reported (CMJ height = 5.9%; DJ height = 4.7%; SLJ distance = 3.4%) (179, 180, 212). Jumping distance (m) was recorded for the SLJ and the variables calculated for the CMJ and DJ tests were as follows:

- CMJ: 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}) and duration of propulsive phase (Time_{prop}).
- DJ: jump height (JH), reactive strength index (RSI), ground contact time (GCT), spring-like correlation (SLC), relative vertical stiffness (Stiffness_{rel}), centre of mass displacement (Δ COM) and absolute peak force (PF_{abs}).

20 m sprint

Maximal sprint data were collected over a 20 m distance on an indoor track using wireless timing gates (Smart Speed; Fusion Sport, Brisbane, Australia) placed at 0 m, 5 m, 10 m, 15 m, and 20 m. The sprinting distance chosen reflects the specific demands of vaulting in artistic gymnastics (206, 247); recent research has also shown that young female gymnasts reach peak speed at either the 10-15 or 15-20 m split intervals (208). Participants completed three trials and verbal encouragement was given throughout to encourage maximal effort. At least two minutes of passive rest was provided to allow participants sufficient time to recover (208). The fastest trial was used for further analyses. Sprinting data were instantaneously collected via the Smartspeed application using a commercially available tablet (iPad mini 2, Apple). Acceptable reliability of over-ground sprinting in youth populations has previously been established ($CV = 0.83\text{--}2.07\%$; (269)). The sprinting variables calculated were peak speed ($Peak_{speed}$) and peak momentum ($Peak_{momentum}$). *Supplementary Table 2* provides further information on the variables calculated (abbreviations, units, descriptions).

Vaulting

Vaulting data were collected via two-dimensional video analysis replicating previously published methods (205). Participants performed three straight vaults from a springboard onto a landing mat. This basic vault was chosen to ensure all participants (including the control group) were capable of performing this skill regardless of gymnastics experience. All gymnasts received the standardized instruction “*perform your highest straight jump to land on the mat.*” 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. Calibration was completed after each testing session 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 coordinate data were filtered (MATLAB, R2018a) using a low-pass 4th order recursive Butterworth filter. Based on residual analysis (317), the most appropriate cut-off frequency was found to be 10 Hz. The best vault was determined as the highest straight jump (using the hip marker position) which was used for further analyses. The following vaulting variables were calculated: vertical take-off velocity from the spring-board, jump height (JH), ratio of vertical to horizontal take-off velocity from the springboard ($\text{Ratio}_{\text{vert-horiz}}$) and contact time (CT). Further information on the variables calculated is provided in *chapters 3-6*.

Training program

The GYM+NMT received NMT twice-weekly (2 x 1 hr sessions) in addition to their normal gymnastics training for a period of 10-months, delivered by a National Strength and Conditioning Association Certified Strength and Conditioning Specialist. The annual training plan and testing weeks were aligned with the gymnasts' academic year (*figure 1*), while school half-terms and holiday periods were used as transition recovery phases. Each training session commenced with a < 5-minute engagement task (e.g. a game or co-ordination challenge), designed to engage the gymnasts both physically and mentally for the training session (154). Subsequently, participants completed a ~10-minute dynamic warm up, which included mobilization and activation exercises in various formats (e.g. obstacle courses, animal shapes). The main part of each session (~35 minutes) was more structured (*tables 2-4*) and involved various recognized resistance training exercises. Each training session ended with a game or challenge.

Given the gymnasts had no previous training experience in formalized strength and conditioning (i.e. training age = 0), all gymnasts initially followed the same training programme regardless of age or maturity status. Term 1 targeted the development of movement competency and increasing base levels of muscular strength (*table 2*). The first 8-weeks of training were designed to develop and challenge the gymnasts' movement competency across a range of athletic motor skill competencies (AMSC) (155), with exercise complexity increasing or changing every two weeks. Most of the exercises were performed with bodyweight or with low load, and higher repetition ranges to allow gymnasts to simultaneously develop competency while also accumulate a sufficient training dosage in a safe manner. The next 6-weeks of training aimed to further develop levels of strength, mainly driven by an increase in the volume of sets.

Term 2 focused on strength development, before focusing on increasing levels of both strength and power (*table 3*). The strength and power blocks of training involved multi-joint exercises with repetition ranges between 6 and 8, and gymnasts increasing the resistance appropriately and progressively (e.g. using barbells, kettlebells, resistance bands and dumbbells) based on technical competency. Basic weightlifting technique drills, ballistic exercises and bilateral plyometric exercises were also introduced. In addition, data from testing session 2 was used to determine individual exercises for each gymnast that targeted movement and/or strength deficits. Of note, the majority of gymnasts had competitions scheduled during this term (see *figure 1*).

The aim of term 3 (*table 4*) was to develop the gymnasts' strength, power and speed; this involved higher loading schemes and/or higher velocities and lower repetition ranges for

exercises (i.e. 3-5 sets of 3-6 repetitions). Gymnasts were given target loads for certain exercises (back squats, deadlifts and hang-cleans) during the final two mesocycles, whereby external load increased each week by ~5-10 %. Importantly, this progressive overload stimulus was applied only when participants demonstrated good technical competency and loads were reduced if technique could not be maintained. More intense and higher velocity movements were introduced, including: plyometric exercises (e.g. drop jumps) and sprinting races over 10-15 m. It should be noted that rest periods in term 1 were typically lower (≤ 60 seconds) due to the lower loads prescribed, but increased in terms 2 and 3 (≤ 2 minutes) to ensure gymnasts were sufficiently recovered from the more intense training stimulus (57).

Annual Training Plan																																																				
Week No.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48				
Week beginning	03-Sep	10-Sep	17-Sep	24-Sep	01-Oct	08-Oct	15-Oct	22-Oct	29-Oct	05-Nov	12-Nov	19-Nov	26-Nov	03-Dec	10-Dec	17-Dec	24-Dec	31-Dec	07-Jan	14-Jan	21-Jan	28-Jan	04-Feb	11-Feb	18-Feb	25-Feb	04-Mar	11-Mar	18-Mar	25-Mar	01-Apr	08-Apr	15-Apr	22-Apr	29-Apr	06-May	13-May	20-May	27-May	03-Jun	10-Jun	17-Jun	24-Jun	01-Jul	08-Jul	15-Jul	22-Jul	29-Jul				
School Holidays									Half term								Holidays	Holidays								Half term							Holidays	Holidays											Holidays	Holidays						
University term dates	Holidays	Holidays	Induction	Term 1												Holidays	Holidays	Holidays	Holidays	Term 2												Holidays	Holidays	Holidays	Term 3												Holidays	Holidays				
Macrocycle	MACROCYCLE 1																																																			
Period of Training	PREPARATION																TRANSITION	PREPARATION														TRANSITION	PREPARATION														TRANSITION					
Phases	GPP																	GPP								SPP									GPP																	
Competition																																																				
Scheduled Testing																																																				
Mesocycle Number	BLOCK 1				BLOCK 2				BLOCK 3				BLOCK 4				BLOCK 5				BLOCK 6				BLOCK 7				BLOCK 8				BLOCK 9				BLOCK 10				BLOCK 11											
Mesocycle Theme	MOVEMENT								1/2 Term (Transition)	BASE STRENGTH								School holidays	BASE STRENGTH								1/2 Term (Transition)	STRENGTH/POWER								School holidays	STRENGTH				1/2 Term (Transition)	MAX STRENGTH & POWER								School holidays		
Block Goals	Observe and assess movement capabilities; games-based activities and fun challenges; introduction to a variety of athletic motor skill competencies; explore "S&C" positions and end ranges									Introduction to lifting area; build strength on movement competency developed in the first 2 blocks using compound lifts; maintain fun but familiarise with recognised "S&C" focused activities									Recap on technical competencies; seek further developments in strength; introduce girls to self-monitoring; prescribe individual work-ons following testing/injury history									Continue with an emphasis on developing strength; introduction to more advanced plyometrics; introduction to weightlifting derivatives									Focus on strength development following the Easter break; targeted prescription based on %RM					Lower rep ranges (3-5) for strength development work and power-based exercises (plyos and loaded squat jumps); ongoing maintenance of individual work-ons and targeted hamstring/core work										
Projected Int. (RPE)	4	4		5	5	6	6	7		6	7	7	8	8	6	5	7		8	8	7	8	8	7	8	8		7	8	9	8	9	9	6	6		8	8	9	9		8	8	9	9	9	6					
Predicted Vol. (Reps)	M	M		M	M	H	H	H		MH	MH	M	M	M	ML	MH	MH		MH	M	M	M		MH	M	ML		ML	L		MH	M	ML	ML	L			MH	M	M		ML	ML	L								

Figure 1. 10-month training plan for the GYM+NMT group

Table 2. Term 1 training program for the GYM+NMT group

Training emphasis	Block No.	Weeks	Ex No.	Session 1 exercises	Sets	Reps	Session 2 exercises	Sets	Reps
Movement competency	1	1-2	1	Countermovement squat	2	10	Glute/hamstring bridges	2	10
			2	Clams (MB)	2	10	Bilateral RDL (hinge to touch wall)	2	10
			3	ISO squat hold	2	10s	Bear position foot slides (object on back)	2	10
			4	Deadbugs (PW)	2	10	Split squat ISO hold (10s)	2	10
			5	Crab shape foot high fives (PW)	2	10	TRX supine row (45-degree body angle)	2	10
			6	Side plank, jump over & stick (PW)	2	10	Push ups (hands raised if needed)	2	10
		3-4	1	Back squat with dowel	2	10	Glute/hamstring bridges > feet raised	2	10
			2	Side lying lateral leg raise (MB)	2	10	RDL with wooden dowel on back	2	10
			3	Goblet squat ISO hold – (KB)	2	10s	KB deadlift	2	10
			4	Box jump + drop landing (5 of each)	2	10	Split squat (dynamic)	2	10
			5	SL vertical hop & stick (5 ES)	2	10	TRX supine row (progress if capable)	2	10
			6	Mini vertical pogo hops	2	10	Push ups (progress if capable)	2	10
	2	5-6	1	Back squat (5kg training bar)	3	10	SL glute bridge	3	10
			2	Monster walks (MB)	3	10	RDL (use wooden dowel like a bar)	3	10
			3	KB goblet squat	3	10	KB deadlifts (use wall to hinge to)	3	10
			4	Reverse lunge (10 ES)	3	20	SL squat - 1 leg down, 2 feet up (5 ES)	2	10
			5	Kneeling pallof press (take band out & in) 5ES	2	10	Half handstand position ISO hold	2	10s
			6	Swiss ball rollout (on knees elbows on ball)	2	8	Band pull down (lying down)	2	8
		7-8	1	Back squat (5kg training bar)	3	10	Glute bridge marches	3	10
			2	Prone glute/hamstring leg raise	3	10	RDL (5kg training bar)	3	10
			3	KB goblet squat	3	10	KB deadlifts (without wall)	3	10
			4	Forward lunge (10 ES)	3	20	Single squat – TRX (5 ES)	3	10
			5	Horizontal jump and stick	3	5	Controlled calf raises	3	10
			6	Pogo hops	3	5	Front & side plank perturbations (PW)	2	20
Half term (week 9)									
Strength	3	10-12	1	Back squat to box (in rack)	3	10	Barbell deadlift (upward phase only)	3	10
			2	Mid-thigh pull (ISO)	3	10s	RDL (barbell)	3	10
			3	Split squat (8 ES)	3	16	SL squat to box (8 ES)	3	16
			4	Deadbugs (opposite arm to leg)	3	10	Pallof press – athletic position (5 ES)	3	10
			5	Push up	2	10	Banded pull ups	2	10
			6	Supine row with bar	2	10	Side plank ISO hold	2	30s
	4	13-15	1	Back squat no box	3	8	Barbell deadlift (up and downward phase)	3	8
			2	Mid-thigh pull (ISO)	3	5s	Bulgarian split squat	3	16
			3	Split squat (8 ES)	3	16	Swiss ball rollout (on knees elbows on ball)	3	10
			4	Deadbugs (Arms & legs together)	3	8	Swiss ball hamstring curl	3	10
			5	Push up > progress	3	8	Side plank ISO	3	30s
			6	Supine row with bar > progress	3	8	Half handstand position push ups	2	8
Testing session 2 (week 16): Winter holidays (weeks 17-18)									

MB = mini band; PW = partner work; KB = kettlebell; ES = each side; ISO = isometric

Table 3. Term 2 training program for the GYM+NMT group

Training emphasis	Block No.	Weeks	Ex No	Session 1 exercises	Sets	Reps	Session 2 exercises	Sets	Reps
Strength	5	19-22	1	Individual exercise e.g. KB squat	3	8	Individual exercise e.g. horizontal jump & stick	3	5
			2	Individual exercise e.g. squat jump (3s pause)	3	5	Individual exercise e.g. ISO mid-thigh pull	3	5
			3	Barbell deadlift	3	8	Back squat	3	8
			4	KB Bulgarian split squat (8 ES)	3	16	RDL	3	8
			5	Press up (individual variations)	3	8	KB split squat	3	16
			6	TRX row (individual variations)	3	8	Side plank (individual variations)	2	30s
	6	23-25	1	Individual exercise e.g. KB squat jump	3	5	Individual exercise e.g. Repeated horizontal jumps	5	2
			2	Individual exercise e.g. repeated CMJs	3	5	Individual exercise e.g. KB deadlift	3	8
			3	Barbell deadlift*	3	8	Back squat	3	8
			4	Step up (8 ES)	3	16	RDL	3	8
			5	Band assisted pull ups	3	8	SL glute bridge (8 ES)	3	16
			6	Half handstand position press ups	3	8	Rolling plank	3	30s
Half term (week 26)									
Strength & power	7	27-29	1	Technique – drop catch for cleans	3	5	Technique – drop snatch + 3 x overhead squats	4	3
			2	Individual exercise – e.g. max hopping	3	5	Individual exercise e.g. KB jump squat	5	3
			3	Front squat	4	6	Trap bar deadlifts	4	6
			4	Glute/hamstring sliders (bilateral)	3	8	Jump shrug	4	4
			5	Split squat (barbell) 6 ES	4	12	Step up (individual variations) 6 ES	3	12
			6	Neutral grip pull ups (band if needed)	3	8	Rollouts on knees	3	8
			7	Banded overhead press	3	8	Side plank + leg lift (5 ES)	3	10
	8	30-32	1	Technique – jump shrug x 2 > catch in front squat	3	3	Technique – drop snatch + 3 x overhead squats	4	3
			2	Individual exercises – e.g. drop jumps	3	5	Individual exercise e.g. KB jump squat	5	3
			3	RDL	4	6	Trap bar deadlifts	4	6
			4	SL squat to box (KB) 6 ES	3	12	Barbell jump squat	4	4
			5	Glute hip lift lying prone over box	3	12	Step up (6 ES)	3	12
			6	Chin ups	3	8	Pallof press split stance (8 ES)	3	16
			7	Barbell overhead press	3	8	Side plank + leg lift (6 ES)	3	12
Testing session 3 (week 32); Spring holidays (weeks 33 and 34)									

MB = mini band; PW = partner work; KB = kettlebell; ES = each side; ISO = isometric; * = target load given

Table 4. Term 3 training program for the GYM+NMT group

Training emphasis	Block No.	Weeks	Ex No.	Session 1 exercises	Sets	Reps	E Session 2 exercises	Sets	Reps
Strength	9	35-38	1	Hang clean	3	3	Drop jump	4	3
			2	Back squat*	4	6	Barbell deadlift*	4	6
			3	Band assisted Nordic	4	6	Jump squat	4	4
			4	SL hip thrust (6 ES)	3	12	SL side step up - downward phase (6 ES)	3	12
			5	Push up (individual variations > loaded)	4	6	Superman's (individual variations)	3	10
			6	TRX row (individual variations)	4	6	Side plank leg lift (individual variations)	3	10
			7	Individual exercise e.g. box jump max height	3	3	Pull ups (individual variations)	3	5
Half term (week 39)									
Max strength/power	10	40-42	1	Sprint speed races	3	4	Drop jump (individual height)	3	3
			2	Hang > jump shrug*	5	5	Barbell or trap bar deadlift*	5	5
			3	Back squat*	4	5	Pin squat	3	5
			4	Jump squat	3	5	Reverse lunge (5 ES)	3	10
			5	Nordic	4	6	Front support shoulder taps (object on back)	3	10
			6	SL step up – downward phase (6 ES)	3	12	SL hip thrust (5 ES)	3	10
			7	Wide grip pull up	3	5	Side plank leg lift (individual variations)	3	10
	11	43-46	1	Hang > jump shrug*	3	5	Sprint speed races	3	5
			2	Back squat*^	4	5	Drop jump (individual height)	4	3
			3	Repeated CMJs^	3	5	Barbell or trap bar deadlift*	5	5
			4	Jump squat	3	5	Pin squat	3	5
			5	Reverse lunge (6 ES)	3	12	Explosive step up hop – land bilateral (6 ES)	3	12
			6	Nordic	3	5	Bear position shoulder taps (object on back)	3	12
			7	Wide grip pull up	4	6	Side plank leg lift (individual variations)	3	12
Testing session 4 (week 46-47): Summer holidays (47 onwards)									

MB = mini band; PW = partner work; KB = kettlebell; ES = each side; ISO = isometric; * = target load given; ^ = superset

7.2.3 Statistical Analyses

Descriptive statistics (means \pm *sd*) were calculated for all variables at each testing session (4-, 7- and 10-months) for each group. A 3 x 4 (group x time) repeated measures analysis of covariance (ANCOVA) with PAH as a covariate was used to determine the effectiveness of the training program for each variable. “Group” refers to GYM+NMT, GYM or CON, and ‘time’ denotes each quarterly testing session at 0-, 4-, 7- and 10-months. The assumption of normality was assessed via the Shapiro-Wilk test. Sphericity was assessed using Mauchly’s Test and where violated, a Greenhouse-Geisser adjustment was implemented. Bonferroni post-hoc analysis was used to identify any significant between- and within-group differences ($p < 0.05$). Hedges’ *g* effect sizes were calculated to interpret the magnitude of between- and within-group effects (106). The following effect size thresholds were used: 0.20 (trivial), 0.20–0.59 (small), 0.60–1.19 (moderate), 1.20–1.69 (large), and 1.70 (very large). Statistical significance was determined as $p < 0.05$, while all statistical analyses were computed using SPSS v.26.

