THE INTERACTION OF RESISTANCE TRAINING AND MATURATION ON DROP JUMP KINETICS IN YOUNG BOYS

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Abstract

Existing paediatric literature has highlighted the various growth- and maturation-related neuromuscular changes that children experience as they move through adolescence into adulthood. These changes have been linked to increased force output, sprint velocities and jump height (Radnor et al., 2021; Radnor et al., 2018; Tumkur Anil Kumar et al., 2021). The performance of these movements is underpinned by the stretch shortening cycle (SSC) muscle action, which involves a braking phase, rapidly followed by a propulsive phase (Komi, 2000). Drop jumps (DJ) are rebound based tasks where the sequence of muscle actions involved in the execution replicate those observed in locomotive tasks, such as sprinting, making it an appropriate tool for the examination of SSC function. When using the DJ as an assessment tool, the measures reported by previous studies have primarily been simple field-based metrics such as jump height, ground contact time and reactive strength index (RSI). However, these metrics fail to provide an insight into the phases of the jump and differences in jump strategy, and it therefore becomes necessary to look beyond these measures and examine the kinetics during the braking and propulsive phase of the DJ. *Study 1* identified that jump height has a relatively greater influence than ground contact time on RSI during a DJ, and subsequently revealed that jump height, ground contact time and RSI might best represent relative net impulse, relative propulsive force and relative power, respectively. The study also identified the various kinetic qualities that these performance measures failed to reflect, thereby highlighting the need for the examination of DJ kinetics. *Study 2* established moderate to excellent relative reliability and acceptable absolute reliability for most DJ kinetic variables across all maturity groups (ICC = 0.59 to 0.91; CV = 3.9% to 9.9%), with the acceptable threshold for random variation being exceeded in some cases, such as braking peak force and braking rate of force development (CV

= 10.4% to 34.3%). The findings of the study revealed similar magnitude of differences in the kinetic variables between successive maturity groups and highlighted that the more mature participants exhibited better SSC performance. *Study 3* highlighted that post-PHV boys responded better to a short-term combined strength and plyometric training intervention compared to their pre-PHV counterparts. The post-PHV boys exhibited large improvements in mean and peak forces, impulse, power, work done and centre of mass velocity, underpinning small to moderate improvements in jump height and RSI. While the pre-PHV boys exhibited moderate increases for several kinetics variables, they showed no significant changes for majority of the kinetics resulting in small increases in jump height and leaving RSI unaffected. *Study 4* revealed that the combination of neuromuscular and traditional resistance training elicited improvements in all absolute impulse, as well as braking and propulsive work done, underpinning small increases in jump height but leaving RSI unchanged. While findings from the study suggested that the combination of neuromuscular and traditional resistance training might help to enhance training-related adaptations, they also highlighted that the adaptations following resistance training are specific to the nature of the stimulus.

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When I completed my Architecture degree 10 years back, it felt like the hardest thing I had done and I was adamant I would not encounter anything tougher. It is safe to say the PhD now tops that list. This PhD has been a roller coaster of a ride, with the pandemic throwing it slightly off-course. I would not be in this position today without the support I have received from so many people along the way, and I owe them all an incredible amount of gratitude.

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Publications and Presentations from the Thesis

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List of Terms and Abbreviations

Children – Pre-pubertal youth

Adolescents – Post-pubertal youth

Youth – Pre- and post-pubertal

SSC – Stretch Shortening Cycle

RSI – Reactive Strength Index

DJ – Drop Jump

CMJ – Countermovement Jump

SJ – Squat Jump

CSA – Cross-sectional Area

PHV – Peak Height Velocity

MTU – Muscle-Tendon Unit

RFD – Rate of Force Development

KE – Knee Extensors

PF – Plantar Flexors

RF – Rectus Femoris

VL – Vastus Lateralis

VM – Vastus Medialis

VI – Vastus Intermedius

CI – Co-contraction Index

EMD – Electromechanical Delay

EMG – Electromyography

GM – Gastrocnemius Medialis

H – hamstrings

MPF – Mean Power Frequency

MVC – maximal voluntary contraction

SOL – Soleus

TA – Tibialis Anterior

TS – Triceps Surae

EF – Elbow Flexors

MUA – Motor Unit Activation

Chapter 1 - Introduction

1.1 OVERVIEW

Muscle function is often considered in terms of isometric, concentric and eccentric actions (Babault et al., 2001; Nakazawa et al., 1993). However, most naturally occurring movements such as running and jumping rely on the stretch shortening cycle (SSC) (Komi, 2000). This implies that the SSC underpins the performance of a large number of athletic movements, thereby making it an important aspect of athletic development throughout growth and maturation. The SSC is a muscle action that is characterised by an eccentric (braking) phase, followed by a concentric (propulsive) phase (Komi, 2000). The prior braking phase has been demonstrated to enhance performance in the subsequent propulsive phase (Bosco et al., 1987; Komi, 2000). Any differences between individuals in the resultant output can be attributed to the mechanisms that underpin this SSC function, such as a greater contraction time, greater working range, elastic energy usage, stretch reflex contributions and levels of neural excitation (Flanagan and Comyns, 2008; Komi and Bosco, 1978; Turner and Jeffreys, 2010).

The SSC muscle action results in the production of greater positive work and power during the propulsive phase, as opposed to isolated propulsive-only muscle actions (Komi, 2000). This enhanced positive work during the propulsive phase of the SSC can be attributed to; (i) The eccentric phase allowing time for the development of considerable force prior to the propulsive contraction, unlike propulsive only contractions (Bobbert et al., 1996). (ii) The mechanical work done during the braking phase being absorbed and stored as potential energy within the series elastic component (Asmussen, 1953; Biewener and Roberts, 2000; Ettema, 1996), and a portion of this energy can subsequently be utilised to amplify the force and power production during the propulsive phase of the SSC movement (Cavagna et al., 1968; Komi and Bosco, 1978; LaStayo et al., 2003). (iii) The high force at the initiation of the propulsive phase leads to greater lengthening of the tendon compared to the fascicle thereby allowing the muscle fibre to contract at a near constant length as the contraction progresses, resulting in a more favourable length-tension relationship for force production (Kurokawa et al., 2001; Kurokawa et al., 2003).

1.1.1 Assessment of Stretch Shortening Cycle Function

Prior research examining SSC function has often utilised countermovement jumps (CMJ) and squat jumps (SJ), with measures of jump height, pre-stretch augmentation, eccentric utilisation ratio and velocity of vertical take-off being reported (Edwen et al., 2014; Harrison and Gaffney, 2001; Sahrom et al., 2013). However, the SJ lacks a braking phase and it has been suggested that the longer amortization phase in a CMJ compared to rebound based activities (Komi and Gollhofer, 1997), would result in the stretch reflex not being activated and thereby SSC function not being appropriately represented (Lloyd et al., 2011a; Schmidtbleicher, 1992). Rebound tasks such as hopping, repeated vertical jumps and drop jumps (DJ) involve a rapid transition from braking to propulsive phase (Komi, 2000) and elicit pre-activation as well as a stretch reflex in the lower limb (Barr and Nolte, 2011; Bassa et al., 2012; Gillen et al., 2019; Komi, 2000), thereby providing a more accurate representation of SSC action. Much like in most sport-based movements, the SSC action during drop jumps has an emphasis on braking overload during a phase of triple flexion of the lower limb, which then is followed by a quick transition to rapid triple extension (Pedley et al., 2017). This makes the DJ a suitable tool for the assessment of an individual's SSC function. While reactive strength index (RSI) is a measure that is commonly utilised to assess an individual's SSC function (Healy et al., 2018), prior research has suggested that such outcome measures fail to account for different jump strategies and do not reflect what is occurring during the different phases of the jump (Healy et al., 2018) that could underpin the resultant jump performance. Furthermore, it is currently unknown what kinetic qualities this measure of RSI represents. With the braking phase of the SSC strongly influencing the propulsive phase (Bosco et al., 1987; Komi, 2000), **understanding the determinants of SSC function and subsequent jump performance requires the examination of braking and propulsive kinetic measures such as mean forces, impulse, mean power, centre of mass (COM) velocity and COM displacement rather than just outcome metrics** (Meylan et al., 2012).

1.1.2 Maturation-Related Development of Stretch Shortening Cycle Function

Youth differ from adults in several muscular performance attributes including normalised strength and power, and this can be attributed to the process of biological maturation (Dotan et al., 2012). Biological maturation refers to progress towards a mature state, and varies in timing and tempo, and between different body systems (Beunen and Malina, 2008). The process of growth and maturation is associated with the occurrence of several of neural and structural changes, and also an increase in circulating androgens as youth transition from childhood, through adolescence and into adulthood (Binzoni et al., 2001; Hiort, 2002; Radnor et al., 2018). The maturation-related changes include increases in muscle CSA, volume and thickness, muscle fascicle length, tendon CSA and stiffness, voluntary muscle activation, pre-activation and stretch-reflex magnitude, alongside decreases in co-contraction (Radnor et al., 2018; Tumkur Anil Kumar et al., 2021). These changes in neuromuscular mechanisms can be expected to facilitate an enhancement of force producing capabilities and also a change in youths' expression of forces. Such an improvement in force producing capabilities would explain the maturity-related improvements in sprint (Meyers et al., 2015; Moeskops et al., 2021; Papaiakovou et al., 2009) and jump performance (Moeskops et al., 2021; Quatman et al., 2006; Taylor et al., 2010) that prior research has consistently reported.

Given the large number of maturation-related neuromuscular changes that youth experience, it is important for pratitioners to consider biological maturation when designing training programmes in order to optimise training adaptations and minimise activity-related risk of injury (Lloyd and Oliver, 2013a). The assessment of biological maturity is slightly more challenging than the determination chronological age due to large variations in magnitude, timing and tempo of the adolescent growth spurt between individuals (Lloyd and Oliver, 2013a). Table 1.1 highlights the various methods of assessing biological maturation.

Table 1.1 Methods of assessing biological maturation.

Asessment	Type	Process of Assessment	Notes
Greulich-Pyle method (Greulich and Pyle, 1959)	Skeletal age	Skeletal age is determined by comparing the radiograph of a child's left wrist against reference x-ray plates of varying levels of skeletal maturation.	Fails to account for individual rates of development of different bones and requires radiographic equipment.
Tanner-Whitehouse method (Tanner et al., 2001)	Skeletal age	Radiographs of the bones are analyzed and compared to a series of statements and detailed shape analyses. The individual bones are given an independent maturation score and the cumulative score is converted to a skeletal age.	Fairly complex and time-consuming process, that requires radiographic equipment.
Fels method (Roche et al., 1988)	Skeletal age	The radius and ulna, carpals and metacarpals, and phalanges are graded according to age and sex; ratios between length and width of the epiphysis and metaphysis of the long bones are measured, and the degree of ossification for the pisiform and adductor sesamoid are recorded. Skeletal aage and standard error of estimate are subsequently calculated using specific software.	Although this skeletal method does have the ability to estimate the standard error which is a benefit for long-term tracking of maturation, it is a complex and time consuming process that requires specialist equipment.
Tanner Criteria (Tanner, 1962)	Sexual age	Assessed via observations of secondary sexual characteristics which are subsequently compared against five distinct reference stages, Tanner Stages 1 to 5.	Invasive in nature and when self-assessment is employed boys and girls, respectively, have been reported to generally overestimate and underestimate their own sexual development.
Age at menarche (Malina et al., 2004; Rowland, 2005)	Sexual age	Specific to females, this method is typically a retrospective measure where biological maturity is assessed by asking the individual to recall the onset of their menstrual first period.	Does not account for the temporal delay between the onset of puberty and subsequent onset of menarche, therefore identifying a girl who is premenarchaeal does not suggest that she is also pre-pubertal.

Growth rates (Stratton and Oliver, 2013)	Somatic assessments	Involves longitudinal anthropometric assessment of breadths, widths and lengths of specific indivudal landmarks: overall stature and body mass; sum of skinfolds to determine levels of adiposity; and a combination of the above to provide an estimate of somatotype.	The repeated collection of measures over a period of time enables the analysis of growth curves, from which the age at maximum rate of growth during the adolescent spurt can be identified. However, regular collection of such data over an extended period of time might not be common practise within some sports/training settings, which would make it challenging to ascertain at which point in time the child started their growth spurts.
Predicting peak height velocity (PHV) (Mirwald et al., 2002)	Somatic assessments	The predictive equation acknowledges that the long bones of the legs experience peak growth ahead of the shorter bones of the trunk and incorporates this growth pattern through the attainment of chronological age, body mass, standing height and seated height to determine years from adolescent growth spurt/PHV.	The prediction equation is suggested to possess a standard error of approximately 6 months, with the error becoming smaller closer to PHV.
Adult stature predictions (Tanner et al., 1970)	Somatic assessments	The somatic maturity is assessd using percentages of predicted adult stature. This process involves calculating midparental height and using a correction of adding or subtracting 6.5 cm for boys and girls respectively based on an average difference in stature between both sexes. Khamis and Roche (1994) subsequently developed a regression equation that also includes current stature and weight of the child, to estimate enetual adult height.	The methods used to predict adult stature have been suggested to typically involve a standard error of approximately 3-5 cm, with the error of prediction narrowing with increasing age.