7.4 RESULTS

No significant differences were present at baseline between the three groups for anthropometric data or maturity status (*table 1*). There were no significant differences between the GYM+NMT and GYM groups for the mean number of gymnastics-specific training hours per week. All gymnasts in the GYM+NMT exceeded the required attendance level of $\geq 80\%$ of total sessions across the 10-month training period.

Isometric mid-thigh pull

Mean (\pm *sd*) changes, effect sizes and interactions in IMTP kinetics are shown in *Figure 2*. There were no significant differences between groups at baseline for PF_{abs} or PF_{rel} . Analysis revealed a significant main effect for group, but not time, in PF_{rel} only. A significant group x

time interaction for both PF_{abs} and PF_{rel} variables was found. Data indicated significant, moderate increases in PF_{abs} in the GYM+NMT group from baseline to each subsequent testing session and in PF_{rel} , from 0-7 months and 0-10 months. Conversely, no significant changes in PF_{abs} or PF_{rel} were evident in the CON group during the study period, and only a small significant increase in PF_{abs} was shown between 0-10 months in the GYM group.

Countermovement jump, drop jump and standing long jump

Mean ($\pm sd$) changes, effect sizes, main effects and interactions for CMJ, DJ and SLJ variables are displayed in *tables 5 and 6 and figure 3*. *Figure 3* depicts changes in JH, CT and RSI for the DJ. While the CMJ results showed a significant main effect for group for JH and PF_{rel} , no significant main effects were found for time. Similarly, there were no significant group x time interactions detected for any of the CMJ variables. Baseline data revealed that only JH was significantly greater in the GYM+NMT and GYM groups compared to the CON group. Data showed that JH and $Impulse_{brake}$ in the CMJ significantly increased from 0-7 months in the GYM+NMT group, while $Impulse_{prop}$ showed small significant increases from baseline to each subsequent testing session. A small significant increase in $Impulse_{prop}$ was found from 0-7 months in the GYM group (0-7 months), but no significant changes were found in the CON group for any CMJ variable.

Significant main effects for group for SLC, RSI, JH and CT were revealed in the DJ; however, no significant main effects were found for time. Significant group x time interactions were present in SLC, RSI and JH only. DJ data revealed that RSI was significantly greater in the GYM+NMT and GYM groups compared to the CON group at baseline. Additionally, JH in the GYM group was significantly higher at baseline compared to the CON group. SLC data showed a moderate significant increase from 0-10 months in the GYM+NMT and GYM

groups, while the CON group moderately decreased SLC between 0-7 months. Significant, moderate improvements in JH and RSI were observed from 0-7 months and 0-10 months in the GYM+NMT group only. No significant changes were found for the GYM or CON groups for RSI or JH. All changes in $\text{Stiffness}_{\text{rel}}$, ΔCOM , PF_{abs} and CT were non-significant and the majority of effect sizes were trivial or small.

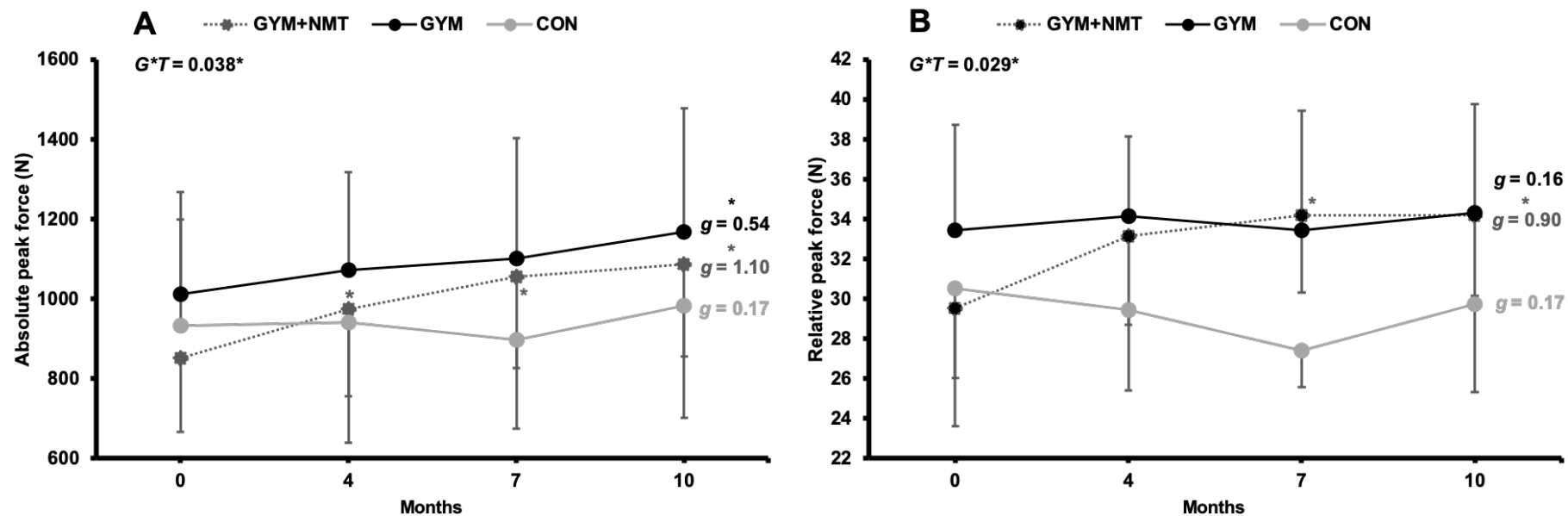


Figure 2. Group mean values for IMTP variables and within-group differences (A = PF_{abs} and B = PF_{rel}); * = sig. increase from baseline; $G*T$ = sig. group x time interaction; g = effect size from baseline to 10-months

Table 5. Group mean values (\pm SD) for CMJ and DJ variables, effect sizes from baseline to 10-months, main effects and interactions for within-group differences

Test	Variable	Group	Group differences				Effect size (Hedges g)			Main effects & interactions	
			T1	T2	T3	T4	T1-T2	T1-T3	T1-T4		
CMJ	JH (m)	GYM+NMT	0.19 \pm 0.03	0.19 \pm 0.04	0.20 ^b \pm 0.03	0.18 \pm 0.03	0.21	0.44	0.10	<i>T</i>	0.292
		GYM	0.20 \pm 0.04	0.20 \pm 0.04	0.20 \pm 0.04	0.19 \pm 0.04	0.22	0.03	0.29	<i>G</i>	0.000*
		CON	0.15 \pm 0.03	0.14 \pm 0.03	0.14 \pm 0.03	0.15 \pm 0.03	0.22	0.20	0.20	<i>G*T</i>	0.184
	Impulse _{brake} (Ns)	GYM+NMT	24.66 \pm 7.78	30.69 \pm 9.82	32.52 ^b \pm 12.53	25.07 \pm 28.50	0.66	0.73	0.02	<i>T</i>	0.704
		GYM	29.29 \pm 18.05	33.44 \pm 11.40	31.52 \pm 17.98	32.59 \pm 20.39	0.27	0.12	0.17	<i>G</i>	0.893
		CON	27.18 \pm 11.55	22.76 \pm 7.31	28.57 \pm 7.69	26.83 \pm 7.20	0.44	0.14	0.04	<i>G*T</i>	0.380
	Time _{brake} (s)	GYM+NMT	0.403 \pm 0.218	0.387 \pm 0.335	0.309 \pm 0.067	0.380 \pm 0.190	0.06	0.57	0.11	<i>T</i>	0.229
		GYM	0.508 \pm 0.368	0.319 \pm 0.096	0.371 \pm 0.265	0.358 \pm 0.305	0.69	0.42	0.43	<i>G</i>	0.463
		CON	0.312 \pm 0.096	0.345 \pm 0.164	0.337 \pm 0.195	0.275 \pm 0.081	0.24	0.16	0.40	<i>G*T</i>	0.454
	Impulse _{prop} (Ns)	GYM+NMT	55.64 \pm 15.38	59.94 ^a \pm 16.05	63.53 ^b \pm 18.10	62.02 ^c \pm 17.89	0.21	0.40	0.31	<i>T</i>	0.194
		GYM	63.34 \pm 16.38	63.65 \pm 17.95	66.87 ^b \pm 18.99	66.14 \pm 19.26	0.13	0.30	0.26	<i>G</i>	0.506
		CON	53.39 \pm 12.93	52.16 \pm 12.94	53.41 \pm 18.85	55.35 \pm 13.45	0.09	0.00	0.14	<i>G*T</i>	0.380
	Time _{prop} (s)	GYM+NMT	0.230 \pm 0.035	0.246 \pm 0.089	0.245 \pm 0.065	0.335 \pm 0.128	0.24	0.28	0.66	<i>T</i>	0.539
		GYM	0.301 \pm 0.142	0.276 \pm 0.044	0.256 \pm 0.096	0.285 \pm 0.161	0.24	0.37	0.11	<i>G</i>	0.277
		CON	0.256 \pm 0.059	0.230 \pm 0.051	0.197 \pm 0.123	0.245 \pm 0.049	0.45	0.59	0.18	<i>G*T</i>	0.331
	PF _{abs} (N)	S&C + GYM	438.08 \pm 147.98	493.62 \pm 186.54	476.71 \pm 151.50	437.40 \pm 121.29	0.32	0.25	0.00	<i>T</i>	0.717
		GYM ONLY	397.19 \pm 91.42	388.32 \pm 105.86	487.04 \pm 130.96	477.56 \pm 104.63	0.09	0.77	0.80	<i>G</i>	0.066
		CON	364.98 \pm 71.61	389.92 \pm 100.80	419.62 \pm 116.54	372.57 \pm 95.93	0.28	0.55	0.09	<i>G*T</i>	0.113
	PF _{rel} (N·kg ⁻¹)	GYM+NMT	14.91 \pm 3.73	16.59 \pm 5.86	15.63 \pm 5.28	13.75 \pm 2.97	0.33	0.25	0.34	<i>T</i>	0.485
		GYM	13.22 \pm 2.24	12.27 \pm 2.13	14.90 \pm 3.28	14.62 \pm 3.56	0.43	0.38	0.46	<i>G</i>	0.006*
		CON	12.26 \pm 2.35	12.79 \pm 2.87	12.94 \pm 3.16	11.52 \pm 2.49	0.19	0.02	0.46	<i>G*T</i>	0.082
DJ	SLC	GYM+NMT	-0.90 \pm 0.06	-0.94 \pm 0.03	-0.94 \pm 0.04	-0.96 ^c \pm 0.03	0.71	0.72	1.15	<i>T</i>	0.154
		GYM	-0.88 \pm 0.01	-0.92 \pm 0.05	-0.93 \pm 0.04	-0.93 ^c \pm 0.03	0.41	0.59	0.63	<i>G</i>	0.023*
		CON	-0.92 \pm 0.04	-0.89 \pm 0.06	-0.85 ^g \pm 0.09	-0.89 \pm 0.06	0.51	0.92	0.47	<i>G*T</i>	0.001*
	Stiffness _{Rel} (BW·m ⁻¹)	GYM+NMT	17.84 \pm 8.55	16.57 \pm 8.57	18.72 \pm 7.45	16.59 \pm 6.63	0.14	0.11	0.16	<i>T</i>	0.518
		GYM	19.83 \pm 11.61	17.53 \pm 6.33	17.88 \pm 9.46	18.87 \pm 6.08	0.24	0.18	0.10	<i>G</i>	0.210
		CON	14.02 \pm 4.90	14.81 \pm 3.76	15.34 \pm 4.49	15.34 \pm 4.49	0.17	0.27	0.49	<i>G*T</i>	0.617
	Δ COM (cm)	GYM+NMT	11.46 \pm 4.32	11.19 \pm 3.31	9.56 \pm 2.50	10.76 \pm 2.79	0.07	0.53	0.19	<i>T</i>	0.367
		GYM	10.99 \pm 3.74	10.84 \pm 2.59	10.70 \pm 3.28	10.88 \pm 3.64	0.05	0.08	0.03	<i>G</i>	0.715
		CON	10.70 \pm 2.61	10.45 \pm 2.95	10.45 \pm 3.14	12.48 \pm 2.53	0.08	0.08	0.69	<i>G*T</i>	0.196
	PF _{abs} (N)	GYM+NMT	1594.43 \pm 548.04	1494.23 \pm 440.01	1450.96 \pm 444.10	1561.24 \pm 325.28	0.20	0.28	0.07	<i>T</i>	0.834
		GYM	1731.35 \pm 592.30	1646.43 \pm 394.21	1604.09 \pm 466.81	1648.58 \pm 490.99	0.16	0.23	0.15	<i>G</i>	0.192
		CON	1294.00 \pm 539.57	1388.58 \pm 348.77	1345.29 \pm 348.18	1329.63 \pm 254.19	0.25	0.14	0.41	<i>G*T</i>	0.877

^a = sig. increase from T1-T2; ^b = sig. increase from T1-T3; ^c = sig. increase from T1-T4; ^g = sig. increase from T2-T4; = sig. greater than control at baseline[#] = sig. greater than the S&C + GYM group at baseline; Effect size: trivial = <0.20; small = 0.20-0.59; moderate = 0.60-1.19; * = sig. difference; *T* = main effect for time; *G* = main effect for group; *G*T* = group x time interaction

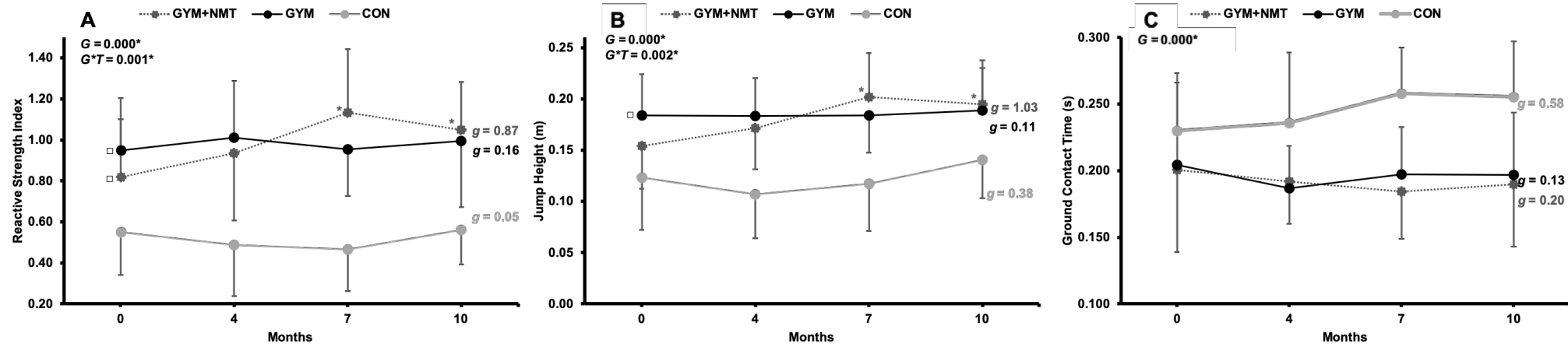


Figure 3. Group mean values for DJ variables and within-group differences (A = RSI, B = JH and C = GCT); = sig. greater than CON group at baseline; * = sig. increase from; G = sig. main effect for group; $G*T$ = sig. group x time interaction; g = effect size from baseline to 10-months

Analysis revealed a significant main effect for group but not time, as well as a significant group x time interaction for SLJ distance. Both the GYM+NMT and GYM groups jumped significantly further than the CON group at baseline. Similarly, SLJ distance in the GYM group was significantly greater than the GYM+NMT group at baseline. Data showed moderate, significant increases in SLJ distance in the GYM+NMT at each time point from baseline, while no changes were found in the GYM and CON groups.

20 m sprint

Mean (\pm *sd*) changes, effect sizes, main effects and interactions for the 20 m sprint variables are shown in *table 6*. Significant main effects for group and time were found for Peak_{speed}. Data showed significant moderate increases in Peak_{speed} in the GYM+NMT from 0-10 months. Analysis revealed significant, trivial to small increases in Peak_{momentum} in the GYM+NMT group from baseline to each subsequent testing session. A significant, trivial increase in Peak_{momentum} was found for the GYM group from 0-4 months.

Table 6. Group mean values (\pm SD) for SLJ and 20m sprint variables, effect sizes from baseline to 10-months, main effects and interactions for within-group differences

Test	Variable	Group	Group differences				Effect size (Hedges g)			Main effects & interactions	
			T1	T2	T3	T4	T1-T2	T1-T3	T1-T4		
SLJ	Distance (m)	GYM+NMT	1.53 \pm 0.12	1.63 ^a \pm 0.13	1.65 ^b \pm 0.17	1.69 ^{ce} \pm 0.16	0.77	0.85	1.14	<i>T</i>	0.202
		GYM ONLY	1.66 [#] \pm 0.18	1.71 \pm 0.21	1.60 \pm 0.26	1.67 \pm 0.23	0.26	0.23	0.09	<i>G</i>	0.000*
		CON	1.23 \pm 0.16	1.28 \pm 0.13	1.27 \pm 0.13	1.29 \pm 0.14	0.32	0.24	0.39	<i>G*T</i>	0.000*
20 m Sprint	Peak _{speed} (m·s ⁻¹)	GYM+NMT	5.79 \pm 0.46	5.91 \pm 0.46	6.03 \pm 0.53	6.14 ^{ce} \pm 0.46	0.26	0.47	0.74	<i>T</i>	0.045*
		GYM	6.04 \pm 0.57	6.01 \pm 0.53	5.97 \pm 0.51	6.24 ^e \pm 0.51	0.05	0.12	0.36	<i>G</i>	0.005*
		CON	5.54 \pm 0.63	5.40 \pm 0.54	5.38 \pm 0.59	5.67 ^e \pm 0.67	0.24	0.26	0.20	<i>G*T</i>	0.133
	Peak _{momentum} (kg·m·s ⁻¹)	GYM+NMT	170.81 \pm 43.09	176.29 ^a \pm 44.28	188.92 ^{bd} \pm 48.68	222.34 ^{ce} \pm 111.54	0.12	0.38	0.59	<i>T</i>	0.795
		GYM	184.90 \pm 54.01	190.45 ^a \pm 52.82	197.30 \pm 54.57	214.38 \pm 61.72	0.10	0.22	0.49	<i>G</i>	0.922
		CON	170.05 \pm 50.22	172.52 \pm 49.39	177.66 \pm 49.43	190.23 \pm 59.02	0.05	0.26	0.36	<i>G*T</i>	0.497

^a = sig. increase from T1-T2; ^b = sig. increase from T1-T3; ^c = sig. increase from T1-T4; ^d = sig. increase from T2-T3; ^e = sig. increase from T2-T4; ^f = sig. increase from T3-T4; ^g = sig. decrease from T1-T2; ^h = sig. decrease from T1-T3; Effect size: trivial = <0.20; small = 0.20-0.59; moderate = 0.60-1.19; [#] = sig. greater than control at baseline; [^] = sig. less than control at baseline; * = sig. difference; *T* = main effect for time; *G* = main effect for group; *G*T* = group x time interaction

Vaulting

Mean (\pm *sd*) changes, effect sizes, main effects and interactions for all vaulting variables are displayed in *figure 4*. Significant main effects for group were found in all vaulting variables but not for time. Data showed significant interactions for group x time in vertical take-off velocity and Ratio_{vert-horiz}. At baseline, vertical take-off velocity and JH were significantly greater in the GYM+NMT and GYM groups compared to the CON group, and their springboard CT was significantly faster. The GYM+NMT group significantly improved take-off velocity and Ratio_{vert-horiz} measures with moderate effect sizes from 0-10 months, whilst neither the GYM or CON groups significantly changed. Moderate, significant increases in JH were also identified in the GYM+NMT between 0-7 months and 0-10 months. No changes in springboard CT were present for any group and all effect sizes were trivial or small.

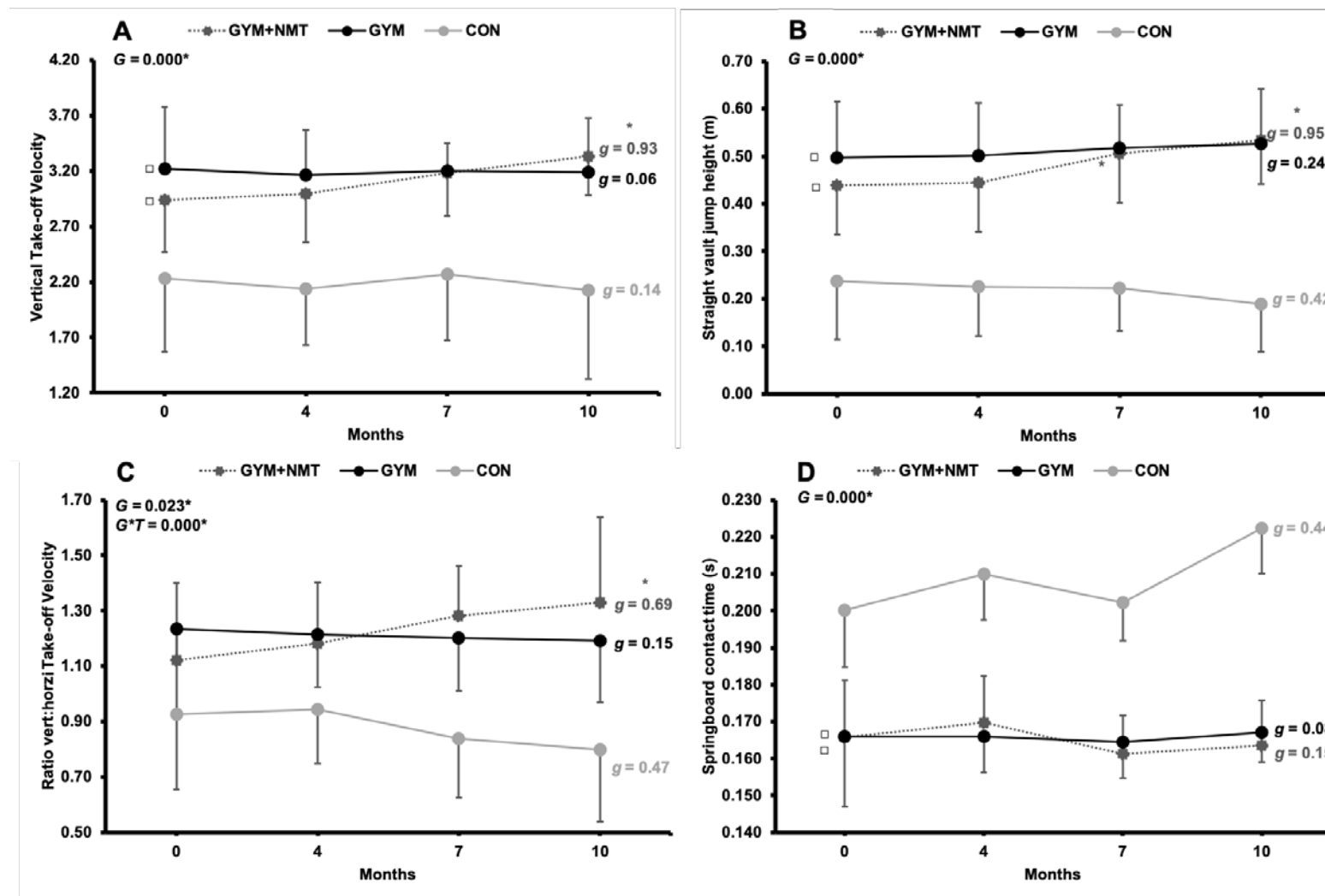


Figure 4. Group mean values for Vaulting variables and within-group differences (A = Vertical take-off velocity, B = JH, C = Ratio_{vert-horzi} and D = CT); □ = sig. greater than CON group at baseline; * = sig. increase from baseline; G = sig. main effect for group; $G*T$ = sig. group x time interaction; g = effect size from baseline to 10-months

7.4 DISCUSSION

The main findings of this study have shown that young female gymnasts significantly improved various kinetic determinants of strength and power, sprint speed and vaulting take-off velocity after participating in 10-months of supplementary NMT; changes that were not typically evident in the GYM group. In instances where the GYM group experienced positive improvements (isometric PF_{abs} , SLC in the DJ and $Peak_{momentum}$ in sprinting), similar gains were also observed in the GYM-NMT group. Notably, the CON group did not experience any significant changes for any variable during the intervention period. Therefore, the initial hypothesis that the addition of NMT to regular gymnastics training would result in significantly greater improvements in kinetic determinants of strength and power, sprint speed and vaulting take-off velocity, than either gymnastics training or controls is accepted. Notably, the observed adaptations in the GYM+NMT group occurred at different stages of the 10-month training program and varied in magnitude. Isometric PF_{abs} , horizontal jump distance and $Peak_{momentum}$ during sprinting significantly improved at each testing session from baseline. After 7-months of NMT, significant improvements were shown in isometric PF_{rel} , CMJ height and RSI and jump height in the DJ. The NMT stimulus took longer to transfer to sprinting and vaulting performance, with peak sprint speed, spring-like behaviour in the DJ, and vaulting vertical take-off velocity significantly improving after 10-months. Overall, these results indicate that supplementary NMT can stimulate improvements in strength, power, speed and vaulting performance above and beyond those achieved through gymnastics training alone. It also appears that adaptations in strength, power, speed and vaulting are time sensitive, and that establishing movement competency and developing muscular strength serve as the foundations upon which further gains in power, speed and vaulting performance can be realised.

Novel data from this study show that twice-weekly NMT can lead to significant, moderate increases in absolute and relative isometric force producing capabilities in young gymnasts after 4- and 7-months of training, respectively. In comparison, gymnastics-training alone was not able to significantly improve PF_{rel} and only elicited a small significant increase in PF_{abs} after 10-months, which was likely driven by changes in size. Conversely, any changes in IMTP variables in the CON group were non-significant and trivial. Cumulatively, these findings indicate that supplementary NMT can enhance isometric PF_{abs} and PF_{rel} beyond the stimulus provided from gymnastics-only training; however, longer periods of training (>7 months) are needed to realise the adaptations in PF_{rel} . Interestingly, previous data indicate that isometric PF_{rel} remains relatively unchanged from the pre-pubertal to pubertal years in young female gymnasts ($d = 0.15$) (205); which could indicate that natural development and sport-specific training alone do not provide an adequate stimulus to promote ongoing adaptations in relative strength as young female gymnast transition towards puberty. However, the current study has shown that relative strength is trainable during this stage of development, with significant, moderate gains apparent after 7-months of NMT. Thus, exposure to NMT appears to be necessary to foster the ongoing development of relative strength in young female gymnasts.

Whilst comparable data in young gymnasts is unavailable, the present study supports the findings of a meta-analysis in youth athletes; whereby, longer-term training periods (>23 weeks) and higher intensities of resistance training were most effective for increasing muscular strength (149). Given that the GYM+NMT group had no previous experience of NMT, term 1 focused primarily on developing movement competency with higher volumes but relatively lower training intensities. Therefore, the significant improvements in relative isometric strength observed later in the intervention, likely reflects the groups' exposure to a greater strength stimulus resulting from higher loading schemes with resistance-training in terms 2 and

3. Given the pre-pubertal maturity status of the GYM+NMT cohort, it is plausible that the training-induced gains in strength were driven by primarily neuromuscular factors, such as increases in motor unit co-ordination, recruitment and firing frequency (70, 91).

Supplementary NMT appears to be a more effective training stimulus than solely gymnastics-training for enhancing gymnasts' jumping performance; as evidenced by the NMT+GYM groups displaying significant improvements in numerous variables across the tests, whilst the GYM group only significantly improved SLC and $\text{Impulse}_{\text{prop}}$ in the DJ and CMJ tests, respectively. Additionally, no changes were observed in the CON group for any of the jumping tests. However, the positive changes observed in the NMT+GYM groups' jumping performance appear to be time sensitive, with responses reflecting the specific training content of the NMT. Specifically, only the gymnasts' horizontal jumping distance increased significantly after 4-months of NMT, with training-induced gains in CMJ height and DJ spring-like behaviour and RSI more evident from seven months onwards. The increase in CMJ height between 0-7 months can be explained by the NMT+GYM group producing significantly greater amounts of both $\text{Impulse}_{\text{brake}}$ and $\text{Impulse}_{\text{prop}}$, which directly influences vertical jump height (138). More specifically, the data showed $\text{Impulse}_{\text{brake}}$ significantly increased whilst the $\text{Time}_{\text{brake}}$ decreased, albeit non-significantly. Interestingly, $\text{Impulse}_{\text{prop}}$ also significantly increased but $\text{Time}_{\text{prop}}$ seemed to remain the same. Previous research has shown training-induced increases in force during the braking phase of a jump squat contributed to improvements in the concentric phase of jump performance (i.e. force, velocity, JH) (46). The authors suggested that these changes positively influenced stretch-shortening cycle (SSC) mechanisms (e.g. the storage and reutilisation of elastic energy and potentiation of contractile elements) (46). Therefore, the findings in the current study indicate that between 0-7 months, the gymnasts in the NMT+GYM group were able to jump higher due to more effective

utilization of the SSC. For example, by absorbing the force more quickly during the braking phase, energy dissipation would be reduced while active state of the muscle increased, which would enable greater amounts of force to be produced during the propulsive phase.

Previous research has shown that 8-weeks of NMT was able to promote increases in both RSI and leg stiffness in certain individual female gymnasts (209). However, the number of positive responders that made improvements above the smallest worthwhile change was not significantly greater than would be expected by chance. It was recommended that longer training periods and more intense loading would be necessary to realise significant whole group changes (209). The current study showed moderate, significant increases in DJ RSI and JH were elicited from 7 months onwards in the NMT+GYM group, whilst no changes were observed in the GYM or CON groups. The positive changes in RSI induced by the NMT stimulus were driven by moderate, significant increases in DJ height and small, non-significant reductions in GCT, a desirable training-effect not observed in the GYM or CON groups. Notably, the GYM+NMT and the GYM groups both enhanced DJ spring-like behaviour after longer training periods (i.e. > 10-months); however, effect sizes revealed a greater magnitude of change was elicited with the supplementary NMT ($g = 1.15$). As both groups displayed good spring-like behaviour ($r = > 0.93$), this suggests effective SSC mechanisms were utilised to facilitate storage and reutilization of elastic energy within connective tissues (242, 243). However, recent data in male youth categorised as having good, moderate or poor SSC function, has shown that being spring-like during the DJ does not necessarily influence the JH achieved (243). Examination of DJ kinetic determinants in the current study indicates that the NMT+GYM group showed PF_{abs} , $Stiffness_{rel}$ and ΔCOM did not significantly change from 0-10 months, despite the shorter GCT. Importantly, DJ strategies that minimize GCT but still maximize JH require force to be generated more quickly (i.e. rate of force development) if

Δ COM does not change (141, 243). Although speculative, the improvements in DJ height and RSI noted for the GYM+NMT group could be due to training-induced reductions in co-contraction or increases in preactivation, which could promote elastic energy reutilization and result in enhanced SSC-function (257). Cumulatively, these results suggest that young female gymnasts' jumping performance can benefit from longer-term training periods of NMT, which include a high strength stimulus (i.e. resistance training) alongside explosive movements (e.g. weightlifting) and those that specifically target enhancing SSC-function (i.e. plyometrics).