Prior research has demonstrated the growth and maturation-related development of SSC function during various hopping and jumping tasks (Laffaye et al., 2016; Lloyd et al., 2011b; Malina et al., 2004). In a review of available literature, Radnor et al. (2018) highlighted that the maturity-related augmentation in hopping and jumping stemmed from improvements in various neural mechanisms and changes in muscle-tendon architecture that youth experience as they transition towards adulthood. Amongst these jumping tasks, the DJ is a rebound based activity in which the sequence of muscle actions involved and the stretch reflex elicited makes it suitable for the evaluation of SSC function (Bobbert et al., 1987b; Marshall and Moran, 2013). While prior research by Gillen et al. (2019) and Pedley et al. (2020) have examined several kinetic measures during DJs in youth, they failed to consider the full range of important kinetic descriptors of DJ performance and SSC function. **With youth experiencing a wide range of neural and structural changes associated with maturation** (Radnor et al., 2018; Tumkur Anil Kumar et al., 2021) **and the influence that the braking phase has on the subsequent propulsive phase** (Bosco et al., 1987; Komi, 2000), **a more detailed understanding of the development of SSC function in youth is required.**

1.1.3 Youth and Resistance Training

Historically there was a notion that youth should not engage in resistance training until they were sufficiently mature (Behm et al., 2008), due to many parents, coaches and physicians believing it to be a dangerous activity (Pierce et al., 2008). This notion led to many strength training and weightlifting facilities restricting access till individuals were 16-18 years of age (Lloyd and Oliver, 2019; Stone and Mizuguchi, 2013). Specifically, the concerns were related to resistance training causing stunting of growth, damage to epiphyseal plate and having high injury rates (Behm et al., 2008; Blimkie, 1993; Stone and Mizuguchi, 2013). Researchers have suggested that these notions were founded on opinion rather than actual scientific evidence (Pierce et al., 2008). Research since these earlier years has succeeded in providing evidence demonstrating the safety and efficacy of resistance training in both children and adolescents (Faigenbaum, 2000; Falk and Eliakim, 2003; Falk and Tenenbaum, 1996; Hamill, 1994). Although limited in number, reviews and studies examining injury types and rates have indicated that those resulting from resistance training are not as excessive and are far less common than those associated with sports such as American football, gymnastics, basketball, rugby or football (Hamill, 1994; Lloyd and Oliver, 2013b; Palmer-Green et al., 2015).

There now exists a large body of evidence highlighting the benefits of youth participating in resistance training, including improvements in a range of measures of physical fitness such as muscle strength, cardiorespiratory fitness and body composition as well as a reduced risk of injury (Faigenbaum, 2007; Faigenbaum and Myer, 2010; Faigenbaum et al., 1999; Sander et al., 2013; Thomas et al., 2009). While research has also highlighted the positive influence of resistance training on various sport based movements such as jumping (Chelly et al., 2009; Chelly et al., 2015) and sprinting (Meylan and Malatesta, 2009; Uzelac-Sciran et al., 2020) in youth, it is remains unclear how resistance training influences SSC function in youth of different maturity status. Furthermore, while research has examined the effect of different types of resistance training interventions, training intensities and training duration in youth, literature examining the effect of what is most achievable in youth settings (i.e., field-based training) vs what is desirable (i.e., field- and gym-based training) is scarce. **With the performance of most sport based movements being underpinned by SSC function, the examination of SSC development in response to resistance training interventions in youth is important** (Cormie et al., 2011a; Newton and Kraemer, 1994).

1.2 AIMS AND OBJECTIVES OF THE THESIS

The purpose of the current thesis is to investigate the influence of growth and maturation on SSC development by examining kinetic measures collected during the braking and propulsive phases of the DJ. Subsequently, the thesis also examines the development of these kinetic variables in response to the interaction of training and maturity status. In order to address the gaps within the literature identified in section 1.1, the specific aims of the thesis are as follows:

1. Determine the relative importance of jump height and ground contact time in the calculation of RSI, and understand the associations between performance measures and kinetic outcomes.
2. Determine the reliability of the kinetic variables measured during the braking and propulsive phases of a DJ, at different stages of maturation, and examine the influence of maturity status on these variables.
3. Examine the development of the DJ kinetic variables in pre- and post- PHV male athletes, in response to a 12-week combined strength and plyometric training programme.
4. Examine the effect of resistance training dosage during a 6-month combined strength and plyometric training intervention on the DJ kinetics in young male athletes.

1.3 ORIGINALITY, SIGNIFICANCE AND RIGOUR OF THE THESIS

1.3.1 Originality

Originality refers to the extent to which research makes a distinctive development to previous literature or introduces a novel way of thinking. Prior research has highlighted the development of SSC function associated with maturation, and suggested that this development can be enhanced through resistance training (Pedley et al., 2020). Drop jumps involve large braking forces, as well as high speed braking action accompanied by a short delay between peak velocity of the braking phase and the start of propulsive phase (Bobbert et al., 1987b; Bobbert et al., 1986) making it a valuable tool for the assessment of SSC function. While existing paediatric literature has examined the development of this SSC function in youth, these studies have predominantly reported measures of jump height, ground contact time and RSI, with limited kinetics. The absence of in-depth kinetics limits our understanding of the full strategy that drives performance of movements underpinned by SSC function. This thesis provides an insight into the maturity-related development of various kinetic measures examined during the braking and propulsive phases of the DJ. The thesis also presents a series of novel studies that provide an understanding of how maturity status and training dosage can influence resistance training-related changes in these kinetic measures. Much like the studies examining maturity-related development of SSC function, research examining training-related development of SSC function in youth have primarily reported simple field-based metrics. An understanding of how resistance training influences the development of kinetic qualities underpinning SSC function will allow practitioners to prescribe efficient training programmes.

1.3.2 Significance

Significance makes reference to the extent that research is likely to exert on an academic field or applied practise. While the empirical studies within the current thesis are yet to be published, the overall quality of work would indicate that the research can have notable reach. *Study 1* is the first study to provide practitioners and researchers with an understanding of the kinetic qualities represented by measures of jump height, ground contact time and RSI collected during a DJ. It goes on to highlight the importance of examining kinetics qualities when assessing SSC function. *Study 2* establishes the reliability of various kinetic variables measured during the braking and propulsive phases of a DJ in youth of different maturity status, highlights maturity status-related improvements in these kinetic qualities and demonstrates that these improvements are not always reflected by outcome measures such as jump height, ground contact time and RSI. *Study 3* is one of the first studies to report in-depth changes in the kinetic outcomes of the DJ in response to resistance training in youth. It provides evidence of maturation-related responses to training, with those who are post-PHV responding more positively to a short-term combined strength and plyometric training programme. With the meta-analysis in the current thesis identifying that majority of previous training studies have failed to report kinetic outcomes from a DJ, *studies 3 and 4* are amongst the first to do so. Finally, *study 4* is one of the first to highlight the influence that training dosage (field-based vs field- and gym-based) has on the development of DJ kinetics during a long-term combined strength and plyometric training programme. Combined, the outcomes of the four studies have the potential to influence applied practise and future scientific research within the field of paediatric strength and conditioning by providing insight regarding the development and trainability of the SSC as observed during a DJ.

1.3.3 Rigour

Rigour refers to the clarity in articulation of the purpose of the research, utilisation of appropriate research design, the intricacy of selected methodologies and strength of the evidence presented. The current thesis presents a series of logical, interrelated studies containing research questions that ultimately address the proposed aims highlighted in *section 1.2*. Some of the notable strengths of the respective research designs include establishing reliability (within-session) of the variables being examined for different maturity status, the application of prediction error rates in the maturity offset equations, use of robust and validated measurement techniques (force plate technology and force-velocity profiling), use of evidence-informed training interventions to understand causation, as well as a range of appropriate and relevant statistical analysis methods to facilitate the correct interpretation and clear presentation of the findings within each study.

1.4 ORGANISATION OF THE THESIS

The focus of this thesis is to further the understanding of growth and maturation-related development of SSC function by examining maturity-related augmentation of DJ kinetics in young males and subsequently examining the interaction of maturation and resistance training on these DJ kinetics. *Figure 1.1* provides a schematic of the thesis organisation.

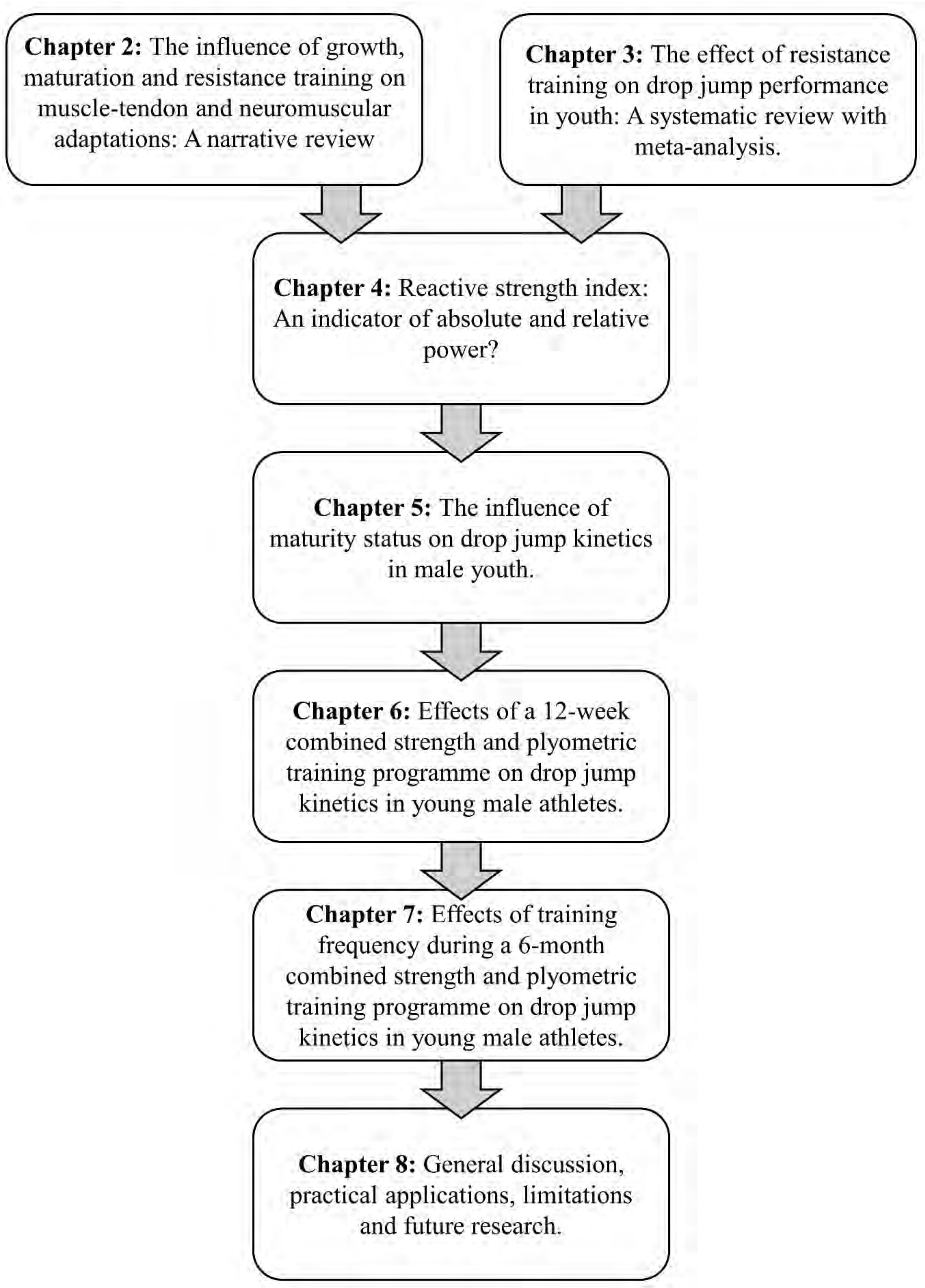


Figure 1.1 Schematic of the organisation of the thesis.

Chapter 2 is a narrative review that highlights the growth and maturity-related changes in muscle-tendon and neuromuscular mechanisms in youth, and the interaction of maturity- and training-related changes in muscle-tendon and neuromuscular mechanisms and their subsequent effect on performance. **Chapter 3** is a systematic review with a meta-analysis that quantifies the effects of resistance training on DJ performance in youth. **Chapter 4** (i) determined the relative importance of jump height and ground contact time in the calculation of RSI, and subsequently provided an understanding of the associations between DJ performance measures and kinetic outcomes. **Chapter 5** utilised a cross-sectional analysis and determined (i) the reliability of the various kinetic variables measured during the braking and propulsive phases of a DJ, and (ii) the influence of maturity status on those kinetic variables. **Chapter 6** examined the development of the DJ kinetic variables in pre- and post-PHV male athletes in response to a 12-week combined strength and plyometric training programme. **Chapter 7** examined the effect of resistance training dosage, neuromuscular training vs neuromuscular and traditional resistance training, on the DJ kinetic variables in young male athletes during a 6-month combined strength and plyometric training programme. **Chapter 8** provides a discussion of the thesis, revisiting the overall aims of the thesis in the context of the empirical studies carried out. Additionally, the chapter provides an overview of areas needing to be addressed by future research.

Chapter 2 – The Influence of Growth, Maturation and Resistance Training on Muscle-Tendon and Neuromuscular Adaptations: A Narrative Review

2.1. INTRODUCTION

Growth and maturation underpin a significant number of natural changes in the neuromuscular system, such as changes in the muscle-tendon architecture and muscle activation, as well as an increase in circulating androgens as youth transition from childhood, through adolescence and into adulthood (Binzoni et al., 2001; Hiort, 2002; Radnor et al., 2018). These neuromuscular changes may begin to explain the improvements observed in sprint (Meyers et al., 2015; Moeskops et al., 2021; Papaiakovou et al., 2009) and jump performance (Moeskops et al., 2021; Quatman et al., 2006; Taylor et al., 2010) as youth mature. However, research comparing the magnitude of these maturity-related changes and their implications on the mechanisms driving performance improvements are scarce.