The NMT+GYM significantly increased sprinting $Peak_{speed}$ from baseline to 10-months, whilst $Peak_{momentum}$ data revealed significant increases from baseline to each subsequent testing session. Although only a significant change in $Peak_{speed}$ occurred after 10-months, small improvements were evident at each time point across the intervention period and these increases together with increases in body mass, were likely responsible for the significantly greater $Peak_{momentum}$. Conversely, no differences in $Peak_{speed}$ were observed in either the GYM and CON groups and only a trivial, significant increase in $Peak_{momentum}$ was found for the GYM group at 4-months. Previous data in young female gymnasts indicates that sprint speed plateaus between the late pre-pubertal and pubertal years, whilst $Peak_{momentum}$ continues to increase (208). Therefore, it appears that NMT is an effective training stimulus to enhance sprint speed in young gymnasts, although longer periods of training may be necessary to realise such improvements. Similarly, Karagianni et al. (132) showed no change in 10-m sprint performance after 10-weeks of strength and power training in female gymnasts, supporting the notion of gymnasts engaging in long-term training programmes to realise gains in speed. Conversely, one study reported a short-term supplementary plyometric programme was effective for improving young gymnasts' sprinting abilities, but did not significantly enhance squat, drop or standing long jump performance (17). These studies indicate longer-term and combined NMT

programmes are needed to ensure development across a range of athletic qualities in young gymnasts. In the current study, the final term of NMT training targeted further developments in strength, power and speed which involved higher loading schemes and/or higher velocity exercises. Consequently, various training modes were combined to promote adaptations in $Peak_{speed}$; including resistance training, plyometrics and speed training, all of which have previously been shown to be effective for enhancing sprinting in youth (149, 163, 184). Thus, the positive responses in the NMT+GYM groups' $Peak_{speed}$ were likely aligned to the periodised design of the training program (i.e. *Term 3* introduced sprint training). Notably, the increases in sprint $Peak_{speed}$ in the NMT+GYM group occurred concomitantly with the significant improvements in relative isometric strength, DJ spring-like behaviour and RSI. As the importance of these strength and power measures for sprinting performance in youth has been documented (197, 270), these improvements may have contributed to the faster sprint speed in the NMT+GYM groups.

Most previous gymnastics-based research has failed to evaluate the effectiveness of training interventions on sport-specific performance measures. Exposure to short-term plyometric training of 6-weeks has been shown to significantly enhance vaulting take-off velocity (100); however, the efficacy of long-term NMT and the interaction between training and maturation on vault performance were previously unknown. Novel findings from this study indicate that longer-term NMT can elicit significant improvements in vault jump height, take-off velocity and $Ratio_{vert-horiz}$; adaptations that were not seen in the GYM or CON groups. The importance of gymnasts achieving fast run-up speeds and take-off velocities for successful vaulting has been well-documented (24, 25, 208, 272), with recent data revealing $Peak_{speed}$ (~59%) and $Ratio_{vert-horiz}$ (12 %) combined explained a large proportion of the total variance in gymnasts' take-off velocity (208). It is therefore likely that the significant increases in $Peak_{speed}$ and

Ratio_{vert-horiz} that occurred only after 10-months of training, contributed to the NMT+GYM groups' improvements in vaulting take-off velocity.

The results from baseline testing and the positive changes found in the GYM group during the intervention period suggest that gymnastics-training alone can improve some aspects of strength, power and speed in young females. For example, at baseline DJ RSI was significantly lower in the CON group compared to both cohorts of gymnasts, indicating that either gymnasts are selected for their innate reactive strength capabilities and/or gymnastics-training itself develops these physical qualities (e.g. tumbling). In addition, both groups of gymnasts jumped significantly higher in the CMJ compared to the CON group. These data are in-line with numerous studies that have shown young gymnasts exhibit superior jumping abilities compared to non-gymnasts (12, 179, 180). Perhaps unsurprisingly, the gymnasts also displayed significantly greater vertical take-off velocities, jump heights and faster springboard CT at baseline, compared to the CON group. However, an important finding of this study is that whilst gymnastics-training alone appears to enhance strength, power and speed; the addition of NMT promotes even greater levels of these athletic qualities.

The current study has shown that supplementary, long-term NMT programmes can enhance various kinetic determinants of strength and power, sprint speed and vaulting take-off velocity beyond changes that result from gymnastics-training alone and/or growth and maturation. However, a key finding was that these changes were time sensitive; for example, the NMT programme took longer to elicit significant increases in isometric PF_{rel} compared to PF_{abs} . These data support the notion of young gymnasts engaging in long-term NMT to enhance relative muscular strength and not relying on maturation and/or gymnastics-training alone (88, 178, 205). Furthermore, the improvements in the NMT+GYM groups CMJ and DJ

performance, coincided with significant increases in relative isometric strength. Notably, movement competency and initial levels of muscular strength were developed during *term 1* and significantly increased isometric PF_{abs} , SLJ distance and $Peak_{momentum}$. In *term 2* the NMT sought to increase muscular strength further and begin to develop power with higher intensities of resistance training, weightlifting derivatives and plyometric activities and significantly increased isometric PF_{rel} , CMJ height and RSI and jump height in the DJ. The final term of NMT aimed to maximise strength and power as well as sprint speed and significant improvements in sprinting $Peak_{speed}$, spring-like behaviour in the DJ, and vaulting vertical take-off velocity were observed. Thus, the findings of the current study corroborate previous research which has emphasised the importance of developing muscular strength to enhance young athletes' abilities to express higher levels of power in athletic tasks (45, 283). It should be noted that a similar temporal response to the sprinting $Peak_{speed}$ results was observed in vaulting, whereby the NMT training-effect took longer to transfer to gymnasts' sports-specific performance (i.e. 10-months). Therefore, to facilitate safe and effective NMT programmes, movement competency and muscular strength should be developed in the early stages of the training, before seeking further adaptations in strength, power, speed and vaulting performance. Practitioners should work closely with technical coaches to design appropriately periodised and engaging NMT programmes that aim to enhance young female gymnasts' sports-specific performance and overall athleticism. These findings also underline how certain performance enhancements may take time to manifest and therefore, adopting a long-term approach with progressive overload and transitional periods to facilitate recovery, regeneration and growth are important for young athletes.

A potential limitation of the current study is that the effects of long-term NMT were not evaluated in young gymnasts in the post-pubertal stage of development. Previous research

indicates that young athletes can benefit from training strategies which complement the adaptations that might be occurring as a result of natural development, a notion termed ‘synergistic adaptation’ (163, 254). Therefore, the manner in which post-pubertal female gymnasts respond to a long-term NMT programme may differ. Future research should therefore investigate the efficacy of NMT on strength, power, speed and vaulting in post-pubertal female gymnasts.

7.5 CONCLUSION

This study aimed to compare the effects of a 10-month supplementary NMT training intervention on kinetic determinants of strength and power, sprint speed and vaulting take-off velocity in young female gymnasts, versus gymnastics-training only and a maturity-matched control. The main findings of this study were that significant, moderate improvements were elicited in young female gymnasts’ isometric strength, horizontal and vertical jumping performance, sprint speed and vaulting take-off velocity after participating in 10-months of supplementary NMT; changes that were not typically evident in the gymnastics only or control groups. Notably, these training-induced adaptations occurred at different time points across the intervention period and varied in magnitude. Overall, the majority of positive changes observed in relative strength, power, sprint speed and vaulting were stimulated after longer training periods (> 7-10-months), which reflected the long-term, periodised nature of the training program. Practitioners should initially prioritise the development of movement competency and muscular strength, as these athletic qualities serve as the foundations upon which further gains in power, speed and vaulting performance can be realised.

Chapter 8:

General discussion, limitations and directions for future research

8.1 OVERALL SUMMARY

The purpose of the current thesis was to investigate the influence of growth, maturation and training upon measures of strength, power and speed, and vaulting vertical take-off velocity in a sample of young female gymnasts. Reliability data revealed measures of peak force were highly reliable for both pre-PHV ($CV \leq 9.4\%$) and post-PHV ($CV \leq 7.3\%$) females, but pre-PHV girls required an additional familiarisation session. The combined body of works also furthers the knowledge of strength, power and speed development in young female gymnasts of varying maturity status; showing that isometric and dynamic measures of PF_{abs} and sprint speed increase with advancing maturity, whilst measures of PF_{rel} remain unchanged. Furthermore, studies from within the thesis demonstrate that across all tests, $Peak_{speed}$ from a 20 m sprint protocol had the highest predictive ability of vaulting vertical take-off velocity in young female gymnasts ($R^2 = 59\%$). However, data indicates that $Peak_{speed}$ increases between the early- and late-pre-pubertal years, before plateauing during the late pre-pubertal and pubertal stages of development. Finally, a supplementary long-term NMT stimulus can elicit positive changes in various kinetic determinants of strength and power, sprint speed and vaulting take-off velocity in young female gymnasts; changes beyond those achieved by gymnastics training alone and/or growth and maturation.

In order to explore and address existing gaps in the existing knowledge base, the current thesis outlined a series of aims in *Chapter 1* that were researched in the subsequent series of empirical studies (*Chapters 3-7*).

Aim 1: *Examine the within- and between-session reliability of the isometric mid-thigh pull protocol in pre- and post-PHV females.*

Whilst consensus exists for prioritising the training of muscular strength in children and adolescents (151, 152), valid and reliable data for assessments of maximal muscular strength were sparse. The IMTP is a force-time diagnostic tool for assessing the maximal force producing capacities of athletes and can provide insight into a range of kinetic variables. Although numerous variables from the IMTP test have been shown to be highly reliable in adult populations (43, 58, 97, 98), there was minimal research demonstrating its reliability in children and adolescents. Therefore, *Chapter 3* aimed to examine the within- and between-session reliability of IMTP force-time variables in pre- and post-peak PHV females.

An important finding was that within- and between-session measures of PF_{abs} and PF_{rel} were found to be highly reliable for both pre-PHV ($CV \leq 9.4\%$, $ICC \geq 0.87$) and post-PHV ($CV \leq 7.3\%$, $ICC \geq 0.92$) females, but systematic bias was evident between-sessions in the pre-PHV group from session 1 to 2. Force at specific sampling intervals were more variable in both cohorts, with CV between 19-37% and 5-24% for pre-PHV and post-PHV athletes, respectively. Overall, time-dependent and RFD-related variables had low reliability and therefore, practitioners should be more cautious when interpreting data using these variables. In general, kinetic variables were more reliable in post-PHV athletes compared to pre-PHV athletes, with the less mature cohort needing additional familiarization to minimize the influence of systematic bias. Cumulatively, this study showed that the IMTP was a reliable and safe method for evaluating peak force in young female athletes with a low training history. Additionally, the study established the typical errors for all IMTP variables, which would need

to be exceeded in order to confidently determine that meaningful changes had occurred as a result of growth, maturation or training.

Aim 2: *Investigate the influence of maturity status on isometric and dynamic force-time variables, SLJ performance, sprint speed and vaulting vertical take-off velocity in a large cohort of young female gymnasts*

Maximizing lower-limb strength, power and speed in artistic gymnastics is important for generating faster take-off velocities and longer flight times to enhance vaulting performance (25, 249). However, the development of these physical qualities follows a nonlinear process throughout childhood and adolescence (170). The majority of current research in young female gymnasts had examined changes based on chronological age as opposed to grouping gymnasts according to maturity status (24, 286). Maturity-related comparisons of strength, power and speed between young female gymnasts of differing maturity status were very limited and often restricted by the homogeneity or size of samples. Additionally, investigations into the mechanical variables underpinning jumping and rebounding performance were not present in the literature. The influence of maturity status on strength, power, speed and vaulting take-off velocities was therefore unclear.

Chapters 4-6 investigated differences in isometric and dynamic force-time variables, SLJ performance, sprint speed and vaulting vertical take-off velocity, in a sample of Early_{pre}, Late_{pre} and pubertal female gymnasts. *Chapter 4* showed that isometric PF_{abs} and absolute force at various sampling intervals increased with maturity, with the most mature cohort of gymnasts significantly able to produce more force than their more immature peers. However, when normalized to body mass, significant between-group differences in PF_{rel} and relative force at different sampling intervals were not evident. *Chapter 5* found that overall vertical jumping

performance improved with biological maturity, evidenced by the most mature gymnasts producing significantly more absolute force, impulse (braking and propulsive) and power than the least mature group, resulting in greater jump heights. While no significant differences were observed in PF_{rel} across multiple tests, measures of PP_{rel} did significantly increase with maturity. *Chapter 6* showed that sprinting variables (speed intervals, $Peak_{speed}$, $Peak_{momentum}$), horizontal jumping distance and vaulting vertical take-off velocity significantly increased with biological maturity. However, a plateau for sprint speed was evident between the late pre-pubertal and pubertal years. Overall, these studies demonstrated that in general, strength, power and speed variables increased with biological maturation in young female gymnasts; however, supplementary NMT may be required to promote ongoing gains at all stages of maturity.

Aim 3: *Determine the relationships between isometric and dynamic force-time variables, SLJ performance, sprint speed and vaulting take-off velocity in young female gymnasts.*

Of the available literature, investigations into predictors of vaulting performance in young female gymnasts had demonstrated the importance of faster run-up speeds and greater levels of squat jump power (24, 272). From a skill perspective, the visual targeting abilities of gymnasts during the approach run-up had been shown to positively influence vaulting performance (21). However, the contribution of biological maturity, isometric and dynamic force-time variables, SLJ performance, and sprint speed to vertical take-off velocity during vaulting was yet to be fully explored. Therefore, the aim of *chapters 4-6* were to identify relationships between isometric and dynamic force-time variables, sprint speed and vaulting take-off velocity in young female gymnasts.

The results of *chapter 4* demonstrated that force at 50 ms was the only IMTP variable to predict vaulting vertical take-off velocity, but accounted for just 15% of variance, thus a large

proportion of variance remained unexplained. However, an important finding from *chapter 5* was that maturation most strongly influenced vaulting vertical take-off velocity, evidenced by %PAH appearing in all regression equations and explaining $\sim 41\%$ of the variance in each jumping test. The drop jump protocol was found to have the highest predictive ability of all jumping tests; explaining 55% of the total variance; specifically, a shorter GCT ($R^2 = 10\%$) and a greater ΔCOM ($R^2 = 4\%$) were identified as the drop jump variables that explained the most variance. A key finding from the multiple regression analyses in *chapter 6* was that peak speed had the strongest association with vertical take-off velocity ($R^2 = 59\%$) and also the $\text{Ratio}_{\text{vert-hori}}$ was identified as a secondary determinant ($R^2 = 12\%$). Combined these two variables were able to explain the largest proportion of vaulting vertical take-off velocity across all of the studies, explaining 71% of the total variance. Cumulatively, these results highlighted the importance of developing high peak speeds and take-off technique (i.e. the transfer of linear speed to vertical take-off velocity) for vaulting performance.

Aim 4: *Establish the effects of a 10-month neuromuscular training programme on isometric and dynamic force-time variables, SLJ performance, sprint speed and vaulting vertical take-off velocity in young female gymnasts.*

Despite a growing body of evidence showing the efficacy of NMT in general youth populations (57, 223), whether similar improvements in fitness could be realised in young gymnasts who already participated in high volumes of gymnastics training was unclear. Furthermore, notable limitations of current gymnastics research were that the efficacy of training on gymnastics-specific measures (e.g. take-off velocity) were rarely included, and that often the maturity status of participants was not reported, meaning the interaction effects between training and maturation were unknown. Thus, the aim of *chapter 7* was to investigate the effects of a 10-

month NMT programme on various determinants of strength and power, sprint speed and vaulting vertical take-off velocity in young female gymnasts.

The results of *chapter 7* showed that supplementary NMT can stimulate improvements in strength, power, speed and vaulting performance above and beyond those achieved through gymnastics training alone or growth and maturation. However, a key finding was that the observed adaptations in the gymnastics and NMT group occurred at different stages of the 10-month training duration and varied in magnitude. Isometric PF_{abs} , horizontal jump distance and $Peak_{momentum}$ during sprinting significantly improved at each testing session from baseline. After 7-months of NMT, the gymnasts showed significant improvements in isometric PF_{rel} , CMJ height and RSI and jump height in the DJ. Interestingly, the NMT stimulus took longer to transfer to sprinting and vaulting performance, with peak sprint speed, spring-like behaviour in the DJ, and vaulting vertical take-off velocity significantly improving after 10-months. The gymnastics-training alone elicited some positive improvements (isometric PF_{abs} , SLC in the DJ and $Peak_{momentum}$ in sprinting), but greater changes were often observed in the gymnasts participating in the NMT. Notably, the control group did not experience any significant positive changes for any variable during the intervention period. Overall, these results indicate that supplementary NMT can stimulate improvements in strength, power, speed and vaulting performance above and beyond those achieved through gymnastics training alone. It also appears that adaptations in strength, power, speed and vaulting are time sensitive, and are specific to the imposed demands of the periodised NMT programme.

8.2 LIMITATIONS OF THE RESEARCH

The current thesis has made an original and significant contribution to the available literature in paediatric strength and conditioning and gymnastics performance. However, it is important to acknowledge some limitations that were present in the research to inform and develop future practice. The key limitations have been outlined below:

- This thesis did not conduct any research on post-pubertal female gymnasts and therefore, the impact of growth, maturation and training on strength, power, speed and vaulting performance across all stages of maturity remains unclear. Unfortunately, it was not feasible to include post-pubertal female gymnasts in the cross-sectional analysis or the training intervention study in the present thesis, largely due to the fact that the average drop-out age for young gymnasts is ~9 years of age (93). Whilst conducting similar research in post-pubertal female gymnasts is likely to be more challenging, future research should target this population to explore how advancing maturation effects gymnasts' physical performance.
- Although kinetic analysis of various assessments (i.e. IMTP, jumping protocols) were included in the thesis, examining kinematic data would have provided additional insights. For example, exploring differences in jumping strategies across maturation, or including an assessment of movement competency in the NMT training study would have possibly improved our understanding of potential training transfer. Furthermore, whilst two-dimensional video analysis was used for evaluating vaulting performance, three-dimensional analysis would have provided additional information (i.e. ability to measure depth with the Z-coordinate). However, owing to the comprehensive neuromuscular testing

battery included in the thesis, further kinematic analysis of the was not possible due to time-constraints and testing logistics.

8.3 DIRECTIONS FOR FUTURE RESEARCH

Research examining the influence of growth, maturation and training on measures of strength, power, speed and vaulting vertical take-off velocity in young female gymnasts has received limited attention. While the current thesis has enabled a better understanding of this under-researched topic, there remains a number of unanswered questions within this field of study. Listed below are the primary areas deemed important to investigate in order to further our understanding of growth, maturation and training on physical performance in youth gymnasts.

- *The effects of growth, maturation and training on strength, power and speed development in post-peak height velocity female gymnasts.* The current body of works has enhanced our knowledge of the impact of growth, maturation and training on strength, power, speed and vaulting performance in pre-pubertal and pubertal female gymnasts. However, the influence of these factors on physical qualities in post-pubertal female gymnasts remains unclear. Previous research indicates that young athletes can benefit from training strategies which complement the adaptations that might be occurring as a result of natural development, termed ‘synergistic adaptation’ (163, 254). Therefore, the manner in which post-pubertal female gymnasts respond to a long-term NMT programme may differ. Given the natural increases in fat-mass females experience during puberty, this type of training could be particularly beneficial to enhance gymnasts’ levels of relative muscular strength, power, and speed.
- *The impact of training on muscle architecture in young female gymnasts.* The studies within

this thesis have enhanced our understanding of how growth, maturation and training may influence gymnasts' strength, power and vault take-off velocity by examining group changes and differences in mechanistic force-time variables. Recent research shows muscle architecture characteristics can positively influence sprint speed and vertical jumping performance in male youth (256). An interesting area for future research will be to explore the role of growth and maturation on muscle architecture and its associations with jumping, sprinting and vaulting in young female gymnasts. Further, examining the interaction between growth, maturation and training upon muscle architecture characteristics over a long-term training intervention would provide practitioners with novel insights that could aid training prescription.

- *The effects of neuromuscular training on injury risk factors in young female gymnasts.* The results from *chapter 7* have shown that supplementary NMT can improve measures of strength, power speed and vaulting, beyond gymnastics-specific training alone. Whilst showing the benefits of NMT on gymnasts' performance is important, exploring the efficacy of NMT from any injury perspective would be similarly valuable. Research shows lower-limb injuries are prevalent in gymnasts and are often a result of uncontrolled or repetitive landings leading to acute or overuse type injuries (22). Research also shows that young female athletes are at a greater risk of lower limb injury in comparison to males (252). Considering NMT has been shown to reduce injury risk factors during landing tasks in females (223), future research should explore the effects of this training modality on variables associated with injury risk in young female gymnasts.

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Appendices

APPENDIX 1 – CHILD INFORMATION FORM (STUDIES 1-3)

Participant Information Form

Project Title: The effects of growth, maturation and training on strength and power development in young female gymnasts

Lead researcher: Sylvia Moeskops

Chief Supervisor: Dr Rhodri S. Lloyd

Contact details: smoeskops@cardiffmet.ac.uk

Dear participant,

Please read this information sheet carefully before deciding whether to take part in the project. If you decide to volunteer, we thank you for helping. If you decide not to take part don't worry and we thank you for thinking about taking part.

Aims of the research

We want to find out how your strength and power changes as you get older and what makes you good at doing your gymnastics vault.

What will happen if you decide to volunteer?

You will need to participate in a number of testing sessions at a University Cardiff. They will be over a few weeks and won't take you very long to do. First, we will find out how tall you are when you are standing up and sitting down. We will also see how much you weigh, and find out the date when you were born. After this we will see how strong you are by doing some jumping and hopping tests, and by getting you to pull really hard against a bar. After this we will video you doing your best gymnastics straight jump vault.

That's it!

What type of participants do we want?

We want to recruit girls aged between 5 and 18 that do gymnastics.

What are the risks of participating in the study?

The risks of participating in the study are very small. You usually do more difficult activities when you are doing gymnastics or running in the playground!!

Benefits to the participant

You will be given a record of your performance during the tests, which will help you understand more about your abilities as a gymnast or for other sports.

What will happen to the information collected?

Everyone that takes part in the project will receive their own results for the tests that they complete. All results will be held securely at the University and will only be looked at by Sylvia Moeskops and Dr Rhodri S. Lloyd. Results of this project may be published in magazines or books, but the results will not have your name with them so nobody will know that it was you.

What next?

Questions are always welcome at any time. If you have any questions about the project, then please contact me (details given at top of page). If you would like to participate in the study then the consent and assent forms, as well as the Physical Activity Readiness Questionnaire, need to be signed by your parent/guardian and yourself as the participant, and returned to myself.

Thank you,

Sylvia Moeskops

Sylvia Moeskops MSc
PhD Researcher (Paediatric Strength and Conditioning)
Principal Investigator
Cardiff School of Sport

Participant Assent Form

Project Title: The effects of growth, maturation and training on strength and power development in young female gymnasts

Lead researcher: Sylvia Moeskops

Chief Supervisor: Dr Rhodri S. Lloyd

Contact details: smoeskops@cardiffmet.ac.uk

I have read the information form that explains what I need to do if I want to take part in the project. All my questions have been answered and I understand that I can ask any questions at any time. **Please fill this form in by circling the face by each question that you think is best for you.**

If you agree and understand, circle this face	: -)
If you aren't sure, circle this face	: -
If you disagree, circle this face	: - (

I understand that:

I have decided to take part in the study because I want to and nobody has made me.	: -)	: -	: - (
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I can ask to stop taking part whenever I want and nobody will ask me why.	: -)	: -	: - (
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I need to go to all the testing sessions to be included in the final project.	: -)	: -	: - (
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My height and weight will be collected.	: -)	: -	: - (
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I will be tested to see how strong I am and how far I can jump.	: -)	: -	: - (
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I will be filmed doing a gymnastics vault.	: -)	: -	: - (
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All my information and results collected will be kept in a secret location.	: -)	: -	: - (
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The results of the study may be put in a book or magazine in the future, but I understand that my name will not be used and nobody will know who I am	: -)	: -	: - (
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I may be spoken to in the future by other researchers who might :-)
want me to help them with another study. :-| :-(

Name: _____

Date: _____

Project Title: The effects of growth, maturation and training on strength and power development in young female gymnasts

Lead researcher: Sylvia Moeskops
Chief Supervisor: Dr Rhodri S. Lloyd
Contact details: smoeskops@cardiffmet.ac.uk

Dear Parent/Guardian,

Purpose of this information sheet

This information sheet is to let you know about my planned research project in the Cardiff School of Sport, Cardiff Metropolitan University. It should help you decide on whether or not you want your child to join the study. Taking part in the research is entirely voluntary and should your child wish to withdraw from the study at any time, **they are entitled to do so without any repercussions.**

What will happen once you agree to participate in the study?

The aims of the study are to see how measures of strength and power change in young gymnasts (children and adolescents) as they get older, and what determines their gymnastics vaulting ability. The tests below will all be collected on the same day, which will take approximately 90 minutes. I am also looking at the reliability of one of the tests (the Isometric mid-thigh pull), and will therefore require your child to be retested on two more occasions, lasting just 30 minutes. All testing will take place at Cardiff Metropolitan University in the research laboratory or gym. The following tests will be included;

- Collection of anthropometric data (i.e. age, body mass, height and sitting height)
- 3 x Sub-maximal hopping test (20 hops at a frequency of 2.5 Hz)
- 3 x Jumping tests (counter-movement jump, squat jump and horizontal jump)
- 3 x Isometric mid-thigh pull (standing still and pulling hard against a bar)
- 3 x Straight jump gymnastics vault (video-analysis)

What type of participants are we hoping to use in the study?

We are looking for gymnasts aged between the ages of 5 and 18 years.

What are the risks of participating in the study?

The risks associated with the study are minimal. Each strength and power test lasts no longer than 20 seconds, and participants will be allowed plenty of time to recover in between each test. There are some risks when participating in any form of exercise, however the risks associated with the current study are no more likely to occur than if participants were taking part in a gymnastics session. All physiological tests involved in the project will mirror those included within any explosive-based training session that the gymnasts routinely participate in.

Benefits to the participant

Participants will be given a written record of their performances in the tests. This will provide them with information about their abilities in strength and power activities, which may help their involvement in gymnastics, and participation in other sports. It will also provide them with a hands-on experience of modern-day sport science fitness testing, otherwise unavailable to other schools in Wales.

Benefits to us, the research team

By completing the research, participants will provide the research team with relevant data which will be used to complete Sylvia Moeskops' PhD thesis (the principal investigator). More importantly the findings of the study will provide the research team with important new information to inform the gymnastics community.

What will happen to the data and information collected during the study?

The information and data we have about each participant will be coded so your child be identified individually. Video footage will initially be stored, rated via digital analysis, and then stored with other data; however, the footage will only be available the research team. Each participant will receive a copy of their test performances at the end of the testing period. Their performance data will only be seen by themselves and the research team. Copies of all data collected during the testing period will be stored centrally within a secure holding location in Cardiff Metropolitan University for up to a period of 7 years. Only the principal researcher and his supervisory team will be able to access the data once stored in Cardiff Metropolitan University. Results of this study may be published but participants will not be identified in a publication, and data included will in no way be associated with any named individual.

What next?

Please feel free to ask any question to a member of the research team at any time. You may contact either Dr Rhodri Lloyd or myself on the above e-mail addresses should you have any concerns about the study. Having discussed this matter with your child, and if you would like them to take part in the study, please complete the *Parental Consent Form*, and help your child to complete the *Participant Assent Form*, and *Physical Activity Readiness Questionnaire* included with this information sheet and return to myself, as soon as possible. This project has been approved by UREC (University Research Ethics Committee).

Many thanks,

Sylvia Moeskops

Sylvia Moeskops MSc
PhD Researcher (Paediatric Strength and Conditioning)
Principal Investigator
Cardiff School of Sport

Adult Consent Form

Project Title: The effects of growth, maturation and training on strength and power development in young female gymnasts.

Lead researcher: Sylvia Moeskops

Chief Supervisor: Dr Rhodri S. Lloyd

Contact details: smoeskops@cardiffmet.ac.uk

I have read the information form regarding the research and fully understand what it entails. The research team has answered any questions I had comprehensively. I understand that I am entitled to ask any further questions at any time throughout the duration of the study.

I understand that I am entitled to withdraw my child from the project at any time without any repercussions.

I understand that:

- ✓ My child has volunteered to participate in the study on their own ☐
accord, and that they are entitled to leave the study at any time
should they wish to.
- ✓ My child will be required to attend the requisite number of testing ☐
and training sessions in order to complete the research project.
- ✓ Personal data (age, weight, height, gender) will be collected, and ☐
they will perform a number of strength and power tests, as well as
a gymnastics vault.
- ✓ All personal information and research data collected during the ☐
study will be kept in a secure location within the university grounds
for a period of 7 years. The results of the study may be published in
the future; however, my child's anonymity will be maintained at all
times.
- ✓ As a member of the research cohort, they may be contacted in the ☐
future by the principal investigator/supervisor or other Cardiff Met
University researchers who may wish for me to contribute in follow-
up studies or research of a similar nature. However, my child's
participation in these studies would not be compulsory.

In order for the research team to determine how biologically mature your child is, we ideally need to know how tall both parents are (in feet and inches or centimetres). Using this data, we can calculate the predicted adult height for your child, and then determine how close to that predicted height your child is at the time of testing.

I understand why the research team wishes to know the height of both parents of my child. I am happy to provide this information and for it to be used for the purposes of research.

Mother's height:

Father's height:

Signed (parent/guardian): _____

Date: _____

Print Name: _____

APPENDIX 5 – ETHICS FORM (STUDIES 1-3)

When undertaking a research or enterprise project, Cardiff Met staff and students are obliged to complete this form in order that the ethics implications of that project may be considered.

If the project requires ethics approval from an external agency (e.g., NHS), you will not need to seek additional ethics approval from Cardiff Met. You should however complete Part One of this form and attach a copy of your ethics letter(s) of approval in order that your School has a record of the project.

The document ***Ethics application guidance notes*** will help you complete this form. It is available from the [Cardiff Met website](#). The School or Unit in which you are based may also have produced some guidance documents, please consult your supervisor or School Ethics Coordinator.

Once you have completed the form, sign the declaration and forward to the appropriate person(s) in your School or Unit.

PLEASE NOTE:

Participant recruitment or data collection MUST NOT commence until ethics approval has been obtained.

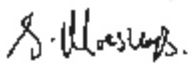

PART ONE

Name of applicant:	Sylvia Moeskops
Supervisor (if student project):	Dr Rhodri Lloyd
School / Unit:	School of Sport
Student number (if applicable):	20000498
Programme enrolled on (if applicable):	PhD
Project Title:	The effects of growth and maturation on strength and power indices and vaulting performance in young female gymnasts
Expected start date of data collection:	01/01/2017
Approximate duration of data collection:	1 year
Funding Body (if applicable):	N/A
Other researcher(s) working on the project:	Dr Rhodri Lloyd (DoS), Dr Jon Oliver (Co-supervisor), Dr Paul Read (Co-supervisor), Dr Greg Myer (Advisor) and Prof John Cronin (Advisor)
Will the study involve NHS patients or staff?	No
Will the study involve human samples and/or human cell lines?	No

Does your project fall entirely within one of the following categories:	
Paper based, involving only documents in the public domain	No
Laboratory based, not involving human participants or human samples	No

Practice based not involving human participants (e.g. curatorial, practice audit)	No
Compulsory projects in professional practice (e.g. Initial Teacher Education)	No
A project for which external approval has been obtained (e.g., NHS)	No
If you have answered YES to any of these questions, expand on your answer in the non-technical summary. No further information regarding your project is required.	
If you have answered NO to all of these questions, you must complete Part 2 of this form	

In no more than 150 words, give a non-technical summary of the project
The sport of artistic gymnastics requires high levels of strength and power from an early age to successfully and safely perform a dynamic and diverse set of skills. However, limited normative data for strength and power measures exists for young female gymnasts. Furthermore, researchers are yet to examine how strength and power indices change in relation to chronological age and stages of maturation in this population, which is essential knowledge for those working with paediatric populations. Therefore, this project will aim to: (i) establish a reliable and valid battery of tests to quantify the strength and power profiles of youth female gymnasts, and (ii) use this battery to assess strength and power characteristics of young female gymnasts of different ages and stages of maturation and (iii) establish the main strength and power determinants of gymnastics vaulting performance.