There currently exists a large body of evidence showing the positive influence of resistance training on outcome measures such as jump height (Chelly et al., 2009; Chelly et al., 2015; Lloyd et al., 2016; Matavulj et al., 2001; Uzelac-Sciran et al., 2020), change in direction speed (Meylan and Malatesta, 2009; Thomas et al., 2009), running velocities (Chelly et al., 2015; Lloyd et al., 2016) and sprint times (Meylan and Malatesta, 2009; Uzelac-Sciran et al., 2020) in youth. However, very few studies have examined the mechanistic changes following resistance training and the subsequent effect on the force producing capabilities that may underpin these training-induced improvements in performance (Daly et al., 2004; Dotan et al., 2013; Metaxas et al., 2014; Mitchell et al., 2011; Ramsay et al., 1990). The interaction between growth, maturation and resistance training to promote neuromuscular adaptations in youth is less well understood compared to just growth- and maturity-related changes alone (Chestnut and Docherty, 1999; Marshall et al., 2011). An awareness of how the different muscle-tendon and neuromuscular changes adapt in response to growth, maturation and training is important in order to design more appropriate training programs and optimise training responsiveness in youth populations. Therefore, the aims of this review are to provide an overview of (i) growth and maturity-related changes in muscle-tendon and neuromuscular mechanisms in youth, and (ii) the interaction of the maturity- and training-related changes in muscle-tendon and neuromuscular mechanisms, and their subsequent effect on performance.

2.2 INFLUENCE OF GROWTH AND MATURATION ON MUSCLE-TENDON STRUCTURE AND PROPERTIES

The ability to generate maximal external force at any given velocity is influenced by a series of morphological or structural factors, such as muscle cross-sectional area (CSA), physiological CSA, muscle volume, pennation angle and fascicle length (Cormie et al., 2011a). Physiological CSA differs from anatomical CSA in that the former is a cross-section perpendicular to the muscle fibre direction and is therefore always larger in pennate muscles (Hudelmaier et al., 2010). While muscle CSA directly correlates with force production (Jones et al., 2008; Tonson et al., 2008), changes occurring in terms of the specific muscle architecture may also underpin natural strength gains as youth transition into adulthood (Radnor et al., 2018). Furthermore, the role that the tendons have in rapid force production and transmission is also vital for performance and is influenced by its properties (Bojsen-Møller et al., 2005; Cormie et al., 2011a; Grosset et al., 2009). Prior research has shown that these structural factors undergo growth and maturity-related changes as children transition into adolescence (Kanehisa et al., 1995; Kubo et al., 2001; Kubo et al., 2014a; Radnor et al., 2018).

2.2.1 Muscle Cross-Sectional Area

Cross-sectional area for an individual muscle is the largest CSA along the length of that muscle (Morris, 2008). Studies have reported increases in muscle CSA during maturation, with some suggesting that the greatest changes occur in boys around the age of 13–15 years (Kanehisa et al., 1995). Furthermore, as highlighted in *table 2.1*, adults demonstrate greater muscle thickness than youth (O'Brien et al., 2010a) and older adolescents exhibit greater muscle thickness relative to their younger peers (Grosset et al., 2009; Morris, 2008). Longitudinal research has shown that adolescents who had experienced their growth spurt increased muscle thickness to a greater extent than those experiencing, or yet to experience peak height velocity (PHV) (Radnor et al., 2021). Similarly, researchers have observed an approximate threefold difference in quadricep muscle volume and twofold difference in quadricep physiological CSA between boys and men (O'Brien et al., 2010a).

Table 2.1 Effects of growth and maturation on muscle morphology in youth (for multiple groups difference and effect size are expressed for consecutive pairs).

Author	Developmental Change	Sample Age Range	Findings		
			Values	**Difference (%)**	**Effect Size (*g*)**
O' Brien et al. **(2010a)**	Muscle PCSA, Volume, Pennation Angle and Fascicle Length	10 men aged 28.2 ± 3.6 years and 10 boys aged 8.9 ± 0.7 years not participating in organised sport or physical activity outside school.	Muscle PCSA - Men vs Boys (cm^2)		
			(VL) 74.04 ± 17.04 vs 31.43 ± 7.40	136%	3.24
			(VM) 55.40 ± 16.12 vs 21.71 ± 5.40	155%	2.80
			(VI) 59.28 ± 17.87 vs 30.99 ± 6.70	91%	2.10
			(RF) 43.06 ± 11.88 vs 20.46 ± 4.80	110%	2.49
			Muscle Volume - Men vs Boys (cm^3)		
			(VL) 691.22 ± 147.90 vs 236.13 ± 42.30	193%	4.18
			(VM) 523.18 ± 133.80 vs 155.46 ± 29.90	237%	3.79
			(VI) 557.58 ± 143.10 vs 200.81 ± 47.60	178%	3.35
			(RF) 280.71 ± 66.10 vs 116.17 ± 23.90	142%	3.31
			Pennation Angle - Men vs Boys (deg)		
			(VL) 15.4 ± 4.3 vs 15.9 ± 2.3	4%	0.16
			(VM) 25.4 ± 7.6 vs 23.3 ± 4.8	9%	0.33
			(VI) 13.6 ± 3.4 vs 11.8 ± 1.6	15%	0.65
			(RF) 29.4 ± 10.2 vs 20.8 ± 4.4	41%	1.10

			<u>Fascicle Length - Men vs Boys (mm)</u>		
			(VL) 94.5 ± 15.4 vs 76.6 ± 10.6	23%	1.35
			(VM) 95.9 ± 15.5 vs 72.7 ± 7.9	32%	1.89
			(VI) 95.3 ± 11.2 vs 64.7 ± 6.8	47%	3.30
			(RF) 67.7 ± 16.5 vs 58.4 ± 15.1	16%	0.59
Kubo et al. **(2014c)**	Muscle Thickness and Fascicle Length	23 sedentary/ moderately active men aged 22.2 ± 2.2 years and 20 boys aged 11.2 ± 1.1 years not participating in organised sport or physical activity outside school.	<u>Muscle thickness - Men vs Boys (mm)</u>		
			(KE) 24.1 ± 3.3 vs 17.5 ± 2.1	38%	2.35
			(PF) 21.3 ± 2.7 vs 14.4 ± 1.4	48%	3.14
			<u>Fascicle length - Men vs Boys (mm)</u>		
			(KE) 90.2 ± 7.9 vs 65.7 ± 4.1	37%	3.81
			(PF) 56.2 ± 6.2 vs 47.2 ± 6.2	19%	1.45
Radnor et al. **(2020b)**	Muscle Thickness, Pennation Angle and Fascicle Length	57 boys aged 12.45 ± 0.54 years (G1), 32 boys aged 14.06 ± 0.68 years (G2), and 37 boys aged 15.81 ± 0.97 years (G3). All boys were involved in regular sport and P.E programs.	<u>Muscle Thickness – G1 vs G2 vs G3 (mm)</u>		
			(GM) 14.7 ± 1.6 vs 16.8 ± 2.4 vs 18.1 ± 3.1	14%, 8%	1.09, 0.46
			(VL) 18.3 ± 2.2 vs 21.3 ± 2.8 vs 23.8 ± 3.7	16%, 12%	0.92, 0.75
			<u>Pennation Angle – G1 vs G2 vs G3 (deg)</u>		
			(GM) 19.25 ± 3.07 vs 20.52 ± 3.60 vs 22.83 ± 3.87	7%, 11%	

			(VL) 16.48 ± 3.22 vs 17.53 ± 3.98 vs 18.36 ± 2.74	6%, 5%	0.39, 0.62
					0.30, 0.25
			Fascicle Length – G1 vs G2 vs G3 (mm)	8%, 3%	
			(GM) 45.5 ± 8.0 vs 49.1 ± 9.4 vs 47.5 ± 9.8	11%, 6%	
			(VL) 66.4 ± 13.2 vs 73.4 ± 15.6 vs 77.5 ± 19.8		0.42, 0.17
					0.50, 0.23
Cunha et al. **(2020)**	Muscle CSA, Muscle Thickness, Muscle Volume, Pennation angle and Fascicle Length	15 boys aged 14.5 ± 0.8 years (G1) and 19 boys aged 16.6 ± 1.2 years (G2). All boys were engaged in formal soccer training.	Muscle CSA – G1 vs G2 (cm^2)		
			(RF) 9.8 ± 1.9 vs 10.3 ± 2.0	5%	0.26
			Muscle Thickness – G1 vs G2 (cm)		
			(KE) 3.6 ± 0.6 vs 3.8 ± 0.6	6%	0.33
			Muscle Volume – G1 vs G2 (ml)		
			(KE) 1526 ± 307 vs 1814 ± 410	19%	0.78
			Muscle Pennation Angle – G1 vs G2 (deg)		
			(VL) 15.0 ± 2.3 vs 14.3 ± 3.2	5%	0.25
			Muscle Fascicle Length – G1 vs G2 (cm)		

(VL) 8.3 ± 1.4 vs 8.9 ± 1.6	7%	0.40

Effect size (*g*): <0.2 (trivial), 0.20-0.59 (small), 0.60-1.19 (moderate), 1.20-1.99 (large), 2.00-3.99 (very large), and >4.0 (extremely large) (Hopkins et al., 2009).

(GM – Gastrocnemius Medialis, KE – Knee Extensors, PCSA – Physiological Cross-sectional Area, PE – Physical Education, PF – Plantar Flexors, RF – Rectus Femoris, VL – Vastus Lateralis, VM – Vastus Medialis and VI – Vastus Intermedius).

Muscle CSA, thickness and volume, indicative of muscle hypertrophy (Krzysztofik et al., 2019), have been shown to have a significant influence on absolute force production in adults (Baxter and Piazza, 2014; Fukunaga et al., 2001; Ikai and Fukunaga, 1970; Maughan et al., 1983; Wagle et al., 2017). Cross-sectional studies in youth have also demonstrated a similar relationship, suggesting that maximal voluntary force that can be exerted by a muscle is strongly influenced by size, whatever the age (Stock et al., 2017; Tonson et al., 2008). This would imply that increases in muscle size would lead to enhanced force producing capabilities and performance improvements as youth mature. This is further supported by recent findings where participants who made large worthwhile changes in jump performance and sprint speed over an 18-month period also experienced large increases in muscle thickness of the vastus lateralis, highlighting the importance of muscle thickness increases underpinning improvements in jump and sprint performance in boys (Radnor et al., 2021). Cumulatively, these findings highlight that muscle size increases as youth mature. This leads to a natural improvement in force production and may explain the improvements in physical performance tests throughout maturation. Practitioners should be aware that these qualities will increase naturally with growth and maturation, and large increases in muscle size with training may need to be observed to have any confidence of training effects above and beyond natural growth and maturation.

2.2.2 Fascicle Length

Within a muscle, fibres are grouped into small bundles termed fascicles (Darby et al., 2013), and the length of a fascicle is typically measured as the distance between the intersection composed of the superficial aponeurosis and fascicle and the intersection composed of the deep aponeurosis and the fascicle (Fukutani and Kurihara, 2015). As shown in *table 2.1*, studies examining differences in fascicle length across maturity groups have reported large to very large differences when comparing boys and men, but small to moderate differences between

14–16-year-old boys (Kubo et al., 2014c; O'Brien et al., 2010a; Radnor et al., 2020b). It was suggested by Kubo et al. (2001), that while adults possessed muscle fascicle lengths not significantly longer than that of 15-year-old adolescents, the 15-year olds had significantly longer muscle fascicle lengths than children (see *table 2.1*), possibly implying that fascicle length reaches adult levels at around 15 years of age (Radnor et al., 2018). In a recent study, Radnor et al. (2020b) reported that the greatest change in gastrocnemius medialis fascicle length was observed in the group experiencing peak height velocity (PHV; ~10% increase) compared to the group that had already experienced PHV (~9%) or were yet to experience their growth spurt (no change). However, the largest change in vastus lateralis fascicle length occurred in the group that had already gone through PHV (~7%) compared with those experiencing or yet to experience PHV (~5 and ~4%, respectively). The differences in fascicle length being reported vary based on the muscle examined, and the site of observation. These child–adult differences in fascicle length might be caused by the longer limb length of adults compared to youth (Legerlotz et al., 2016; O'Brien et al., 2010a, 2010c). Kubo et al. (2001) demonstrated that this lengthening of the fascicle with maturation is driven by the muscle catching up with bone growth, which occurs prior to muscle lengthening. The increase in fascicle length might suggest a maturity-related change in fascicle: tendon length ratio, which would have consequences for the contractile properties of the muscle-tendon unit (MTU) as a whole (Blazevich, 2006; Legerlotz et al., 2016; Radnor et al., 2018). However, O'Brien et al. (2010c) suggested that the increase in the length of the MTU was a result of proportional increase in fascicle, muscle and tendon lengths, implying that the fascicle: tendon length ratio is unlikely to change with maturation.

While studies of animal skeletal muscle suggest that muscle fascicle length plays an important role in determining maximal contraction velocities (Sacks and Roy, 1982; Spector et al., 1980), evidence of such a relationship between human skeletal muscle fascicle length and contraction velocity is limited. It has been suggested that longer fascicles may also allow muscles to remain close to optimal length for force production, meaning greater force at longer lengths (Baroni et al., 2013), and allow the muscle to operate effectively over a greater range of motion (Guex et al., 2016). With the fascicle: tendon length ratio is unlikely to change during maturation, the longer fascicles in adults or adolescents would allow for greater absolute maximum shortening velocity, while the relative maximum shortening velocity in adults and youth would remain equal (Legerlotz et al., 2016). With fascicle length strongly influencing the distance over which force is produced (Baroni et al., 2013) and contraction velocities (Cormie et al., 2011a), increases in fascicle length would be expected to lead to improved athletic performance (Abe et al., 2000; Mont et al., 1994; Nasirzade et al., 2014). Radnor et al. (2021) reported a small but significant correlation between fascicle length and maximal sprint speed, relative peak force, and relative peak power in boys, thereby suggesting that individuals with longer fascicles can produce quicker movements, but it is an innate quality that may not develop with maturity. While these findings suggest that fascicle length in boys may increase naturally with growth and maturation and could influence force production through greater ranges, it may be beneficial for practitioners to understand the potential innate quality of fascicle length and use this for talent identification purposes (Radnor et al., 2021).