DECLARATION:	
I confirm that this project conforms with the Cardiff Met Research Governance Framework	
I confirm that I will abide by the Cardiff Met requirements regarding confidentiality and anonymity when conducting this project.	
STUDENTS: I confirm that I will not disclose any information about this project without the prior approval of my supervisor.	
Signature of the applicant: 	Date: 09/11/2016
FOR STUDENT PROJECTS ONLY	
Name of supervisor: Rhodri S. Lloyd	Date: 22/11/16
Signature of supervisor: 	

Research Ethics Committee use only	
Decision reached:	Project approved <input type="checkbox"/> Project approved in principle <input checked="" type="checkbox"/> Decision deferred <input type="checkbox"/> Project not approved <input type="checkbox"/> Project rejected <input type="checkbox"/>
Project reference number: 17/1/02R	
Name: Dr Brendan Cropley	Date: 18/01/2017

Signature:



Details of any conditions upon which approval is dependant:

1. The researcher must hold an up-to-date DBS Form (a copy of which must be stored with this ethics application) – this must be confirmed prior to the start of the research
2. In the case where a child is unable to understand the participant information sheet and/or assent form the researcher should ensure that the parent/guardian has explained everything to the child.

PART TWO

A RESEARCH DESIGN	
A1 Will you be using an approved protocol in your project?	Yes
A2 If yes, please state the name and code of the approved protocol to be used ¹	
<p>To be used with a paediatric population:</p> <ul style="list-style-type: none"> • Isometric Mid-Thigh Pull (IMTP) Protocol 16/10/09L • Jumping Performance Force Plate Protocol 16/10/04L • Sub Maximal Contact Mat Protocol 16/10/05L (Protocol adapted by using a force plate instead of a contact mat) 	
A3 Describe the research design to be used in your project	
<p>Testing will take place in the SCRAM Research Laboratory and the Strength and Conditioning gym located on Cyncoed Campus in NIAC. However, for the gymnastics-specific protocol (e.g. vaulting performance), 2D video analysis may take place at Sport Wales or the local gymnastics club where the participants will be recruited from. Descriptive data will be collected for all participants in each study including: age, body mass, height, sitting height. Prior to any testing, a 10-minute dynamic warm up will be performed and led by the researcher to physically prepare the participants for the testing battery.</p> <p>The purpose of this cross-sectional study is to assess how strength and power indices change as a result of chronological age and biological maturation, and how they influence vaulting performance in young female gymnasts. This cross-sectional design will attempt to recruit approximately 250 gymnasts of differing ages and maturational status (e.g. pre- vs post-peak height velocity). The participants will be recruited from a number of local Women's Artistic gymnastics clubs. Each participant will be required to attend an initial familiarisation session during which they will be provided opportunities to familiarise themselves with the range of strength and power tests and the vaulting task. Following this session, participants will be required to attend another testing session lasting approximately 90 minutes during which the experimental data for all protocols will be collected. Strength and power profiles of each participant will be assessed using a range of tests, specifically: IMTP (16/10/09L), countermovement jump (16/10/04L), squat jump (16/10/04L), drop jump (16/10/04L), sub-maximal hopping (16/10/05L), horizontal broad jump (not yet approved) and a loaded squat jump (not yet approved). The data collected from the above tests will then be used to determine the anthropometric and kinetic variables that determine vaulting performance. Force plates with the associated software will be used for all jump protocols, while a radar gun and video analysis will be used to assess vaulting performance. Vaulting performance will be assessed using a "straight vault", which is the least technically demanding vault within the gymnastics curriculum that all participating gymnasts will be able to perform. Video footage will initially be stored, rated via digital analysis, and then stored with other data; however, footage will only be available to the research team. Video footage will be analysed by the principal researcher for a sub-set of participants (approximately n = 30) on three separate occasions to determine the intra-rater reliability.</p> <p>From the above sample of n = 250, approximately 30 pre-peak height velocity gymnasts and 30 post-peak height velocity gymnasts will be recruited to participate in a follow-up study to determine the inter-session reliability of the IMTP protocol (16/10/09L). Following the initial test session highlighted above, participants will then attend a further two testing sessions over a two-week period. During each test session, participants will complete three trials of the IMTP with 3-4 minutes' recovery between tests. The protocol will use a custom-designed IMTP rig and a Kistler force plate sampling at 1000Hz to collect all kinetic variables for further analysis. Each testing session will last approximately 30 minutes per participant (including the warm up).</p>	
A4 Will the project involve deceptive or covert research?	No
A5 If yes, give a rationale for the use of deceptive or covert research	
N/A	
A6 Will the project have security sensitive implications?	No
A7 If yes, please explain what they are and the measures that are proposed to address them	
N/A	

¹ An Approved Protocol is one which has been approved by Cardiff Met to be used under supervision of designated members of staff; a list of approved protocols can be found on the Cardiff Met website here

B PREVIOUS EXPERIENCE
B1 What previous experience of research involving human participants relevant to this project do you have?
The researcher is currently a technician-demonstrator within the Sports Conditioning, Rehabilitation and Massage (SCRAM) discipline and has vast experience in the administration of field-based testing protocols with children in both an applied and research setting. The researcher is also a certified strength and conditioning specialist (CSCS), holds a Level 2 coaching award in Women's Artistic gymnastics, and has a wealth of experience in coaching young athletes.
B2 Student project only
What previous experience of research involving human participants relevant to this project does your supervisor have?
Dr Rhodri Lloyd has published in excess of 60 peer reviewed research articles within the paediatric literature and completed a PhD in the field of paediatrics. He currently supervises or co-supervises nine PhD students. Dr Jon Oliver is a Reader in Applied Paediatric Exercise Science, has over 70 peer reviewed research articles, supervises 9 PhD students, and has five successful PhD completions. Dr Paul Read completed his PhD in paediatric exercise science with a specific focus on testing and evaluating injury risk. He currently serves on the supervisory team of 3 PhD students and has in excess of 25 peer-reviewed publications. Dr Greg Myer is a world leader in paediatric sports medicine, has published in excess of 250 research manuscripts, and has served on the supervisory team of more than 20 PhD students. Professor John Cronin is a world leader in strength and conditioning, has published in excess of 200 research manuscripts and has 44 successful PhD completions.

C POTENTIAL RISKS
C1 What potential risks do you foresee?
<ol style="list-style-type: none"> 1. There are risks when working with vulnerable populations, in this case, young children. 2. There is the possibility of underlying medical conditions or existing injuries leading to an increased risk of injury during the testing period 3. There is the possibility the participants may experience some fatigue following testing, albeit the probability of this is low. 4. There is the possibility of injury during physical tests. 5. Environmental risks might include the risk of fire or bad lighting 6. The identification of participants from within the study
C2 How will you deal with the potential risks?
<ol style="list-style-type: none"> 1. The supervisory team have all attended a child welfare and safeguarding workshop, have complete DBS checks, and will not work in a 1-to-1 situation with any of the participants. Appropriate, non-technical child and adult participant information sheets will be provided (see appendices for all documentation). As the project involves participants under the age of 18 years old, both assent for each child and consent from a parent or guardian will be obtained prior to commencement of the study. Where necessary, parents will be asked to read through the participant information sheets with their child to ensure that the participants have a clear understanding of the details of the study. 2. A physical activity readiness questionnaire (PAR-Q) which is approved by Research Ethics Sub-Committee (RESC) will be completed by each parent of the participant. The researcher will review the form prior to testing in order to determine any health risks that may prevent the subject from participating. Acceptance in the study will only be granted after successful completion of the PAR-Q. 3. Participants will be allowed enough rest time to ensure full recovery between trials and different tests. 4. All physiological tests and vaulting activities involved within the battery and those that have been proposed for inclusion, will mirror those included within any explosive-based training session that the gymnasts routinely participate in. Therefore, the participants should be well accustomed to performing such exercises, which should reduce the associated risk of fatigue or injury to the participants. 5. Testing will take place in the SCRAM Research Laboratory and the Strength and Conditioning gym in NIAC, both of which have full risk assessments. There should be no risks to the researcher carrying out the testing procedures or for using the equipment. 6. All raw data, including videos, will be stored electronically and treated confidentially, and all participants' results will be reported anonymously. All methods will be based on RESC approved laboratory procedures (laboratory procedures manual).

When submitting your application, you **MUST** attach a copy of the following:

- All information sheets
- Consent/assent form(s)

An exemplar information sheet and participant consent form are available from the Research section of the Cardiff Met website.

Participant Information Form - Neuromuscular Training Group

Project Title: The effects of growth, maturation and training on strength and power development in young female gymnasts

Lead researcher: Sylvia Moeskops
Director of Studies: Dr Rhodri S. Lloyd

Contact e-mail: smoeskops@cardiffmet.ac.uk
Contact e-mail: rlloyd@cardiffmet.ac.uk

Dear participant,

Please read this information sheet carefully before deciding whether to take part in the project. If you decide to volunteer, we thank you for helping. If you decide not to take part don't worry and we thank you for considering taking part.

Aims of the research

We want to find out how your gymnastics training affects your vaulting performance. We also want to find out if taking part in a different sort of training makes you better at doing your gymnastics vault. We also want to know if this training changes depending on how old you are.

What will happen if you decide to volunteer?

You will need to participate in a number of testing sessions at a University in Cardiff. The sessions will take place every 3 months (4 times in total) and won't take you very long to do. First, we will find out how tall you are when you are standing up and sitting down. We will also see how much you weigh, and find out the date when you were born. Next we will ask you to stand on a piece of equipment that measures your strength when you pull on a bar. After this we will see how strong you are by asking you to perform some jumping and hopping tests. A clever machine will also be put on your skin to look at the shape of the muscle below your knee. Finally, we will video you doing your best gymnastics straight jump vault. That's it for the testing!

If you are in the group that will be taking part in the neuromuscular training programme, you will be coming to the university for training twice a week with myself. To begin with, you will be doing lots of movement training and then we will aim to improve your strength and power, to help you with your gymnastics and other sports. Some of the exercises you will have done before, and other exercises will be new and exciting.

What type of participants do we want?

We want to recruit girls aged between 5 and 18 that do gymnastics.

What are the risks of participating in the study?

The risks of participating in the study are very small. You usually do more daring activities when you are doing gymnastics or running in the playground!

Benefits to the participant

You will be given a record of your performance during the tests, which will help you understand more about your abilities as a gymnast and other sports. If you're taking part in the training programme at the university with me, you will get to learn some new movement skills and exercises to make you stronger than you might not have done before.

What will happen to the information collected?

Everyone that takes part in the project will receive their own results for the tests that they complete. All results will be held securely at the University and will only be looked at by myself (Sylvia Moeskops) and my supervisors

Rhodri Lloyd and Jon Oliver. Results of this project may be published in magazines or books, but the results will not have your name with them so nobody will know that it was you.

What next?

Questions are always welcome at any time. If you have any questions about the project, then please contact me yourself or get an adult to speak to me (details given at top of page). If you would like to participate in the study then the consent and assent forms, as well as the Physical Activity Readiness Questionnaire, need to be signed by your parent/guardian and yourself as the participant, and returned to myself.

Thank you,

Sylvia Moeskops

PhD Researcher (Paediatric Strength and Conditioning)
Principal Investigator
Cardiff School of Sport and Health Sciences

Participant Assent Form - Neuromuscular Training Group

Project Title: The effects of growth, maturation and training on strength and power development in young female gymnasts

I have read the information form that explains what I need to do if I want to take part in the project. All my questions have been answered and I understand that I can ask any questions at any time.

Please fill this form in by circling the face by each question that you think is best for you.

If you agree and understand, circle this face ☺

If you aren't sure, circle this face ☹

If you disagree, circle this face ☹

I understand that:

I have decided to take part in the study because I want to and nobody has made me ☺ ☹ ☹

I can ask to stop taking part whenever I want and nobody will ask me why ☺ ☹ ☹

I need to go to all of the testing sessions, unless I decide I don't want to take part anymore ☺ ☹ ☹

My height and weight will be collected ☺ ☹ ☹

Testing will involve some jumping and hopping tests to see how strong I am ☺ ☹ ☹

A clever machine will be put on my skin to look at the shape of the muscle below my knee. ☺ ☹ ☹

A video of me doing a straight jump gymnastics vault will be taken ☺ ☹ ☹

All my information and results collected will be kept in a secret location. ☺ ☹ ☹

The results of the study may be put in a book or magazine in the future, but I understand that my name will not be used and nobody will know who I am

I may be spoken to in the future by the researchers on this project who might want me to help them with another study. However, I won't have to participate if I don't want to.



Name: _____

Date: _____

Parent/ Guardian Information Form – Neuromuscular Training Group

Project Title: The effects of growth, maturation and training on strength and power development in young female gymnasts

Lead researcher: Sylvia Moeskops
Director of Studies: Dr Rhodri S. Lloyd

Contact e-mail: smoeskops@cardiffmet.ac.uk
Contact e-mail: rlloyd@cardiffmet.ac.uk

Dear Parent/Guardian,

Purpose of this information sheet

This information sheet is to let you know about my planned research project in the Cardiff School of Sport and Health Sciences, Cardiff Metropolitan University. It should help you decide on whether or not you want your child to join the study. Taking part in the research is entirely voluntary and should your child wish to withdraw from the study at any time, **they are entitled to do so without any repercussions.**

Professional and medical organisations advocate youth resistance training and long-term athletic development (Lloyd et al., 2014, Lloyd et al., 2016) have suggested that it is beneficial for all children, and particularly those involved in sports to engage in strength and conditioning. The benefits can include improved health and wellbeing, reduced injury risk and improved athletic performance. While gymnastics training improves strength via bodyweight training and the performance of skills, few studies have explored the benefits of strength and conditioning for gymnasts, and whether or not it transfers to vaulting performance. The aims of the study are therefore to see how a long-term neuromuscular training programme effects young gymnasts' (children and adolescents) physical strength and power, and to see if these changes transfers to vaulting performance. These results will be compared against gymnasts who are not participating in the strength and power programme, to evaluate the effects of the additional neuromuscular training.

What will happen once you agree to participate in the study?

Your daughter will be invited to the gymnastics + neuromuscular training intervention group. To participate in the study your daughter must be participating in gymnastics and aged 5-18 years old.

Training will take place twice a week for 45-60 minutes per session at Cardiff Metropolitan University and your daughter must also attend 4 testing sessions approximately 3 months apart.

***Please note: the training will be free of charge.** Participants attendance must however remain above 80% during each term to continue being involved in the training intervention.

The testing sessions will be performed in groups, which will take approximately 2 hours with a break. All testing will take place at Cardiff Metropolitan University in the research laboratory or in the Youth Physical Development Centre. The following tests will be included;

- Collection of anthropometric data (i.e. age, body mass, height and sitting height)
- 3 x Sub-maximal hopping test (20 hops at a frequency of 2.5 Hz) and maximal hopping (5 hops)
- 3 x Jumping tests (counter-movement jump, squat jump, drop jumps horizontal jump)
- 3 x Isometric mid-thigh pulls (standing on a platform that collects force data through pulling on a bar)
- 3 x Straight jump gymnastics vaults (video-analysis)
- 3 x Non-invasive ultrasound images of lower legs muscle-tendon structure

What type of participants are we hoping to use in the study?

We are looking for gymnasts between the ages of 5 and 18 years.

What are the risks of participating in the study?

The risks associated with the study are minimal. The training intervention will be designed and coached by Sylvia Moeskops (the PhD researcher), who is a qualified gymnastics coach and an accredited strength and conditioning coach who has extensive experience of working with young athletes in a training environment. Initially, all exercises will be learned and performed with the participants body weight only. Once the gymnasts' technique is competent and consistent, additional load will be progressively added over time on an individual basis. For the testing sessions, the strength and power tests last no longer than 20 seconds, and participants will be allowed plenty of time to recover in between each test. There are some risks when

participating in any form of exercise, however the risks associated with the current study are no more likely to occur than if participants were taking part in a gymnastics session. All physiological tests involved in the project will mirror those included within any explosive-based training session that the gymnasts routinely participate in. The researcher has also successfully used all tests to collect data on a large number of young female gymnasts in previous studies, without any gymnasts experiencing an injury.

Benefits to the participant

Participants will be given termly reports on their training and performances in the tests. This will provide them with information about their abilities in strength and power activities, which may help their performance in gymnastics, and participation in other sports. It will also provide them with a hands-on experience of modern-day sport science fitness testing, otherwise unavailable to other clubs in Wales. For the gymnasts participating in the neuromuscular training intervention, research has shown that these programmes can have multiple benefits to participants including: improved health and wellbeing, reduced injury risk and improved athletic performance.

Benefits to us, the research team

By completing the research, participants will provide the research team with relevant, novel and impactful data which will be used to complete Sylvia Moeskops' PhD thesis (the principal investigator). More importantly the findings of the study will provide the research team with important, new information which gymnastics coaches and strength and conditioning coaches will ultimately find useful. The results of the studies will also be published in Internationally-renowned sport science journals and presented at national and international conferences.