2.2.3 Pennation Angle

Pennation angle of a muscle can be defined as the angle between the muscle's fascicles and the line of action (Spector et al., 1980). *Table 2.1* shows that several studies that have reported changes in pennation angle resulting from maturation to be muscle and site specific (O'Brien et al., 2010a; Radnor et al., 2020b). Researchers have reported that as an individual transitions from childhood to adulthood, the pennation angle of the vastus lateralis appears to remain fairly consistent (O'Brien et al., 2010a), while that of the gastrocnemius medialis increases from birth and becomes stable after the adolescent growth spurt (Binzoni et al., 2001).

An increase in pennation angle allows for more sarcomeres to be arranged in parallel, meaning more contractile tissue is able to attach to a given area of aponeurosis or tendon resulting in greater PCSA (Gans, 1982; Kawakami et al., 2000), which in turn facilitates greater force production by the muscle (Kawakami et al., 2000). Fascicle pennation not only influences strength by enabling a greater PCSA, but it is functionally important due to the process known as "*gearing*" (Wakeling et al., 2011). Due to the pennation angle, and the fact that fibres rotate as they shorten, during muscle contractions the muscle fascicles may shorten at a rate different from the whole muscle, and the ratio of these velocities is its gearing (Wakeling et al., 2011). Therefore, fascicles are not required to shorten as much as the whole muscle, resulting in the muscle operating on a more optimal region of its force-velocity curve, and working at a favourable region of its length-tension relationship over a longer period. This maximises the force that the muscle can develop, without impacting on the capacity for rapid movement production (Askew and Marsh, 1998).

The pennation angle of the lateral gastrocnemius has been shown to correlate with higher early rate of force development (RFD) in adults during drop jumps (Earp et al., 2011). Researchers have speculated that this could be a result of the indirect line of pull of fibres in pennate muscles, resulting in the muscle having an increased ability to resist external forces, greater muscular stiffness and isometric-like qualities during muscle lengthening (Earp et al., 2010). However, previous studies have reported that smaller pennation angles of the VL are associated with greater sprinting ability in boys (Radnor et al., 2021), and this could be due to the fact that smaller pennation angles would allow for longer fascicles (Earp et al., 2010). It is useful for practitioners to understand how maturity-related changes in pennation angle are site-specific, and that the requirement for either large or small pennation angles could be dependent on the task, specific muscle, and population.

Studies that have examined growth- and maturity-related changes in muscle structure and morphological factors are summarised in *table 2.1*. The table also highlights the magnitude of differences between children, adolescents and adults. Effect sizes observed for muscle size appear greater than those for muscle architecture, with very large differences being observed for muscle PCSA as well as muscle volume and thickness. Studies have reported significant correlations between muscle thickness and pennation angle (Kawakami et al., 1993; Kawakami et al., 1995), suggesting that an increase in muscle thickness is accompanied by changes in pennation angle (Kawakami et al., 1993). The effect sizes for changes in muscle architecture appear to be more site-dependent, with moderate differences being observed for VL fascicle length and small differences for GM fascicle length, when comparing pre- and post-pubertal boys.

2.2.4 Tendon Architecture and Stiffness

Tendons are interposed between muscles and bones to form an MTU which transmits muscular forces directly to the bone, thereby creating movement and stability about a joint (Benjamin et al., 2008; Franchi et al., 2007). Tendon stiffness can be referred to as its resistance to elongation when a force is applied, and is attributed to the greater number of spring-like materials arranged in parallel (Radnor et al., 2018). The dimensions of the tendons largely affect their function and properties, and while longer, more compliant tendons are suggested to more readily absorb energy (Witvrouw et al., 2007), they have been linked to longer electromechanical delay (EMD; a delay in the detection of force onset) (Dotan et al., 2012; Grosset et al., 2009; Radnor et al., 2018). Shorter and thicker tendons (greater CSA) are stiffer and more effective at transferring muscular forces to bone and thereby associated with greater RFD and reduced EMD (Earp et al., 2011; Radnor et al., 2018).

The level of tendon stiffness or compliance can influence maximal muscular force (Cormie et al., 2011a). An increase in tendon stiffness can be explained by increases in tendon size or Young's modulus (Couppe et al., 2008; Roberts, 2002). Young's modulus, which can be defined as the ratio of tensile stress to tensile strain, is an inherent property of any viscoelastic structure to withstand changes in length under tension and compression (Hughes et al., 1979). Young's modulus can be affected by tendon microstructural changes such as collagen fibril diameter (Parry et al., 1978), increased collagen cross-linking (Bailey et al., 1998), and reduced collagen crimping (Kastelic et al., 1980). *Table 2.2* highlights prior research that has examined changes in tendon dimensions across maturity groups and reported that plantar flexor tendon length was 20% greater in adults than in younger boys (~11 years), with no significant difference being observed between adults and older boys (~14 years) (Kubo et al., 2014a). This may suggest that these variables become stable in boys around the age of 14 years, which is the average time of PHV (Rogol et al., 2000). Prior studies have also reported an approximate two-fold increase in patellar tendon CSA from childhood to adulthood (Kubo et al., 2014b), suggesting an increased tendon stiffness given the association with tendon CSA (Earp et al., 2011; Radnor et al., 2018). Increases approximately two-fold in magnitude have been reported for stiffness of both the patellar (Kubo et al., 2014b; O'Brien et al., 2010b) and Achilles (adults 2.5 times greater than youth) (Waugh et al., 2012) tendons with age. These studies also reported little to no significant difference between older youth (~14 years) and adults, further supporting the suggestion that adult values may be reached approximately at the time of PHV (Kubo et al., 2001; Kubo et al., 2014a; Kubo et al., 2014b). With increases in tendon stiffness being suggested to inversely affect EMD (Cavanagh and Komi, 1979; Falk et al., 2009b; Grosset et al., 2009; Halin et al., 2003), and elicit an improved stretch reflex amplitude (Radnor et al., 2018), the growth and maturity-related changes may lead to an increased RFD and greater force production. In a study examining the implications of differences in dynamic muscle-tendon behaviour, Waugh et al. (2017) reported that during hopping, MTU length change in youth was accomplished with greater muscle excursion in youth compared to adults, suggesting greater energy cost of producing mechanical work. The authors suggested that although both adults and youth choose movement frequencies that maximise elastic energy storage potential of the tendon, youth's energy saving mechanisms might not be as effective as adults, and this was attributed to differential development of muscle and tendon mechanics during childhood (Waugh et al., 2017). The findings indicate that as youth mature, they develop greater tendon stiffness that might positively influence the energy-saving mechanisms. Practitioners need to be aware of the impact this could have on performance and ensure the prescription of appropriate training to allow for the development of these qualities alongside the natural development from growth and maturation.

Table 2.2 Effects of growth and maturation on tendon architecture and properties in youth (for multiple groups difference and effect size are expressed for consecutive pairs).

Author	Developmental Change	Sample Age Range	Findings		
			Values	**Difference (%)**	**Effect Size (*g*)**
O'Brien et al. **(2010b)**	Tendon CSA and Tendon stiffness	10 sedentary men aged 28.2 ± 3.6 years and 10 boys aged 8.9 ± 0.7 years not involved in any formal strength training	Patellar Tendon CSA – Men vs Boys (mm2) 114.8 ± 17.8 vs 75.3 ± 15.0	52%	2.40
			Patellar Tendon stiffness - Men vs Boys (N/mm) 1076 ± 87 vs 555 ± 71	94%	6.56
Kubo et al. **(2014b)**	Tendon CSA, Tendon Length and Tendon Stiffness	22 adults aged 22.3 ± 0.4 years, 21 children aged 11.2 ± 0.2 years (G1) and 18 children aged 13.8 ± 0.1 years (G2) not involved in any formal strength training	Patellar Tendon CSA - Adults vs G2 vs G1 (mm2) 82.7 ± 2.1 vs 65.4 ± 2.8 vs 49.2 ± 2.3	26%, 33%	7.10, 6.37
			Patellar Tendon length - Adults vs G2 vs G1 (mm) 47.0 ± 0.8 vs 45.3 ± 0.6 vs 38.5 ± 0.8	4%, 18%	2.37, 9.51
			Patellar Tendon stiffness - Adults vs G2 vs G1 (N/mm) 1507.2 ± 148.1 vs 1211.9 ± 136.0 vs 742.9 ± 55.2	24%, 63%	2.07, 4.66
Waugh et al. **(2012)**	Tendon Stiffness	10 men aged 27 ± 2.0 years and nine women aged 24.8 ± 3.2 years	Achilles Tendon Stiffness - Adults vs G2 vs G1 (N/mm) 259.2 ± 44.2 vs 162.4 ± 42.9 vs 100.8 ± 30.4	60%, 61%	2.23, 1.61

		(Adults). 21 children aged 6.4 ± 0.8 years (G1), and 29 children aged 9.1 ± 0.5 years (G2) not involved in any formal strength training			
Kubo et al. **(2014a)**	Tendon CSA and Tendon Length	23 men aged 22.2 ± 2.2 years, 22 children aged 11.2 ± 1.1 years (G1) and 19 children aged 13.8 ± 0.6 years (G2) not involved in any formal strength training	Achilles Tendon CSA – Adults vs G2 vs G1 (mm2)		
			74.7 ± 14.7 vs 76.9 ± 16.7 vs 60.1 ± 13.6	3%, 28%	0.14, 1.11
			Achilles Tendon Length - Adults vs G2 vs G1 (mm)		
			275.1 ± 20.8 vs 263.9 ± 17.5 vs 229.1 ± 15.2	4%, 15%	0.58, 2.13
O'Brien et al. **(2010c)**	Tendon Length	10 sedentary men aged 28.2 ± 3.6 years and nine boys aged 8.9 ± 0.7 years not involved in any formal strength training	Tendon length - Men vs Boys (mm)		
			(VL) 51.7 ± 3.4 vs 42.2 ± 3	23%	2.95
			(VM) 63 ± 4.8 vs 49 ± 5.3	29%	2.78
			(VI) 30.2 ± 3.2 vs 25 ± 3.9	21%	1.47
			(RF) 124.1 ± 7.7 vs 96.9 ± 3.8	28%	4.40
Kubo et al. **(2014c)**	Tendon Length, Tendon Thickness and Tendon Stiffness	23 sedentary men aged 22.2 ± 2.2 years and 20 boys aged 11.2 ± 1.1 years not involved in any formal strength training	Tendon length - Men vs Boys (mm)		
			(KE) 313.8 ± 15.6 vs 269 ± 15.3	17%	2.90
			(PF) 275.1 ± 20.8 vs 229.1 ± 15.2	20%	2.50
			Tendon thickness Men vs Boys (mm)		

	(KE) 3.30 ± 0.38 vs 2.61 ± 0.30	26%	2.00
	(PF) 5.14 ± 0.17 vs 4.72 ± 0.46	9%	1.25
	Tendon stiffness – Men vs Boys (N/mm)		
	(KE) 57.6 ± 19.8 vs 23.2 ± 14.0	148%	1.98
	(PF) 35.3 ± 13.1 vs 20.3 ± 9.5	74%	1.30

Effect size (*g*): <0.2 (trivial), 0.20-0.59 (small), 0.60-1.19 (moderate), 1.20-1.99 (large), 2.00-3.99 (very large), and >4.0 (extremely large) (Hopkins et al., 2009).

(CSA – Cross-sectional Area, KE – Knee Extensors, PF – Plantar Flexors, RF – Rectus Femoris, VL – Vastus Lateralis, VM – Vastus Medialis and VI – Vastus Intermedius).

A summary of studies examining the magnitude of differences in tendon architecture between adults and youth as a result of growth and maturation is provided in *table 2.2*. Extremely large differences between youth and adults in tendon CSA are accompanied by extremely large differences in tendon stiffness. Differences in tendon length appear to be greater for the patellar tendon compared to Achilles tendon, and this could potentially be explained by greater growth occurring in the femur compared to tibia during childhood and adolescence (Hume and Russell, 2014).

2.3 INFLUENCE OF GROWTH AND MATURATION ON NEURAL MECHANISMS

Research has consistently indicated that youth differ from adults in several muscular performance attributes, such as maximal force production and RFD (Dotan et al., 2012; Lambertz et al., 2003; Seger and Thorstensson, 2000). These attributes are closely associated with performance of activities such as jumping and sprinting (Meyers et al., 2017; Pedley et al., 2020; Radnor et al., 2021; Radnor et al., 2018). In addition to the growth and maturity-related development of muscle-tendon structure and properties, the ability to generate high levels of muscle activity develops with maturity and will influence the ability to generate force rapidly (Dotan et al., 2012). There are a number of neural mechanisms that improve with maturation that could partly account for the differences in these qualities, such as variance in muscle activation rates, differential motor unit recruitment, reduced electromechanical delay, increased muscle pre-activation, reduced agonist–antagonist co-contraction, and improved stretch reflex control and conduction velocity (Dotan et al., 2012; Falk et al., 2009a).

2.3.1 Muscle Activation

When considering the production of force, muscular activation plays a vital role (Knight and Kamen, 2001). While maximal muscle activation refers to all available motor units being recruited and driven to their maximal firing rates (Knight and Kamen, 2001), voluntary activation is commonly defined as the level of neural drive to muscles during a maximal voluntary contraction (MVC), and a lack of full voluntary activation is termed as voluntary activation deficit (Allen et al., 1998; Stokes and Young, 1984). As shown in *table 2.3*, studies have reported that activation deficit during an MVC decreases significantly from pre- to post-puberty, with 7-year-old children displaying deficit levels approximately three times greater than 10-year-olds, four times greater than 11-year-olds and nine times greater than adults (Grosset et al., 2008; Koh and Eyre, 1988). The increase in levels of voluntary activation with age is suggested to reflect changes in central command, where muscle control may involve enhanced motor unit recruitment, an increased firing rate of activated motor units, change in motor unit firing pattern, or an increase in conduction velocity within motor pathways (Grosset et al., 2008; Koh and Eyre, 1988).

The size principle for the orderly recruitment of motor units ensures that the slowest, most fatigue-resistant motor units are recruited first for any task, with the faster motor units with greater force-producing capabilities being reserved for high intensity tasks where they can provide high forces for a short period of time (Henneman, 1957; Hodson-Tole and Wakeling, 2009; Milner-Brown et al., 1973). However, research has indicated that the recruitment order of the motor units differs based on the velocity of the contraction (Grimby and Hannerz, 1968), suggesting that the sequence of activation could be modified or even reversed in rapid voluntary movements (Desmedt and Godaux, 1977a; Hannerz, 1974). However, it is unclear as to which motor units are less activated in youth, and whether the lower activation levels are also a result of potentially inferior motor unit synchronisation.

Given that type-II motor units have a faster contraction velocity than type-I (Dotan et al., 2012), differential motor unit recruitment should have implications that extend beyond just maximal force (Dotan et al., 2012). Several studies have demonstrated that RFD during maximal isometric contractions is higher in adults compared to youth (rate of torque development in men is approximately 4.5 times greater than boys), and this difference is still observed when normalised to muscle cross-sectional area (Cohen et al., 2010; Dotan et al., 2012; Falk et al., 2009a). It can be speculated that the differences in RFD could link back to differences in motor unit recruitment (Dotan et al., 2012), evidenced by an association between type-II motor units and peak RFD, especially in the early phase of muscle contraction (Bottinelli et al., 1999; Harridge et al., 1996). The lower RFD levels in youth are thereby suggested to be a reflection of lesser utilisation of type-II motor units compared to adults (Dotan et al., 2012).

During fast maximal muscle contractions, lesser activation of type-II motor units is suggested to result in higher levels of EMD (Dotan et al., 2012). This delay has been reported to be approximately 50% longer in boys and girls compared to adults (Falk et al., 2009a; Falk et al., 2009b), suggesting lesser activation of the type-II motor units in youth (Cohen et al., 2010; Dotan et al., 2012). Additionally, although an inverse relationship has been suggested between tendon stiffness and EMD (Radnor et al., 2018), certain studies have reported that the MTU stiffness only accounts for <20% of variance in EMD changes (Falk et al., 2009b; Grosset et al., 2009; Halin et al., 2003). These findings suggest that lower muscle activation, as well as lesser recruitment and utilisation of higher-threshold motor units in youth could also account for child–adult differences in EMD (Cavanagh and Komi, 1979; Falk et al., 2009b; Grosset et al., 2008; Halin et al., 2003).

Mean power frequency of an electromyography (EMG) signal, which is the mean relative distribution of EMG frequencies, has previously been used to infer differential motor unit recruitment, with men being reported to have values 20% greater than boys (Halin et al., 2003). The authors attributed this difference to the greater utilisation of type-II motor units in adults (Halin et al., 2003), and this was further supported by the observation of a greater drop off in mean power frequency in men (~50%) than in boys (~12%), following a fatiguing isometric MVC protocol. Decreases in mean power frequency, during intense fatiguing contractions, have been reported to be greater in individuals with higher composition and utilisation of type-II motor units (Kupa et al., 1995). It has also been hypothesised that the difference in mean power drop off could be due to greater lactic acid accumulation in men compared to boys, an occurrence that is expected more of type-II than of type-I motor units (Dotan et al., 2012; Kupa et al., 1995).

The findings of the studies highlighted in *table 2.3* suggest that as youth mature, they are better able to recruit higher threshold motor units. This improved differential motor unit recruitment is accompanied by moderate to very large increases in muscle activation which could result in growth related improvements in maximal force producing capabilities and an enhanced ability to rapidly produce force, potentially leading to increases in RFD, peak force and impulse. Given the magnitude of changes in muscle activation strategies that youths experience as they mature, and with prior research suggesting that training-related changes in pre-pubertal children are primarily neural (Lillegard et al., 1997), practitioners should be aware that they might benefit from designing training programs that are complementary to the natural adaptive processes.

Table 2.3 Effects of growth and maturation on neural mechanisms in youth (for multiple groups difference and effect size are expressed for consecutive pairs).

Author	**Developmental Change**	**Sample Age Range**	**Test**	**Findings**		
				Values	**Difference (%)**	**Effect Size (*g*)**
Grosset et al. (2008)	Muscle Activation	9 sedentary adults aged 21 ± 2.3 years, 6 children aged 7 years (G7), 7 children aged 8 years (G8), 8 children aged 9 years (G9), 11 children aged 10 years (G10) and 5 children aged 11 years (G11)	MVC isometric plantar flexion	TS Amplitude - G7 vs G8 vs G9 vs G10 vs G11 vs Adults (µV) 189 ± 38 vs 216 ± 45 vs 286 ± 81 vs 289 ± 92 vs 365 ± 109 vs 641 ± 122	14%, 32%, 1%, 26%, 76%	0.64, 1.05, 0.03, 0.78, 2.34
Halin et al. (2003)	Differential Motor Unit Recruitment	12 men aged 21.5 ± 4.5 years and 15 young boys aged 10.5 ± 0.9 years, all physically active but not involved in intensive training	MVC isometric elbow flexion	Bicep Brachii MPF – Men vs Boys (Hz) 106.78 ± 30.88 vs 86.77 ± 14.02	23%	0.87
Falk et al (2009b)	Electromechanical Delay	16 men aged 22.1 ± 2.8 years and 15 boys aged 9.6 ± 1.6 years, all physically active	MVC isometric elbow flexion and extension	Bicep Brachii EMD (flexion) – Men vs Boys (ms) 47.6 ± 17.5 vs 75.5 ± 28.4	59%	1.17
				Tricep Brachii EMD (extension) – Men vs Boys (ms) 38 ± 12 vs 65 ± 15 Ŧ	71%	1.98

Lazaridis et al. (2010)	Pre-activation	12 adult males aged 25 ± 2.7 years 12 and prepubescent boys aged 9.8 ± 0.6 years, all untrained	20 cm drop jump	Preactivation EMG Duration - Men vs Boys (ms)		
				(GM) 58 ± 19 vs 35 ± 17 Ŧ	66%,	1.28
				(SOL) 47 ± 18 vs 28 ± 7 Ŧ	68%	1.39
				(TA) 41 ± 17 vs 29 ± 12 Ŧ	41%	0.82
				Preactivation Amplitude - Men vs Boys (normalised to max)		
				(GM) 0.2 ± 0.8 vs 0.1 ± 0.7 Ŧ		
				(SOL) 0.1 ± 0.7 vs 0.1 ± 0.6 Ŧ	29%	0.05
				(TA) 0.3 ± 0.2 vs 0.1 ± 0.1 Ŧ	27%	0.05
					79%	0.78
Lloyd et al. (2012b)	Stretch reflex activity	11 boys aged 9.44 ± 0.27 (G9), 11 boys aged 12.68 ± 0.30 (G12), and 10 boys aged 15.89 ± 0.31 (G15), physically active but not involved in any formal strength training	Sub-maximal (SMax) and maximal hopping	SMax Hopping – SOL+ VL Muscle Activity (% GC)		
				Short Latency – G9 vs G12 vs G15		
				26.89 ± 4.21 vs 31.88 ± 4.60 vs 33.71 ± 4.60	19%, 6%	1.13, 0.40
				Medium Latency – G9 vs G12 vs G15		
				21.48 ± 3.28 vs 20.84 ± 3.37 vs 21.37 ± 2.36	3%, 1%	0.19, 0.18
				Long Latency – G9 vs G12 vs G15		
				12.22 ± 3.12 vs 10.15 ± 3.16 vs 9.70 ± 2.94	20%, 26%	0.66, 0.15

				Maximal Hopping – SOL + VL Muscle Activity (% GC)		
				Short Latency – G9 vs G12 vs G15		
				18.51 ± 6.14 vs 22.57 ± 5.81 vs 18.63 ± 4.20	22%, 21%	0.68, 0.78
				Medium Latency – G9 vs G12 vs G15		
				19.12 ± 4.36 vs 20.34 ± 3.85 vs 20.07 ± 4.47	6%, 1%	0.30, 0.06
				Long Latency – G9 vs G12 vs G15		
				16.79 ± 3.47 vs 16.59 ± 3.33 vs 16.95 ± 4.15	1%, 2%	0.06, 0.10
Grosset et al. (2008)	Co-contraction	9 sedentary adults aged 21 ± 2.3 years, 6 children aged 7 years (G7), 7 children aged 8 years (G8), 8 children aged 9 years (G9), 11 children aged 10 years (G10) and 5 children aged 11 years (G11)	MVC isometric plantar flexion	CI (TS:TA) - G7 vs G8 vs G9 vs G10 vs G11 vs Adults 0.27 ± 0.03 vs 0.26 ± 0.02 vs 0.24 ± 0.03 vs 0.20 ± 0.03 vs 0.19 ± .04 vs 0.13 ± 0.01 Ŧ	4%, 8%, 20%, 5%, 46%	0.40, 0.77, 1.33, 0.30, 2.45
Frost et al. (1997)	Co-contraction	10 children aged 7-8 years (G1), 10 children aged 10-12 (G2), 10 adolescents aged 15-16 years (G3).	Submaximal treadmill running	CI (running speed at 1.34 m/s) – G1 vs G2		
				(SOL:TA) 13.5 ± 6.3 vs 10 ± 4.7 Ŧ	35%	0.63
				(VL:H) 8.0 ± 3.2 vs 6.5 ± 3.2 Ŧ	23%	0.47
				CI (running speed at 2.46 m/s) – G2 vs G3		

	(SOL:TA) 16 ± 4.7 vs 13.5 ± 7.9 Ŧ	19%	0.38
	(VL:H) 14.5 ± 7.8 vs 8 ± 4.7 Ŧ	81%	1.01

Ŧ – Estimated from graph.

Effect size (*g*): <0.2 (trivial), 0.20-0.59 (small), 0.60-1.19 (moderate), 1.20-1.99 (large), 2.00-3.99 (very large), and >4.0 (extremely large) (Hopkins et al., 2009).

(CI – Co-contraction Index, EMD – Electromechanical Delay, EMG – Electromyography, GC – Ground Contact, GM – Gastrocnemius Medialis, H – hamstrings, MPF – Mean Power Frequency, MVC – maximal voluntary contraction, SOL – Soleus, TA – Tibialis Anterior, TS – Triceps Surae and VL – Vastus Lateralis).

2.3.2 Muscle Pre-activation

Pre-activation is a term that is commonly used to refer to the levels of muscle activity prior to an impact or landing, and which is prominent in the early phase of stretch shortening cycle (SSC) sequence (Fukutani et al., 2016; Komi, 2000). Pre-activation plays an important role in regulating ankle stiffness during rebounding and jumping activities (Hobara et al., 2008; Jones and Watt, 1971), and is vital for torque enhancement in the knee extensors and plantar flexors during such activities (Fukutani et al., 2015; Fukutani et al., 2016).

During activities such as hopping, youth have been reported to have significantly lower pre-activation compared to adults, particularly at higher movement speeds (Hobara et al., 2008; Jones and Watt, 1971; Lazaridis et al., 2010; Oliver and Smith, 2010). It has been suggested that the delayed and lower levels of pre-activation could be explained by a relationship between maturation and the ability to predict an event; the behaviour of youth prior to landing has at times been compared to that of 'untrained jumpers' (Assaiante and Amblard, 1996; Horita et al., 2002; Lazaridis et al., 2010). This delayed and lower level of pre-activation results in longer ground contact times, which in turn reduces the magnitude of elastic energy contribution leading to sub-optimal SSC function and thereby a lower peak force and impulse in the subsequent concentric phase (Bobbert et al., 1987a; Lloyd et al., 2012b; Radnor et al., 2018). Additionally, lower levels of pre-activation have been suggested to cause the peak vertical ground reaction force to manifest as an impact peak (defined as a force of high magnitude resulting from the collision of two bodies over a relatively short period), during the early phase of ground contact (Hreljac, 2004; Nicol et al., 1991). Prior research has reported that a greater proportion of pre-PHV boys, compared to post-PHV, display the presence of an impact peak (Pedley et al., 2020). This reduction in prevalence of an impact peak in older youth can be attributed to pre-activation improving with age, as evidenced by significantly greater muscle pre-activity being observed in 15-year old boys compared to nine- and 12-year old boys (Lloyd et al., 2012b), and greater background muscle activity compared to men (Oliver and Smith, 2010).

Improved SSC function associated with the maturity-related increases in the levels of pre-activation allows for greater joint stiffness during the braking phase of the SSC and enables more rapid force production upon ground contact (Hoffren et al., 2007; Radnor et al., 2018). This may result in greater RFD immediately following ground contact, a shorter ground contact time and reduced centre of mass displacement (Oliver et al., 2014). The development of these feed-forward mechanisms with growth and maturation may allow for youth to become more pre-active than reactive, which might be useful for practitioners to consider when implementing or progressing training tasks such as plyometrics. Additionally, improvements in pre-activation could also play a role in reducing risk of non-contact injuries.