What will happen to the data and information collected during the study?

The information and data we have about each participant will be coded so your child cannot be identified individually. Video footage will initially be stored, rated via digital analysis, and then stored with other data; however, the footage will only be available to the research team. Each participant will receive a copy of their test performances at the end of the testing period. Their performance data will only be seen by themselves and the research team. Copies of all data collected during the testing period will be stored centrally within a secure, password-protected holding location in Cardiff Metropolitan University for up to a period of 10 years. Only the principal researcher and their supervisory team will be able to access the data once stored in Cardiff Metropolitan University. Results of this study may be published, but participants will never be identified in a publication, and data included will in no way be associated with any named individual.

What next?

Please feel free to ask any question to a member of the research team at any time. You may contact either Dr Rhodri Lloyd or myself on the above e-mail addresses should you have any concerns about the study. Having discussed this matter with your child, and if you would like them to take part in the study, please complete the *Parental Consent Form*, and help your child to complete the *Participant Assent Form* and *Physical Activity Readiness Questionnaire* included with this information sheet and return to myself, as soon as possible. This project has been approved by UREC (University Research Ethics Committee).

Many thanks,

Sylvia Moeskops MSc - PhD Researcher (Paediatric Strength and Conditioning)
Principal Investigator
Cardiff School of Sport and Health Sciences

Adult Consent Form – Neuromuscular Training Group

Project Title: The effects of growth, maturation and training on strength and power development in young female gymnasts.

Lead researcher: Sylvia Moeskops

Contact e-mail: smoeskops@cardiffmet.ac.uk

Director of Studies: Dr Rhodri S. Lloyd

Contact e-mail: rlloyd@cardiffmet.ac.uk

I have read the information form regarding the research and fully understand what it entails. The research team has answered any questions I had comprehensively. I understand that I am entitled to ask any further questions at any time throughout the duration of the study.

I understand that I am entitled to withdraw my child from the project at any time without any repercussions.

I understand that:

✓ My child has volunteered to participate in the study on their own accord, and they are entitled to leave the study at any time should they wish to.

☐

✓ My child will be required to attend the requisite number of testing (4 in total approximately 3 months apart) order to complete the research project.

☐

✓ My child will be required to attend 2 neuromuscular training sessions a week at the university in order to complete the research project.

☐

✓ Personal data (age, weight, height, gender) for my child will be collected, and they will perform a number of strength and power tests, non-invasive ultrasound imaging of the lower leg, as well as a gymnastics vault.

☐

✓ All personal information and research data collected during the study will be kept in a secure location within the university grounds for a period of 7 years. The results of the study may be published in the future; however, my child's anonymity will be maintained at all times.

☐

✓ As a member of the research cohort, they may be contacted in the future by the principal investigator/supervisor or other Cardiff Met University researchers who may wish for me to contribute in follow-up studies or research of a similar nature. However, my child's participation in these studies would not be compulsory.

☐

✓ In order for the research team to determine how biologically mature your child is, we ideally need to know how tall both parents are (in feet and inches or centimetres). Using this data, we can calculate the predicted adult height for your

☐

child, and then determine how close to that predicted height your child is at the time of testing.

- ✓ I understand why the research team wishes to know the height of both parents of my child. I am happy to provide this information and for it to be used for the purposes of research.

☐

Mother's height:

Father's height:

Signed (parent/guardian): _____

Date: _____

Print Name: _____

Participant Information Form - Control groups

Project Title: The effects of growth, maturation and training on strength and power development in young female gymnasts

Lead researcher: Sylvia Moeskops
Director of Studies: Dr Rhodri S. Lloyd

Contact email: smoeskops@cardiffmet.ac.uk
Contact email: rlloyd@cardiffmet.ac.uk

Dear participant,

Please read this information sheet carefully before deciding whether to take part in the project. If you decide to volunteer, we thank you for helping. If you decide not to take part don't worry and we thank you for considering taking part.

Aims of the research

We want to compare your strength and power measures against girls who do gymnastics, and girls who do gymnastics and are taking part in a training programme at the university. We also want to know if this training changes depending on how old you are.

What will happen if you decide to volunteer?

You will need to participate in a number of testing sessions at a University in Cardiff. The sessions will be every 3 months (4 times in total) and won't take you very long to do. First, we will find out how tall you are when you are standing up and sitting down. We will also see how much you weigh, and find out the date when you were born. Next, we will ask you to stand on a piece of equipment that measures your strength when you pull on a bar. After this we will see how strong you are by asking you to perform some jumping and hopping tests. A clever machine will also be put on your skin to look at the shape of the muscle below your knee. That's it for the testing!

What type of participants do we want?

We want to recruit girls aged between 5 and 18 that either participate or don't participate in gymnastics, but are definitely not involved in any formalised strength and conditioning programme (i.e. fitness training such as weight training).

What are the risks of participating in the study?

The risks of participating in the study are very small. You usually do more daring activities when you are running in the playground or playing sport!

Benefits to the participant

You will be given a record of your performance during the tests, which will help you understand more about your abilities in sport. At the end of the study, we will offer you a training programme based off of your results. You will be invited to the university for two taster training sessions, and then we will give you a copy of your training programme (of body-weight exercises) to take home, and complete with the supervision of your parents. An additional resource will also be provided to help you with this!

What will happen to the information collected?

Everyone that takes part in the project will receive their own results for the tests that they complete. All results will be held securely at the University and will only be looked at by Sylvia Moeskops and my supervisors Rhodri Lloyd and Jon Oliver. Results of this project may be published in magazines or books, but the results will not have your name with them so nobody will know that it was you.

What next?

Questions are always welcome at any time. If you have any questions about the project, then please contact me yourself or get an adult to speak to me (details given at top of page). If you would like to participate in the study then the consent and assent forms, as well as the Physical Activity Readiness Questionnaire, need to be signed by your parent/guardian and yourself as the participant, and returned to myself.

Thank you,

Sylvia Moeskops

PhD Researcher (Paediatric Strength and Conditioning)

Principal Investigator

Cardiff School of Sport and Health Sciences

Participant Assent Form - Control Groups

Project Title: The effects of growth, maturation and training on strength and power development in young female gymnasts

I have read the information form that explains what I need to do if I want to take part in the project. All my questions have been answered and I understand that I can ask any questions at any time.

Please fill this form in by circling the face by each question that you think is best for you.

If you agree and understand, circle this face ☺

If you aren't sure, circle this face ☹

If you disagree, circle this face ☹

I understand that:

I have decided to take part in the study because I want to and nobody has made me ☺ ☹ ☹

I can ask to stop taking part whenever I want and nobody will ask me why ☺ ☹ ☹

I need to go to all of the testing sessions, unless I decide I don't want to take part anymore ☺ ☹ ☹

My height and weight will be collected ☺ ☹ ☹

Testing will involve some jumping and hopping tests to see how strong I am ☺ ☹ ☹

A clever machine will be put on my skin to look at the shape of the muscle below my knee, and I will be videoed doing a gymnastics vault if I am a gymnast. ☺ ☹ ☹

All my information and results collected will be kept in a secret location. ☺ ☹ ☹

The results of the study may be put in a book or magazine in the future, but I understand that my name will not be used and nobody will know who I am

I may be spoken to in the future by the researchers on this project who might want me to help them with another study. However, I won't have to participate if I don't want to. ☺ ☹ ☹

Name: _____

Date: _____

Parent/ Guardian Information Form – Control Groups

Project Title: The effects of growth, maturation and training on strength and power development in young female gymnasts

Lead researcher: Sylvia Moeskops
Director of Studies: Dr Rhodri S. Lloyd

Contact e-mail: smoeskops@cardiffmet.ac.uk
Contact e-mail: rlloyd@cardiffmet.ac.uk

Dear Parent/Guardian,

Purpose of this information sheet

This information sheet is to let you know about my planned research project in the Cardiff School of Sport and Health Sciences, Cardiff Metropolitan University. It should help you decide on whether or not you want your child to join the study. Taking part in the research is entirely voluntary and should your child wish to withdraw from the study at any time, **they are entitled to do so without any repercussions.**

Strength and conditioning is becoming a popular form of physical training and involves a variety of exercises including resistance and weight training. While gymnastics training improves strength via bodyweight training and the performance of skills, few studies have explored the benefits of strength and conditioning for gymnasts, and whether or not it transfers to vaulting performance.

The aims of the study are to assess how a long-term strength and power training programme effects young gymnasts' (children and adolescents) strength and power measures, and whether or not improving these measures transfers to vaulting performance. In addition, the study will compare the training groups results to gymnasts who are not participating in strength and conditioning training programme, and non-gymnasts (females of the same age).

What will happen once you agree to participate in the study?

Your daughter will need to attend 4 testing sessions approximately 3-months apart.

The testing sessions will be performed in groups, which will take approximately 2 hours with a break. All testing will take place at Cardiff Metropolitan University in the research laboratory or in the gym. The following tests will be included;

- Collection of anthropometric data (i.e. age, body mass, height and sitting height)
- 3 x Sub-maximal hopping test (20 hops at a frequency of 2.5 Hz) and maximal hopping (5 hops)
- 3 x Jumping tests (counter-movement jump, squat jump, drop jumps horizontal jump)
- 3 x Isometric mid-thigh pulls (standing on a platform that collects force data through pulling on a bar)
- 3 x Non-invasive ultrasound images of lower legs muscle-tendon structure

Why am I/why is my child being asked to volunteer

We are looking for females aged 5 to 18 years old who are **not** involved in any formalised strength and conditioning programme (i.e. fitness training such as weight training) but who either:

1. Participate in gymnastics
2. Do not participate in gymnastics

What are the risks of participating in the study?

The risks associated with the study are minimal. For the testing sessions, the strength and power tests last no longer than 20 seconds, and participants will be allowed plenty of time to recover in between each test. There are some risks when participating in any form of exercise, however the risks associated with the current study are no more likely to occur than if participants were taking part in sports. The researcher has also successfully used all tests to collect data on a large number of young female gymnasts in previous studies, without any gymnasts experiencing an injury.

Benefits to the participant

Participants will be given termly reports on their performances in the tests. This will provide them with information about their abilities in strength and power activities, which may help their involvement in the participation in other sports. It will also provide them with a hands-on experience of modern-day sport science fitness testing, otherwise unavailable to other schools in Wales. At the end of the study, your daughter will be given a training programme based off of her your results collected over the 12-month period. Your daughter will also be invited to the university for two taster training sessions. Following this, will be give your daughter a copy of her training programme (of body-weight exercises) to take home and complete under the supervision of a parents/guardian. An additional resource will also be provided to help you and your daughter with the training programme!

Benefits to us, the research team

By completing the research, participants will provide the research team with relevant, novel and impactful data which will be used to complete Sylvia Moeskops' PhD thesis (the principal investigator). More importantly the findings of the study will provide the research team with important, new information which gymnastics coaches and strength and conditioning coaches will ultimately find useful. The results of the studies will also be published in Internationally-renowned sport science journals and presented at national and international conferences.

What will happen to the data and information collected during the study?

The information and data we have about each participant will be coded so your child cannot be identified individually. Each participant will receive a copy of their test performances at the end of the testing period. Their performance data will only be seen by themselves and the research team. Copies of all data collected during the testing period will be stored centrally within a secure holding location in Cardiff Metropolitan University for up to a period of 10 years. Only the principal researcher and their supervisory team will be able to access the data once stored in Cardiff Metropolitan University. Results of this study may be published, but participants will never be identified in a publication, and data included will in no way be associated with any named individual.

What next?

Please feel free to ask any question to a member of the research team at any time. You may contact either Dr Rhodri Lloyd or myself on the above e-mail addresses should you have any concerns about the study. Having discussed this matter with your child, and if you would like them to take part in the study, please complete the *Parental Consent Form*, and help your child to complete the *Participant Assent Form*, and *Physical Activity Readiness Questionnaire* included with this information sheet and return to myself, as soon as possible. This project has been approved by UREC (University Research Ethics Committee).

Many thanks,

Sylvia Moeskops MSc - PhD Researcher (Paediatric Strength and Conditioning)
Principal Investigator
Cardiff School of Sport and Health Sciences

Adult Consent Form – Control Groups

Project Title: The effects of growth, maturation and training on strength and power development in young female gymnasts.

I have read the information form regarding the research and fully understand what it entails. The research team has answered any questions I had comprehensively. I understand that I am entitled to ask any further questions at any time throughout the duration of the study.

I understand that I am entitled to withdraw my child from the project at any time without any repercussions.

I understand that:

- ✓ My child has volunteered to participate in the study on their own accord, and they are entitled to leave the study at any time should they wish to. ☐
- ✓ My child will be required to attend the requisite number of testing sessions (4 in total approximately 3 months apart) in order to complete the research project. ☐
- ✓ Personal data (age, weight, height, gender) for my child will be collected, and they will perform a number of strength and power tests, non-invasive ultrasound imaging of the lower leg, as well as a gymnastics vault (if my daughter does gymnastics). ☐
- ✓ All personal information and research data collected during the study will be kept in a secure location within the university grounds for a period of 7 years. The results of the study may be published in the future; however, my child's anonymity will be maintained at all times. ☐
- ✓ As a member of the research cohort, they may be contacted in the future by the principal investigator/supervisor or other Cardiff Met University researchers who may wish for me to contribute in follow-up studies or research of a similar nature. However, my child's participation in these studies would not be compulsory. ☐
- ✓ In order for the research team to determine how biologically mature your child is, we ideally need to know how tall both parents are (in feet and inches or centimetres). Using this data, we can calculate the predicted adult height for your child, and then determine how close to that predicted height your child is at the time of testing. ☐
☐

✓ I understand why the research team wishes to know the height of both parents of my child. I am happy to provide this information and for it to be used for the purposes of research.

Mother's height:

Father's height:

Signed (parent/guardian): _____

Date: _____

Print Name: _____

APPENDIX 14 – ETHICS FORM (STUDY 4)

When undertaking a research or enterprise project, Cardiff Met staff and students are obliged to complete this form in order that the ethics implications of that project may be considered.

If the project requires ethics approval from an external agency (e.g., NHS), you will not need to seek additional ethics approval from Cardiff Met. You should however complete Part One of this form and attach a copy of your ethics letter(s) of approval in order that your School has a record of the project.

The document ***Ethics application guidance notes*** will help you complete this form. It is available from the [Cardiff Met website](#). The School or Unit in which you are based may also have produced some guidance documents, please consult your supervisor or School Ethics Coordinator.

Once you have completed the form, sign the declaration and forward to the appropriate person(s) in your School or Unit.

PLEASE NOTE:

Participant recruitment or data collection MUST NOT commence until ethics approval has been obtained.

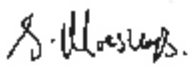

PART ONE

Name of applicant:	Sylvia Moeskops
Supervisor (if student project):	Dr Rhodri Lloyd
School / Unit:	School of Sport
Student number (if applicable):	20000498
Programme enrolled on (if applicable):	PhD
Project Title:	The effects of a 12-month neuromuscular training intervention on strength and power, and gymnastics performance in young, female, artistic gymnasts
Expected start date of data collection:	01/09/2018
Approximate duration of data collection:	1 year
Funding Body (if applicable):	N/A
Other researcher(s) working on the project:	Dr Rhodri Lloyd (DoS), Dr Jon Oliver (Co-supervisor), Dr Paul Read (Co-supervisor), Dr Greg Myer (Advisor) and John Cronin (Advisor)
Will the study involve NHS patients or staff?	No
Will the study involve human samples and/or human cell lines?	No

Does your project fall entirely within one of the following categories:	
Paper based, involving only documents in the public domain	No
Laboratory based, not involving human participants or human samples	No

Practice based not involving human participants (eg curatorial, practice audit)	No
Compulsory projects in professional practice (eg Initial Teacher Education)	No
A project for which external approval has been obtained (e.g., NHS)	No
If you have answered YES to any of these questions, expand on your answer in the non-technical summary. No further information regarding your project is required.	
If you have answered NO to all of these questions, you must complete Part 2 of this form	

In no more than 150 words, give a non-technical summary of the project
Recent position statements on youth resistance training have suggested that it is beneficial for all children, and particularly those involved in sports. Despite gymnastics typically involving high volumes of sport-specific training, the long-term effects of strength and power training on young female gymnasts are unclear. Additionally, how strength and power indices change in relation to chronological age, stage of maturation and training experience in this population remain unknown. Specifically, the current study will examine the effects of a 12-month training intervention on a range of strength and power indices in young female artistic gymnasts of varying stages of maturation. Therefore, this project will aim to: explore the effects of a 12-month neuromuscular training intervention on young female artistic gymnasts of different maturity status, comparing their results to gymnasts not participating in a neuromuscular training, and to age-matched controls. Data will be collected quarterly throughout the year long intervention.