2.3.3 Stretch Reflex Control

When examining muscle activity during landings or impact, mean EMG values between 30 and 60 ms, 61 and 90 ms and 91 and 120 ms can be used to represent short-, medium- and long-latency stretch reflex components, respectively (Hobara et al., 2008). While the short-latency stretch reflex signifies muscle activity as a result of spinal involuntary commands, the medium- and long-latency stretch reflexes signify activation resulting from supraspinal commands (Hobara et al., 2007; Oliver and Smith, 2010).

Research has utilised plyometric movements to study stretch reflex activity, based on the fact that the reflex amplitude influences MTU stiffness which in turn affects SSC performance (Lazaridis et al., 2010; Oliver and Smith, 2010). When quantifying the stretch reflex by means of plyometric exercises, higher amplitudes of stretch reflex have been observed in adults compared to youth, with youth exhibiting a greater reliance on longer-latency stretch reflexes (Lazaridis et al., 2010; Lloyd et al., 2012b; Oliver and Smith, 2010), thereby resulting in sub-optimal MTU stiffness (Lazaridis et al., 2010). However, youth have been shown to regulate lower-limb stiffness more effectively as they mature, and this has been attributed to a greater utilisation of short-latency stretch reflexes (Oliver and Smith, 2010) which may underpin the increases in spring like behaviour displayed by more mature youth (Pedley et al., 2020). The improved utilisation of these stretch reflexes has been attributed in part to improved spindle sensitivity and maturation of the sensorimotor pathways (Grosset et al., 2007; Oliver and Smith, 2010). Additionally, increases in muscle pre-activation have also been suggested to facilitate a greater short-latency stretch reflex response (Dietz et al., 1981). The amplitude and timing of the stretch reflex has been evidenced to underpin lower limb stiffness (Hobara et al., 2008; Jones and Watt, 1971; McMahon et al., 2012), and increased stiffness leads to shorter ground contact times and in turn a more efficient reutilisation of elastic energy due to a quick transition between eccentric and concentric phases (Bobbert et al., 1987a; Henchoz et al., 2006). Cumulatively, there exists sufficient evidence to suggest that the stretch reflex contributes significantly to rapid force generation during touchdown in activities such as jumping, hopping and running (Komi and Gollhofer, 1997). Practitioners need to be aware that although maturity-related improvements in the feed-back mechanisms positively influence lower limb stiffness and hence force output during SSC-driven activities, the amplitude of the short-latency stretch reflex might vary considerably depending on the activity.

2.3.4 Co-contraction

Co-contraction refers to the simultaneous contraction of the agonist and antagonist muscles about a joint, and is known to stabilise limb movements (Cormie et al., 2011a; Milner and Cloutier, 1995). While this co-contraction may increase joint stability, high levels of antagonist activity result in an increase in agonistic muscle energy expenditure to complete a task (Frost et al., 2002). During activities such as jumping and running, when the magnitude of co-contraction exposes the MTU to excessive tensile forces, the activity of the Golgi tendon organs increases and results in an inhibition of the motoneurons innervating the agonist muscle, and facilitation of those innervating the antagonist muscles (Brooks et al., 1996). This then may lead to increased ground contact times and lower force outputs due to a reduction in the efficiency of the SSC (Radnor et al., 2018).

As seen in *table 2.3*, research has suggested that co-contraction decreases with growth and maturation, i.e., the co-contraction index has been reported to be almost twice as high in 10–12-year-olds compared to 15–16-year-olds (Frost et al., 1997; Grosset et al., 2008; Lambertz et al., 2003). This maturity-related reduction in co-contraction is underpinned by a greater density and size of the Golgi tendon organs in youth compared to adults (Ovalie, 1987). During maturation, the Golgi tendon organs undergo a process of desensitisation leading to a reduction in the magnitude of co-contraction, which results in decreased agonist inhibition thereby allowing for a more efficiently functioning SSC and an increased net force (Radnor et al., 2018). Such maturity-related decreases in co-contraction allow youth to naturally become more efficient and may subsequently have a positive effect on performance during SSC driven activities.

Studies that have examined growth- and maturity related changes in the neural mechanisms are summarised in *table 2.3*. The magnitude of differences between adults and youth in neural mechanisms appear to be similar to those observed for structural factors, with very large differences in muscle activation and co-contraction, large differences in EMD, and moderate differences in mean power frequency. When comparing pre- and post-pubertal boys, large differences were observed in neural mechanisms such as short latency stretch-reflex activity, with the magnitude being similar to differences observed in muscle size but greater than those observed for muscle architecture.

2.4 SUMMARY OF THE INFLUENCE OF GROWTH AND MATURATION ON MUSCLE-TENDON NEUROMUSCULAR MECHANISMS

Youth experience a significant number of growth- and maturity-related changes in neuromuscular mechanisms, including changes in muscle-tendon architecture and properties (O'Brien et al., 2010a, 2010c; Radnor et al., 2020b) as well as muscle activation strategies (Falk et al., 2009b; Grosset et al., 2008; Lazaridis et al., 2010; Oliver and Smith, 2010), as they transition from childhood, through adolescence and into adulthood (*figure 2.1*). These changes in neuromuscular mechanisms can be expected to facilitate an enhancement of force producing capabilities, which would explain the maturity-related improvements observed in sprint (Meyers et al., 2015; Moeskops et al., 2021; Papaiakovou et al., 2009) and jump performance (Moeskops et al., 2021; Quatman et al., 2006; Taylor et al., 2010) as well as other activities.

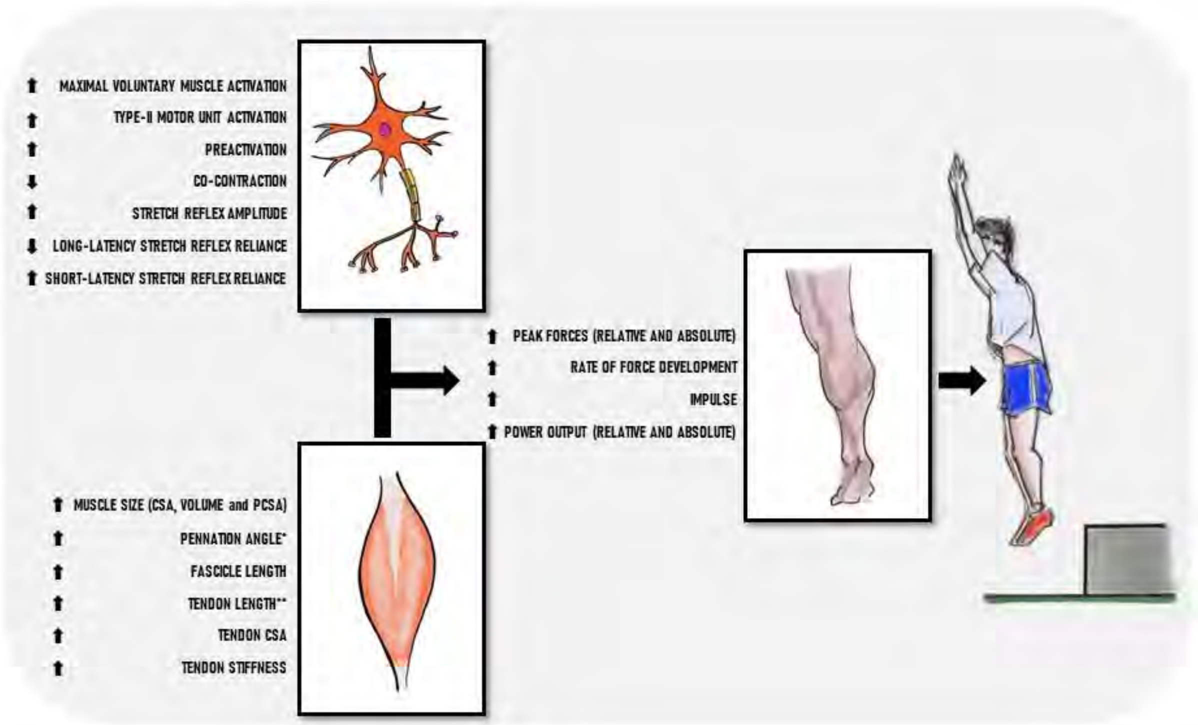


Figure 2.1 Effect of growth and maturation on various neuromuscular mechanisms and their influence on force producing capabilities that underpin performance.

CSA – Cross-sectional Area, PCSA – Physiological Cross-sectional Area.

2.5 EFFECT OF RESISTANCE TRAINING ON MUSCLE-TENDON AND NEUROMUSCULAR MECHANISMS

Resistance training involves the progressive use of a wide range of resistive loads and a variety of training modalities to increase an individual's ability to exert or resist force (Benjamin and Glow, 2003; Lloyd et al., 2014; Williams et al., 2017). Traditional resistance training involves exercises such as squatting, pressing and pulling where a significant amount of the movement duration, towards the end of the range of motion, involves a deceleration phase (Cormie et al., 2007; Elliott et al., 1989; Newton et al., 1996). While this method is vital for developing strength (Campos et al., 2002; Kraemer and Ratamess, 2004), there is the need for movements which are more mechanically specific to performance, such as ballistic exercises, plyometrics, and weightlifting exercises (Cormie et al., 2011b). Prior research has defined ballistic contractions as those in which there is no opportunity to alter a movement pattern once it is executed and attributed this to the short duration of the movement (Desmedt and Godaux, 1977a; Desmedt and Godaux, 1977b). Ballistic exercises of a dynamic nature are typically utilised as a method of training to improve maximal power output (McEvoy and Newton, 1998). Plyometric exercises, characterised by rapid SSC actions, are also utilised within power training programmes and are typically performed with little or no external resistance (Cormie et al., 2011b). While weightlifting movements, such as the clean and jerk and the snatch, are similar to ballistic exercises (Cormie et al., 2011b), the two differ in that weightlifting involves a specific set of movements (typically involving a concentric phase only or a concentric phase followed by an eccentric phase) and might often be performed with a higher resistance and therefore lower velocities compared to ballistic exercises (Channell and Barfield, 2008; Cormie et al., 2007; Cormie et al., 2011b). There exists a substantial amount of empirical evidence indicating that resistance training is safe for children and adolescents (Faigenbaum, 2000; Hamill, 1994). Injury epidemiology studies have shown that injuries resulting from resistance training are far less common than those associated with popular sports such as American football, gymnastics, basketball, rugby, or soccer (Hamill, 1994; Lloyd and Oliver, 2013b; Palmer-Green et al., 2015). Studies have reported positive correlations between motor skill performance and the intensity (% 1 repetition maximum) of the resistance training program (Behringer et al., 2011), suggesting that children and adolescents can make improvements in performance following exercise at a high intensity. Meta-analytical data including 42 studies showed that the average resistance training prescription for youth was typically two to three sets, with 8–15 repetitions, using loads of 60%–80% 1 repetition maximum, with training periods lasting approximately 10 weeks (Behringer et al., 2010). However, a more recent meta-analysis that examined resistance training specifically in young athletes attempted to examine the optimal dose–response for youths. The research showed that the most effective training prescription for strength gains required longer periods of training (>23 weeks), the use of heavier loads (80%–90% of 1 repetition maximum) and greater training volumes (5 sets of 6-8 repetitions) (Lesinski et al., 2016). Cumulatively, it would appear that as a child becomes more experienced and acquires higher levels of athleticism, resistance training prescription would need to change, especially in terms of the volume and intensity of training. Additionally, the development of physical literacy is deemed of equal importance, since physically literate youths perform exercises with greater technical ability, confidence and competence (Faigenbaum et al., 2016). Researchers have suggested that a combination of supervised, structured training along with free play can maximize youth's ability as well as their confidence and adherence to physical activity long term (Baker et al., 2003; Faigenbaum et al., 2016; Faigenbaum and Myer, 2012). Owing to its numerous health benefits, numerous professional organisations promote resistance training as a safe, worthwhile and necessary activity for youth to engage in (Bergeron et al., 2015; Lloyd et al., 2012a; Lloyd et al., 2014).

While the effect of resistance training on measures of jump height (Chelly et al., 2009; Chelly et al., 2015; Lloyd et al., 2016; Matavulj et al., 2001; Uzelac-Sciran et al., 2020) and running velocities (Chelly et al., 2015; Lloyd et al., 2016) in youth have been thoroughly examined, studies investigating muscle-tendon and neuromuscular adaptations following resistance training are sparse (Daly et al., 2004; Dotan et al., 2013; McKinlay et al., 2018; Metaxas et al., 2014; Mitchell et al., 2011; Ramsay et al., 1990; Waugh et al., 2014). Although limited in number, *table 2.4* highlights studies that have examined resistance training-related structural and morphological changes in youth. While the studies reported increases in maximal strength and jump height following resistance training, in terms of muscle morphology they observed moderate to large changes in adolescents and trivial to small changes in pre-pubertal children (Fukunaga and Funato, 1992; Granacher et al., 2011; Ramsay et al., 1990; Waugh et al., 2014). In accordance with prior research, the authors attributed the training-induced gains in pre-pubertal children primarily to neural adaptations (Behm et al., 2008; Falk and Tenenbaum, 1996; Lillegard et al., 1997).

Table 2.4 Effects of training on structural and neural factors in youth (for multiple groups difference and effect size are expressed for consecutive pairs).

Author	Sample Age Range	Training Intervention	Findings		
			Values	Difference (%)	Effect Size (*g*)
Ramsay et al. **(1990)**	CON-13, EXP-13, aged between 9-11 years	20 weeks, 3 sessions/week	Muscle CSA – Baseline vs Post-intervention (cm^2)		
		Circuit Training	(KE) CON: 37.5 ± 5.4 vs 41 ± 7.2 Ŧ	9%	0.55
		Phase 1: 70-75% 1RM	EXP: 40 ± 7.2 vs 44 ± 7.2 Ŧ	10%	0.56
		Phase 2: 80-85% 1 RM	△EXP v △CON		0.08
		Preacher curl, double leg extension, leg press, bench press, behind the neck pulldown and sit-ups/trunk curls	(EF) CON: 8.6 ± 2.5 vs 9.4 ± 1.8 Ŧ	9%	0.37
			EXP: 7.4 ± 2.9 vs 8.2 ± 2.2 Ŧ	11%	0.31
			△EXP v △CON		0.00
			MUA – Baseline vs Post-intervention (% MUA)		
			(KE) CON: 80 vs 79 Ŧ	1%	
			EXP: 75 vs 86 Ŧ	15%	
			(EF) CON: 94.5 vs 93 Ŧ	2%	
			EXP: 84 vs 96 Ŧ	14%	
Fukunaga et al. **(1992)**	(G1) 7 ± 0.3 years. CON-8, EXP-8	12 weeks, 3 sessions/week, 2/day	Upper Arm CSA – Baseline vs Post-intervention (cm^2)		

	(G2) 9 ± 0.3 years. CON-8, EXP-10	Three maximally sustained isometric contractions of elbow flexion for 10 seconds	(G1) CON: 14.4 ± 3.9 vs 14.8 ± 4.2	3%	0.07
	(G3) 11 ± 0.2 years. CON-8, EXP-10		EXP: 12.5 ± 2.6 vs 13.5 ± 1.3	8%	0.28
			△EXP v △CON		0.17
			(G2) CON: 16.3 ± 2.9 vs 16.7 ± 2.7	2%	0.10
			EXP: 14.8 ± 3.0 vs 15.9 ± 3.1	7%	0.29
			△EXP v △CON		0.23
			(G3) CON: 17.6 ± 2.3 vs 18.7 vs 2.8	6%	0.36
			EXP: 16.6 ± 2.6 vs 19.1 ± 3.1	15%	0.78
			△EXP v △CON		0.55
Granacher et al. **(2011)**	CON-15, aged 8.7 ± 0.5 years	10 weeks, 2 sessions/week, 90 mins	<u>M. Quadricep CSA – Baseline vs Post-intervention (mm^2)</u>		
	EXP- 17, aged 8.6 ± 0.5 years	3 sets of 10-12 reps, 70-80% 1RM	CON: 295.0 ± 49.7 vs 299.4 ± 55.2	1%	0.08
		Leg press, knee extension/flexion, seated calf raises, hip abduction/adduction and core exercises.	EXP: 311.0 ± 41.8 vs 318.0 ± 14.4	2%	0.15
			△EXP v △CON		0.06
Waugh et al. **(2014)**	CON-10, aged 8.9 ± 0.3 years	10 weeks, 2 sessions/week	<u>Achilles Tendon CSA – Baseline vs Post-intervention (mm^2)</u>		
	EXP-10, aged 8.9 ± 0.2 years	Plantar flexion resistance training, within a circuit, with intensity based on progressive loading starting at 8-15 RM	CON: 40.7 ± 7.2 vs 41.8 ± 7.9	3%	0.12
			EXP: 35.8 ± 6.3 vs 36.7 ± 5.9	3%	0.12
			△EXP v △CON		

		Control group had the plantar flexion resistance training replaced by rest.			0.03
			<u>Achilles Tendon Length – Baseline vs Post-intervention (mm)</u>		
			CON: 151.6 ± 32.9 vs 153.8 ± 29.4		
			EXP: 160.3 ± 21.3 vs 164.5 ± 24.3	1%	0.05
			△EXP v △CON	3%	0.16
					0.07
			<u>Achilles Tendon Stiffness – Baseline vs Post-intervention (N/mm)</u>		
			CON: 162.5 ± 41.8 vs 167.4 ± 36.0		
			EXP: 138.4 ± 36.7 vs 177.8 ± 31.9	3%	0.09
			△EXP v △CON	28%	0.87
					0.84
McKinlay et al. **(2018)**	CON-14, aged 12.5 ± 0.3 years	8 weeks, 3 sessions/ week, 45 mins	<u>VL Thickness – Baseline vs Post-intervention (mm)</u>		
	EXP 1-14, aged 12.5 ± 0.7 years	EXP 1-Traditional resistance training, 3 sets of 8-12 reps, <80% 1RM	CON: 20.3 ± 1.9 vs 20.4 ± 1.7	0%	0.05
	EXP 2-13, aged 12.6 ± 0.7 years	Squats variations, lunge variations, step-ups	EXP 1: 19.9 ± 2.4 vs 21.2 ± 3.8	7%	0.47
		EXP 2-plyometric training, 3 sets, 10-12 foot contacts/exercise	EXP 2: 20.1 ± 1.2 vs 21.6 ± 3.6	7%	1.07
			△EXP2 v △EXP1 v △CON		0.10, 0.54
			<u>VL EMD – Baseline vs Post-intervention (ms)</u>		
			CON: 48.4 ± 9.5 vs 49.7 ± 14.6	3%	0.12

		CMJ variations, TJ variations, DJ, long jumps, jumping lunges, lateral hops	EXP 1: 47.2 ± 9.5 vs 47.8 ± 7.0	1%	0.05
			EXP 2: 43.2 ± 7.6 vs 40.7 ± 6.9	6%	0.28
			△EXP2 v △EXP1 v △CON		0.35, 0.07
Ramsay et al. **(1990)**	CON-13, EXP-13, aged between 9-11 years	20 weeks, 3 sessions/week	Muscle CSA – Baseline vs Post-intervention (cm^2)		
		Circuit Training	(KE) CON: 37.5 ± 5.4 vs 41 ± 7.2 Ŧ	9%	0.55
		Phase 1: 70-75% 1RM	EXP: 40 ± 7.2 vs 44 ± 7.2 Ŧ	10%	0.56
		Phase 2: 80-85% 1 RM	△EXP v △CON		0.08
		Preacher curl, double leg extension, leg press, bench press, behind the neck pulldown and sit-ups/trunk curls	(EF) CON: 8.6 ± 2.5 vs 9.4 ± 1.8 Ŧ	9%	0.37
			EXP: 7.4 ± 2.9 vs 8.2 ± 2.2 Ŧ	11%	0.31
			△EXP v △CON		0.00
			MUA – Baseline vs Post-intervention (% MUA)		
			(KE) CON: 80 vs 79 Ŧ	1%	
			EXP: 75 vs 86 Ŧ	15%	
			(EF) CON: 94.5 vs 93 Ŧ	2%	
			EXP: 84 vs 96 Ŧ	14%	

Ŧ – Estimated from graph.

Effect size (*g*): <0.2 (trivial), 0.20-0.59 (small), 0.60-1.19 (moderate), 1.20-1.99 (large), 2.00-3.99 (very large), and >4.0 (extremely large) (Hopkins et al., 2009).

(CMJ – Countermovement Jump, CSA – Cross-sectional Area, DJ – Drop Jump, EF – Elbow Flexors, EMD – Electromechanical Delay, KE – Knee Extensors, MUA – Motor Unit Activation, RM – Rep Max, TJ – Tuck Jump, VL – Vastus Lateralis).

While resistance training-related structural changes in pre-pubertal children are suggested to be minimal (Behm et al., 2008; Lillegard et al., 1997) there are several studies that have observed morphological changes in youth across maturity groups following resistance training (Fukunaga and Funato, 1992; McKinlay et al., 2018; Ramsay et al., 1990). While the study by Granacher et al. (2011) did not elicit significant hypertrophic changes in pre-pubertal participants, it could be argued that because the study was examining the effect of strength training, the prescribed rest periods between sets (3–4 min) were not rest periods that would be prescribed when the goal of the program is to elicit hypertrophic adaptations (de Salles et al., 2009). Conversely, while McKinlay et al. (2018) utilised similar repetitions, sets and intensities as in Granacher et al. (2011), their rest periods were restricted to 60–90 s and the authors reported significant baseline to post-intervention increases in muscle thickness in boys aged 12–13 years. It is interesting to note that while both studies reported an increase in knee extensor peak torque (Granacher et al., 2011; McKinlay et al., 2018), only the study by McKinlay et al. (2018) reported an increase in countermovement jump height. This increase could potentially be explained by muscle thickness being suggested to positively influence jump performance (Radnor et al., 2021). Additionally, prior research has suggested that when trying to elicit meaningful changes, longer exposures to training (>23 sessions) with appropriate training stimuli are required to elicit significant adaptations (Faude et al., 2017). It is important to note that the participants in Granacher et al. (2011) received 20 training sessions, while those in McKinlay et al. (2018) received 24 sessions. This suggests that the distinct neuromuscular adaptations observed following resistance training in youth might be specific to the training program design, duration of the program and maturity status of the participants (Blazevich et al., 2020; Legerlotz et al., 2016; Tillin and Folland, 2014).

In adults, increased pennation angle has been reported following heavy strength training (Aagaard et al., 2001; Kawakami et al., 1995), and this results in a greater number of sarcomeres arranged in parallel within a given CSA, which is associated with increased maximal force producing capabilities (Blazevich et al., 2007; Duclay et al., 2009; Seynnes et al., 2007). Research suggests that fascicle length in adults increases following resistance training with light loads (Alegre et al., 2006) as well as jump and sprint training (Blazevich et al., 2003), indicative of adaptations potentially being associated with the force-velocity characteristics of the exercises. However, increases in fascicle length have also been observed following heavy eccentric training (accentuated and eccentric-only) in adults (Baroni et al., 2013; Guex et al., 2016; Walker et al., 2020), with the adaptation being suggested to be a protective mechanism against exercise-induced muscle damage in a subsequent eccentric exercise session (Proske and Morgan, 2001). To the author's knowledge, research is yet to examine the effects of resistance training on muscle pennation angle and fascicle length in youth.

When comparing a control group to an experimental group, Waugh et al. (2014) reported resistance training to elicit significant increases in tendon stiffness with no significant change in tendon CSA. This indicates that although ~78% of child–adult differences in tendon stiffness can be attributed to loading due to increased body mass and force production capabilities associated with maturation, increased external loading due to resistance training also promotes improvements in tendon stiffness. Studies have reported an increase in tendon stiffness in youth following resistance training to be accompanied by a paralleled decrease in EMD (Cavanagh and Komi, 1979; Grosset et al., 2008; Mitchell et al., 2011; Waugh et al., 2014). Given this association of tendon stiffness with a reduction in EMD (Falk et al., 2009b; Grosset et al., 2009) and improved rate and efficiency of transfer of muscular forces (Bojsen-Møller et al., 2005) and amplitude of stretch reflex (Radnor et al., 2018), such increases in tendon stiffness following resistance training might allow for greater RFD (Lambertz et al., 2003; Radnor et al., 2018). This suggestion can potentially be supported by the findings of several studies which have reported resistance training-related increases in eccentric and concentric RFD following resistance training in adults (Cormie et al., 2009; de Villarreal et al., 2011; Kijowksi et al., 2015).

Very few studies have directly examined the effect of training on maximal voluntary activation in youth. Ramsay et al. (1990) observed significant improvements in strength measures resulting from resistance training and while they found no significant differences in muscle CSA, the authors reported a trend towards an increased percentage of motor unit activation in the experimental group. Researchers have speculated that youth might be able to make larger resistance training-related increases in voluntary activation compared to adults, and this has been attributed to youth's comparatively lower levels of voluntary activation (Dotan et al., 2012; Grosset et al., 2008; Streckis et al., 2007), suggesting a larger potential for adaptive change. With an increase in motor unit activation being linked to augmentation in force production, such increases following resistance training may result in an enhanced ability to produce force.

To the author's knowledge, no previous studies have directly investigated the effect of resistance training on differential motor unit recruitment; however, an increased RFD in response to explosive sport training has been reported in young gymnasts and this has been linked to increased type-II motor unit recruitment and higher motor unit synchronisation (Dotan et al., 2012; Dotan et al., 2013). Such training-related improvements in the ability to recruit higher threshold motor units would result in a reduction in EMD and an enhanced ability to rapidly produce high levels of force (Radnor et al., 2018), potentially reflected in the improved jump (Chelly et al., 2009; Chelly et al., 2015; Lloyd et al., 2016; Matavulj et al., 2001; Uzelac-Sciran et al., 2020) and sprint times (Meylan and Malatesta, 2009; Uzelac-Sciran et al., 2020) observed in youth following resistance training. While other factors such as pre-activation, reflex control, co-contraction and activation deficit also affect the force producing capabilities that underpin performance, their responses to resistance training are yet to be investigated. *Table 2.4* summarises studies that have examined neuromuscular adaptations following resistance training in youth and highlights the magnitude of change from baseline to post-intervention.

Further longitudinal research is required to determine how youth across different maturity groups respond to resistance training and determine how the structural and neural responses may differ dependent on type of training and the interaction with growth and maturation. Future research should also investigate the effect of long-term training interventions on neural mechanisms such as differential motor unit recruitment, pre-activation, reflex control, co-contraction and activation deficit in youth, and the subsequent effect on performance of sprinting, jumping and rebound activities.

2.6 CONCLUSION

The current review aimed to provide an overview of existing research that has examined muscle-tendon and neuromuscular changes associated with growth, maturation and training and how this influences force production. Studies have reported growth and maturation to elicit moderate to very large changes in muscle physiological CSA, volume and thickness, tendon CSA and tendon stiffness, fascicle length, muscle activation, pre-activation and stretch reflex control accompanied by large reductions in EMD and co-contraction. Although research examining the changes in neuromuscular mechanisms following resistance training in youth across maturity groups is scarce, the available literature reports trivial to moderate differences in tendon stiffness, muscle CSA and thickness, as well as small increases in motor unit activation and small reductions in EMD in pre-pubertal children.