DECLARATION:	
I confirm that this project conforms with the Cardiff Met Research Governance Framework	
I confirm that I will abide by the Cardiff Met requirements regarding confidentiality and anonymity when conducting this project.	
STUDENTS: I confirm that I will not disclose any information about this project without the prior approval of my supervisor.	
Signature of the applicant: 	Date: 09/02/18
FOR STUDENT PROJECTS ONLY	
Name of supervisor: Rhodri S. Lloyd	Date: 09/02/18
Signature of supervisor: 	

Research Ethics Committee use only	
Decision reached:	Project approved <input checked="" type="checkbox"/> Project approved in principle <input type="checkbox"/> Decision deferred <input type="checkbox"/> Project not approved <input type="checkbox"/> Project rejected <input type="checkbox"/>
Project reference number: 18/4/02R	
Name: Peter O'Donoghue	Date: 30/04/2018

Signature:



Details of any conditions upon which approval is dependant:

[Click here to enter text.](#)

PART TWO

A RESEARCH DESIGN

A1 Will you be using an approved protocol in your project? Yes

A2 If yes, please state the name and code of the approved protocol to be used²

To be used with a paediatric population:

- Isometric Mid-Thigh Pull (IMTP) Protocol 16/10/09L
- Jumping Performance Force Plate Protocol 16/10/04L
- Sub Maximal & Maximal Hopping Contact Mat Protocol 16/10/05L (Protocol adapted by using a force plate instead of a contact mat)
- 40-meter sprint Test Protocol 16/10/02L (Protocol adapted by using 20 meters)

A3 Describe the research design to be used in your project

Participants

Using freely available statistical software (G*Power version 3.1.9.2) a priori power analysis indicates that the training intervention will require a total sample size of $n = 90$ from the sample population to be examined with a margin of error of 20%, alpha level of 0.05 and confidence interval of 95%. Sample size estimation is based on published literature (Muehlbauer et al., 2012) with the margin of error of 20% selected due to the anticipated training response to the training stimulus, and influence of growth and maturation in the sample population. The total sample will then be divided into different sub-groups, including: a) gymnasts participating in the neuromuscular training intervention (GYM+NMT) ($n = 30$), b) gymnasts continuing in gymnastics training but not participating in the neuromuscular training intervention (GYM) ($n = 30$), and c) age-matched controls (CON) ($n = 30$). Each sub-group will be contain 15 pre- and 15 post-peak height velocity (PHV) girls. Peak height velocity will be determined from a sex-specific regression equation using basic somatic measures (e.g. body weight, seated height and standing height). The gymnasts (both GYM+NMT and GYM) will be recruited from local gymnastics clubs, while the non-gymnasts (CON) will be recruited from schools. The principle investigator will email the parents of the gymnasts who participated in previous studies, as well as the head-coaches of gymnastics clubs. The gymnasts participating in the training study and those that are not will be given separate information sheets, consent and assent forms to complete.

Study Overview

The gymnasts participating in the training intervention will be trained by the lead researcher in the Youth Physical Development Centre in National Indoors Athletic Centre (NIAC) on Cyncoed Campus. Testing for the tracking of strength and power characteristics, vaulting performance and maturational status (age, body mass, height, sitting height) will take place every 3-months in the SCRAM Research Laboratory also located within NIAC. Prior to any training or testing, a dynamic warm up will be performed and led by the researcher to physically prepare the participants for the demands of the session or testing battery. Figure 1 shows the annual plan for the gymnasts participating in the training intervention and includes an overview of the expected content of each training block and outlines the testing periods.

Testing procedures

Strength and power testing protocols

Each participant will be required to attend an initial familiarisation session during which they will be provided opportunities to familiarise themselves with the range of strength and power tests and the vaulting task. Following

² An Approved Protocol is one which has been approved by Cardiff Met to be used under supervision of designated members of staff; a list of approved protocols can be found on the Cardiff Met website here

this session, all participants will return for a baseline testing session and will be subsequently be re-tested every 3-months as a group. Strength and power profiles and vaulting performance of each participant will be assessed using a range of tests including: Isometric midthigh pull (IMTP) (16/10/09L), countermovement jump (16/10/04L), squat jump (16/10/04L), drop jump (16/10/04L), sub-maximal and maximal hopping (16/10/05L), 20-meter sprint (16/10/02L), horizontal broad jump, and 2D analysis of a straight vault. Although these approved protocols do not cover vulnerable populations such as children, these protocols are routinely used with youth populations and the procedures within the approved protocols will be followed. Ethics has previously been approved for the first three studies of the applicant's PhD with the use of children, which included using all of the above testing protocols with paediatric populations (code: 17/1/02R). Force plates with the associated software will be used for all jump protocols and the IMTP test, while video analysis will be used to assess vaulting performance at the beginning and at the end of the training intervention. Video footage will initially be stored, rated via digital analysis, and then stored with other data; however, footage will only be available to the research team.

*Note, the following are not approved protocols, but have been used previously by the research team with paediatric populations:

- Broad jump: Participants will stand behind a marked line and will be asked to jump as far as possible and 'stick' their landing. The distance jumped will then be measured from the participant's heels.
- Vaulting: Each gymnast will perform a "straight vault", which is the least technically demanding vault within the gymnastics curriculum that all participating gymnasts will be able to perform. Specifically, the vault involves an approach run up, take-off from a spring board and a straight shape during the flight phase, before landing on a safety mat. The vaults will be recorded using 2D video capture, with cameras positioned in the sagittal and frontal planes.

Ultrasonography

Participants will be requested to lie prone on a massage bed to enable muscle and tendon architectural characteristics of the lower limb to be assessed using a non-invasive, linear ultrasound probe. The static ultrasound images will be taken by a member of staff from the CSSHS (John Radnor), who has used the same ultrasonography techniques with pediatric populations as part of his PhD (ethics code: 15/4/01R). The variables collected will include: muscle thickness, pennation angle and fascicle length.

Neuromuscular training intervention

The purpose of this study will be to provide a comparative examination of the effects of a 12-month neuromuscular training intervention on young female artistic gymnasts (GYM+NMT) *versus* both gymnasts not participating in the intervention (GYM) and age-matched controls who are not participating in either gymnastics or neuromuscular training (CON). The GYM+NMT group will be trained in two separate groups (pre-PHV and post-PHV), to ensure the training intervention is delivered at a developmentally appropriate level. The age-matched CON group will be allowed to participate in regular physical activity but will not participate in the neuromuscular training programme. Figure 1 gives an overview of the content of the training programme. Internationally recognised resistance training guidelines will be followed when prescribing resistance training exercise (e.g. volumes, intensities, exercise selection). In general, the early focus of the intervention will be on the mastery of technical competence in a range of different exercises, with the volume and/or intensity of training being progressively increased over the course of the 12 months. The training intervention will involve the lead researcher delivering two sessions per week for 1 year to explore long-term adaptations in strength and power and vaulting performance in young artistic gymnasts, beyond that of gymnastics-specific training programmes. Changes in anthropometry, strength/power measures, ultrasonography, and vaulting performance will be collected every 3 months to examine the effects of the training intervention. Furthermore, some basic information will be collected on training intensity/volume throughout the training intervention: number of hours of gymnastics training and other physical activity per week, and rated perceived exertion (RPE) following the neuromuscular training sessions.

Statistical Analysis

Descriptive statistics (means \pm standard deviations) will be calculated for each quarterly measures of all anthropometric data, strength/power measures, vaulting, and ultrasound data. A mixed-model 3 x 4 x 2 (group x time interval x maturity status) repeated measures analysis of variance (ANOVA) will be used to test for significant differences in all variables, with a Bonferroni post-hoc analysis used to establish the origin of any between-group

differences. Correlation analysis will be used to examine the relationships between any changes in strength/power measures and changes in vaulting performance. Regression analyses will also be used to detect the main predictors of any changes in vaulting performance that occur. Finally, effect size (r^2) calculations will be used to assess the magnitude of change for all performance variables and will be classified as either; small (≤ 0.2), medium (0.21-0.5), large (0.51- 0.8), or very large (0.81-1.3).

References

Muehlbauer T, Gollhofer A, and Granacher U. Sex-related effects in strength training during adolescence: a pilot study. *Percept Mot Skills* 115: 953-968, 2012.

A4 Will the project involve deceptive or covert research?	No
A5 If yes, give a rationale for the use of deceptive or covert research	
N/A	
A6 Will the project have security sensitive implications?	No
A7 If yes, please explain what they are and the measures that are proposed to address them	
N/A	

B PREVIOUS EXPERIENCE

B1 What previous experience of research involving human participants relevant to this project do you have?

The researcher is currently a technician-demonstrator within the Sports Conditioning, Rehabilitation and Massage (SCRAM) discipline and has vast experience in the administration of field-based testing protocols with children in both an applied and research setting. The researcher is also a certified strength and conditioning specialist (CSCS), and holds a level 2 in Women's Artistic gymnastics, and has experience in coaching young athletes within Gymnastics clubs and the Youth Physical Development Centre. The researcher has successfully completed 3 other studies related to her PhD prior to submitting this ethical application. The researcher is now seeking ethical approval for the final project of her PhD.

B2 Student project only

What previous experience of research involving human participants relevant to this project does your supervisor have?

Dr Rhodri Lloyd has published in excess of 70 peer reviewed research articles within the paediatric literature and completed a PhD in the field of paediatrics. He currently supervises or co-supervises 11 PhD students. Dr Jon Oliver is a Reader in Applied Paediatric Exercise Science, has over 70 peer reviewed research articles, supervises 11 PhD students, and has eight successful PhD completions. Dr Paul Read completed his PhD in paediatric exercise science with a specific focus on testing and evaluating injury risk. He currently serves on the supervisory team of 3 PhD students and has in excess of 25 peer-reviewed publications. Dr Greg Myer is a world leader in paediatric sports medicine, has published in excess of 250 research manuscripts, and has served on the supervisory team of more than 20 PhD students. Professor John Cronin is a world leader in strength and conditioning, has published in excess of 200 research manuscripts and has 44 successful PhD completions.

C POTENTIAL RISKS

C1 What potential risks do you foresee?

7. There are risks when working with vulnerable populations, in this case, young children.
8. There is the possibility of underlying medical conditions or existing injuries leading to an increased risk of injury during the testing period.
9. There is the possibility that participants may experience some fatigue following training and testing, albeit the probability of this is low.
10. There is the possibility of injury during training and physical tests.
11. Environmental risks.
12. The identification of participants from within the study.
13. There is a possibility that the participants could choose to stop participating in the study.

C2 How will you deal with the potential risks?

7. The supervisory team have all attended a child welfare and safeguarding workshop, those coaching and testing have completed DBS checks, and will not work in a 1-to-1 situation with any of the participants. Appropriate, non-technical child and adult participant information sheets will be provided (see appendices for all documentation).
8. A physical activity readiness questionnaire (PAR-Q) which is approved by Research Ethics Sub-Committee (RESC) will be completed by each parent of the participant prior to each testing session. The researcher will review the form prior to testing in order to determine any health risks that may prevent the subject from participating. Acceptance in the study will only be granted after successful completion of the PAR-Q. For participants taking part in the training study, the principle investigator (coach) will perform a verbal PAR-Q at the beginning of each training session to ensure the gymnasts are fit to participate. Reasons for not participating (e.g. injury or illness) will also be documented.
9. Participants will have at least 24 hours recovery between each training session each week. For the physiological testing sessions, the athletes will be given enough rest time to ensure full recovery between trials, and different tests.
10. Training will be provided by the candidate who is a qualified strength and conditioning coach and has experience of coaching youth in both strength and conditioning and gymnastics. Initially, all exercises will be performed with only the participants body weight. Once these movements are deemed competent and consistent, additional load will be progressively added on an individual basis. All physiological tests involved within the battery and those that have been proposed for inclusion (the straight jump vault), will mirror those included within any explosive-based training session that the gymnasts routinely participate in. Therefore, the participants should be well accustomed to performing such exercises, which should reduce the associated risk of fatigue or injury to the participants.
11. Training will be implemented in the Youth Physical Development Centre in NIAC and testing will take place in the SCRAM Research Laboratory, which has full risk assessments. There should be no risks to the researcher carrying out the testing procedures or for using the equipment.
12. All raw data, including videos, will be stored electronically and treated confidentially, and all participants' results will be reported anonymously. All methods will be based on RESC approved laboratory procedures (laboratory procedures manual). As the project involves participants under the age of 18 years old, both consent for each child and assent from a parent or guardian will be obtained prior to commencement of the study. The university will keep stored data securely for a period of up to 10 years.
13. Risk management strategies to reduce the risk of participants dropping out of the study will include the production of termly reports for parents/athletes/coaches and include individualized targets for the gymnasts. The neuromuscular training provision will be free to the athletes participating in the study and the researcher will ensure the parents, athletes and coaches understand the aims of the project to optimize adherence to the training programme. Furthermore, the Youth Physical Development Centre has a proven track record of retaining young athletes within training programmes across 6 different sports. Finally, the target duration of the training intervention is 12-months, however, should the number of athletes participating in the study drop off over the year, the researcher will have collected quarterly measures of performance and therefore still have an appropriate research design.

When submitting your application, you **MUST** attach a copy of the following:

- All information sheets
- Consent/assent form(s)

An exemplar information sheet and participant consent form are available from the Research section of the Cardiff Met website

Term	Autumn term														Spring term														Summer term															
Week No.	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	
School holidays									HT						H								HT							H					HT									H
Mesocycle	T	1						2					T	NT	3						4					T	NT	5						6					T	NT				
Training emphasis		Shapes & technique						Base strength & shapes							Strength						Strength - Power							Strength - Power						Power (maintain strength)										
Microcycle		1	2	3	4	5	6	1	2	3	4	5			1	2	3	4	5	6	1	2	3	4	5			6	1	2	3	4	5	6	1	2	3	4			5			
Block content		Primary focus is to develop movement competency in fundamental movement skills & athletic motor skill competencies e.g. squat, hinging. High repetitions (10-15) of body-weight exercises performed with good technique.						Start to introduce exercises with external load. High exercise repetitions (10-15), 3 sets and body weight or low loads to develop a base level of strength.							Develop strength. Higher intensities but the prescription of load is based on the individual. Lower repetitions (< 8), 3-5 sets, longer rest periods between sets.						Primary strength exercise first (prescription similar to previous block), followed by a ballistic exercise e.g. jump squat (load is exercise dependent, lower reps).							Emphasis is the same as previous block. Variations in exercises/loads will be introduced.						Power exercise programmed first (prescription of loads based on exercise selection), 2-5 repetitions, 1-5 sets, followed by a strength exercises.										
HT = Half term; H =school holiday; T = testing; NT = No training;																																												

Figure 1. Shows an overview of the annual training plan that the gymnasts' participating in the training intervention will follow.

APPENDIX 15– PHYSICAL ACTIVITY READINESS QUESTIONNAIRE (STUDIES 1-4)

Physical Activity Readiness Questionnaire (PAR-Q)

Please read the questions carefully and answer each one honestly. Circle your answer and write extra information if you need to. You and your parent/ guardian must complete this form together. Once you are finished, write your name. Then, make sure you ask your parent/ guardian or guardian to sign it and then you can hand it back to myself (Sylvia Moeskops) before the programme is started. All information you give will be kept a secret.

Full name (Child): _____

Address: _____

Telephone Number: _____

E-mail: _____

1. Has your doctor ever said that you have a heart condition or that you should only do physical activity recommended by a doctor?

Yes No

2. Have you experienced chest pain when exercising within the last month?

Yes No

3. Are you currently taking any medication?

Yes No

4. Do you lose balance because of dizziness or do you ever lose consciousness?

Yes No

5. In the past year have you had any major illness or major surgery?

Yes No

6. Do you have any bone or joint problems that could be made worse by physical activity?

Yes No

6. Do you have low or high blood pressure?

Yes No

7. Do you suffer from diabetes, epilepsy or asthma?

Yes No

If yes please give details:

8. Have you had a cold in the last two weeks?

Yes No

9. Do you know of any other reason why you should not participate in physical activity?

Yes No

If you have answered YES to one or more questions we may need you to contact your doctor before starting to exercise. If your health changes so that you may then answer YES to any of these questions, tell the programme leader as soon as possible.

I have read, understood and completed this questionnaire.

Any questions that I had were answered to my full satisfaction.

Name of Child: _____

Name of parent/guardian: _____

Signed: _____

Date: _____