Chapter 3 Prelude

Chapter 2 highlighted the various growth and maturation- related neuromuscular changes that youth experience as they transition from childhood, through adolescence, into adulthood. The previous chapter also provided an overview of the interaction of maturation- and training-related changes on these structural and neural mechanisms, and the subsequent effect on performance. Prior to carrying out the empirical studies, it was deemed important to examine and understand existing paediatric literature that has investigated training-related development of stretch shortening cycle as assessed during a drop jump. The next chapter utilised a systematic approach with a meta-analysis to identify and quantify the effects of resistance training on DJ performance in youth.

Chapter 3 – The Effect of Resistance Training on Drop Jump Performance in Youth: A Systematic Review with Meta-Analysis

3.1 INTRODUCTION

The various growth and maturation-related changes that youth experience include increases in muscle volume and thickness, fascicle length, tendon cross-sectional area and stiffness, as well as improvements in muscle activation, pre-activation and stretch reflex control (Tumkur Anil Kumar et al., 2021). These adaptations from natural growth and maturation are suggested to explain the observed increases in strength (Asmussen and Heebøll-Nielsen, 1955; Housh et al., 1996; Moeskops et al., 2020) and power output (Carvalho et al., 2011; Ferretti et al., 1994) as children transition through adolescence into adulthood. Furthermore, the maturity-related increases in strength and power subsequently influence the performance of key sporting tasks, such as sprinting (Meyers et al., 2015; Moeskops et al., 2021) and jumping (Quatman et al., 2006; Taylor et al., 2010), which are underpinned by the stretch-shortening-cycle (SSC) (Cormie et al., 2011a; Newton and Kraemer, 1994). While natural developments stemming from growth and maturation positively influence this SSC function (Radnor et al., 2018), resistance training can help to further develop these underpinning qualities in youth (Tumkur Anil Kumar et al., 2021).

Resistance training has been accepted as a safe and effective training modality for both children and adolescents (Faigenbaum, 2000; Hamill, 1994). Researchers have highlighted the positive influence of resistance training on muscular strength (Faigenbaum et al., 1999; Granacher et al., 2016), jump height (Chelly et al., 2009; Chelly et al., 2015), sprint times (Meylan and Malatesta, 2009; Uzelac-Sciran et al., 2020) and running velocities (Chelly et al., 2015; Lloyd et al., 2016) in youth. Lesinski et al. (2016) reported that resistance training in youth elicited moderate improvements in muscle strength and countermovement jump performance, with small improvements in linear sprint performance, agility and sport-specific tasks such as throwing velocity. Similarly, Peitz et al. (2018) reported improvements in reactive strength index (RSI), leg stiffness, sprint times and countermovement jump performance following traditional resistance and plyometric training in youth. With performance of these movements being underpinned by SSC function, quantifying SSC development following resistance training is important (Cormie et al., 2011a; Newton and Kraemer, 1994).

The drop jump (DJ) is a popular rebound based exercise that has been utilised in prior research to examine SSC function in youth (Bassa et al., 2012; Birat et al., 2020; Gillen et al., 2019; Pedley et al., 2020). It involves jumping vertically immediately after landing from a drop or fall from a pre-determined height (Young et al., 1995). The SSC action during a DJ has an emphasis on eccentric overload during triple flexion of the lower limb during the landing phase, which is followed by a rapid triple extension to propel the body into the air (Pedley et al., 2017). This sequence of movements replicates those in human locomotive tasks such as sprinting, thereby making it a suitable tool to evaluate SSC function (Bobbert et al., 1987b; Marshall and Moran, 2013). When assessing an individual's SSC function during a DJ, jump height, ground contact time and RSI are the most commonly reported measures (Bassa et al., 2012; Birat et al., 2020; Flanagan and Comyns, 2008). This RSI is calculated as the ratio of jump height and ground contact time (Flanagan and Comyns, 2008), typically collected during rebound based activities such as hopping, DJs, or multiple vertical rebound jumps (Flanagan and Comyns, 2008; Young, 1995). However, different jump strategies such as greater centre of mass displacement during the braking phase or greater braking centre of mass velocity can influence the subsequent outcome (Jidovtseff et al., 2014; Meylan et al., 2010). Therefore, it might be necessary to examine kinetic qualities such as mean forces, impulse and velocity to truly understand what underpins the DJ performance.

While studies such as Gillen et al. (2019) and Pedley et al. (2020) have highlighted that SSC function improves with increasing maturity status, research examining the effect of resistance training on SSC function in youth measured during a DJ is scarce. Unlike rebound activities such as maximal hopping, the DJ involves large amounts of braking loading (Bobbert et al., 1986), often leading to neuromuscular inhibition prior to reflex activation (Bobbert et al., 1987a; Komi and Gollhofer, 1997). This makes performance in the propulsive phase of the DJ relatively more reliant on the individual's force producing capabilities (Bobbert et al., 1987b; van Ingen Schenau et al., 1997b). Earlier research examining development of SSC function have most commonly reported countermovement jump and squat jump performance (Edwen et al., 2014; Harrison and Gaffney, 2001; Sahrom et al., 2013). However, with it being suggested that SSC function might not be appropriately represented by these activities (Lloyd et al., 2011a; Schmidtbleicher, 1992), more recent research has utilised rebound based activities such as maximal hopping and DJs (Gillen et al., 2019; Pedley et al., 2020; Ramirez-Campillo et al., 2018).

With DJ force-time profiles being suggested to change as a result of growth and maturation (Hewett et al., 2006; Pedley et al., 2020; Quatman et al., 2006), an awareness of how resistance training influences DJ performance in youth could inform the design of resistance training programmes to positively influence sport performance. Therefore, the aim of the meta-analysis was to quantify the effects of resistance training on DJ performance in youth.

3.2 METHODS

The meta-analysis was conducted in accordance with the 2020 Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines (Page et al., 2021).

Consultation of Prospero indicated that the review did not need to be registered, as it was a performance based meta-analysis and not health-based.

3.2.1 Eligibility Criteria

In line with the Population, Intervention, Comparison and Outcomes (PICO) framework for eligibility in the review, studies must have; recruited boys or girls who were under 18 years of age; conducted a resistance training intervention; included an appropriate comparison CON group that performed no structured resistance training beyond sports practise; attained pre and post training data for DJ performance variables. To be considered as an appropriate training intervention, the study must have; utilised traditional resistance training, neuromuscular training, plyometric training, ballistic training, weightlifting or a combination of the above. While traditional resistance training was defined as a form of training where participants lifted external load, neuromuscular training was defined as integrating development of fundamental movement skills with muscular strength and power. Plyometric training was defined as a form of training which involved body weight jumps, hops, bounds, and/or skips, while ballistic training was defined as utilising movements such as a jump squat or bench press throw where an external load was accelerated through the entire range of motion to the point of projection. To be deemed as weightlifting the intervention must have more than one weightlifting exercise within the training session. No intervention duration exclusions were applied.

3.2.2 Information Sources and Search Strategy

In order to obtain relevant literature, four electronic databases were searched on December 15th, 2021: PUBMED, MEDLINE (via OVID), SPORTDiscus (EBSCOhost) and SCOPUS. Search terms were identified by screening titles, abstracts and subject indexing of known, relevant studies. These terms were utilised in a pilot search to identify if there was a need for any additional terms. The following Boolean search syntax were used: ((("jump" OR "rsi" OR "reactive strength" OR “stretch shortening cycle”) AND (“young” OR "youth" OR "children" OR "adolescents" OR "peak height velocity" OR "boys" OR "girls") AND ("training" OR "intervention" OR “resistance” OR "plyometrics" OR "ballistics" OR "weightlifting")) NOT ("disorder" OR "disability")) to search title and/or abstract and/or keywords of articles. Searches were restricted to journal sources; excluding dissertations, theses, magazine articles and non-peer reviewed publications. There was no search limitation for publishing date. The reference list of each study that met all the inclusion criteria was screened by title to identify any additional suitable studies for inclusion within the review.

3.2.3 Study Records

Two reviewers screened the study titles and abstracts from the initial search to remove: duplicates, non-English language publications, non-empirical research (e.g., letters, commentaries, reviews and meta-analyses), research without comparative repeated measures design (e.g., cross-sectional studies and single-group studies) and clearly irrelevant studies (e.g., cueing interventions and injury-related or medical studies) (Gartlehner et al., 2020). The complete text of the remaining articles was then reviewed by the two reviewers for inclusion based on the following criteria: (i) full text of the article being available, excluding abstract-only articles; (ii) the study utilised either a traditional resistance, plyometric or combined training intervention; (iii) the study included an appropriate CON group; (iv) the study reported pre- and post-training measurements of performance variables collected during a DJ.

3.2.4 Data Items

The following data were extracted from the articles: (i) sample size; (ii) participants characteristics (age and maturity status); (iii) intervention duration; (iv) intervention prescription (training frequency, exercises prescribed, sets, repetitions, intensity and rest); (v) means and standard deviation (*SD*) of performance variables reported from the DJ at the pre-and post-intervention testing. Where a study had multiple training groups, each training group was reported as a separate intervention. In instances where insufficient information was available for mean and *SD* data extraction, lead authors were contacted and asked to provide the data. In instances where no response was received, the study was excluded. For studies where results were reported in graph format, data was extracted using GetData Graph Digitizer Software. All study exclusion and data extraction was verified by a second reviewer to minimise potential selection bias and data extraction errors (Buscemi et al., 2006). In the event of a disagreement, a third reviewer was included and the decision was reached by a vote.

3.2.5 Risk of Quality Assessment

The methodological quality of the included studies was assessed using the Tool for assEssment of Study qualiTy and reporting in EXercise (TESTEX) Scale, as this is considered a reliable and valid tool to report on the methodological quality in exercise training studies (Smart et al., 2015). Study quality was classified as "excellent" (12-15 points), "good" (9-11 points), "fair" (6-8 points), or "poor" (< 6 points) (Nunes et al., 2021). Two reviewers rated the studies independently and Cohen's kappa was calculated to assess the measurement agreement between the two raters. In the event of a disagreement which could not be settled via discussion, a third reviewer was included and the decision was reached by a vote. Any studies scoring "poor" methodological quality (TESTEX score < 6) were excluded from the analysis.

3.2.6 Data Synthesis

In order to allow for the comparison of outcome measures between the selected studies, effect sizes (ES) with 95% confidence intervals (CI) were calculated. Effect sizes (Hedges' *g*) were calculated from the difference between the standardized mean change for the training and CON group, divided by the pooled and weighted estimates of *SD* (Hedges and Olkin, 2014). A correction factor was applied to account for the positive bias associated with small sample sizes

(Hedges and Olkin, 2014). The studies included in the review were drawn from different populations, included different training intervention prescriptions and reported various performance variables; all factors which may have influenced the training effect. Hence, the random-effects model was used to conduct the meta-analysis (Borenstein et al., 2010), using the DerSimonian and Laird inverse variance method (DerSimonian and Laird, 1986) in RevMan 5 (Cochrane, 2020). If there were less than two studies reporting a certain variable, that variable was not reported in the meta-analysis. Additionally, if less than two studies utilised a certain intervention or specific drop height, that intervention or drop height was excluded from the respective sub-group analysis. Forest plots with 95% CI were created and ES were categorised using the following thresholds trivial: <0.20; small: 0.20 – 0.59; moderate: 0.60 – 1.19; large: 1.20- 1.69; and very large: > 1.70 (Sullivan and Feinn, 2012). Effects were considered statistically significant at $p < 0.05$.

The presence of statistical heterogeneity was assessed using the chi-square test (χ^2). To compensate for low power of the chi-square test when few studies are included, heterogeneity level was tested at an alpha level of $p < 0.10$ rather than $p < 0.05$ (Gavaghan et al., 2000; Higgins et al., 2003). The I^2 statistic was used together with observed effects in order to quantify the percentage of variation across studies due to heterogeneity (Higgins et al., 2003). The importance of the observed I^2 value was interpreted in relation to the magnitude and direction of effects and strength of evidence for heterogeneity. Previous research has suggested I^2 values of 25%, 50% and 75% to be indicative of low, moderate and high heterogeneity, respectively (Higgins et al., 2003).

3.3 RESULTS

3.3.1 Study Characteristics

The process of study selection and search findings are presented in *Figure 3.1*. The online database search returned 8078 results and once duplicates between the results from the databases were removed, 4968 articles remained. The initial examination of the titles and abstracts resulted in the removal of a further 4929 articles due to the pre-determined inclusion criteria listed above. Full texts of the remaining articles (*n* = 41) were reviewed and a further 18 studies were removed due to not meeting the inclusion criteria. Amongst these, one study met the inclusion criteria but was removed due to insufficient information for data extraction (Tsimahidis et al., 2010). Two studies satisfied all the inclusion criteria but failed to report the drop height for the DJ, resulting in their exclusion (Vitale et al., 2018; Zghal et al., 2019). Four other studies fit the inclusion criteria, but the measures reported were focussed on injury mechanics, such as valgus, knee flexion-extension range of motion and hip abduction, rather than kinetic or DJ performance variables (Hopper et al., 2017; Lagas et al., 2019; Lindblom et al., 2020; Myer et al., 2005). Although Myer et al. (2005) and Katsikari et al. (2020) did report several kinetic variables, the studies did not examine any of the same measures and hence the kinetic qualities were not considered for the analysis. From the remaining studies (*n* = 23), no additional articles were identified from the screening process by examining the reference lists for relevant missed articles. Following all screening processes, a total of 23 studies met the inclusion criteria and were used for the meta-analysis (*figure 3.1*).

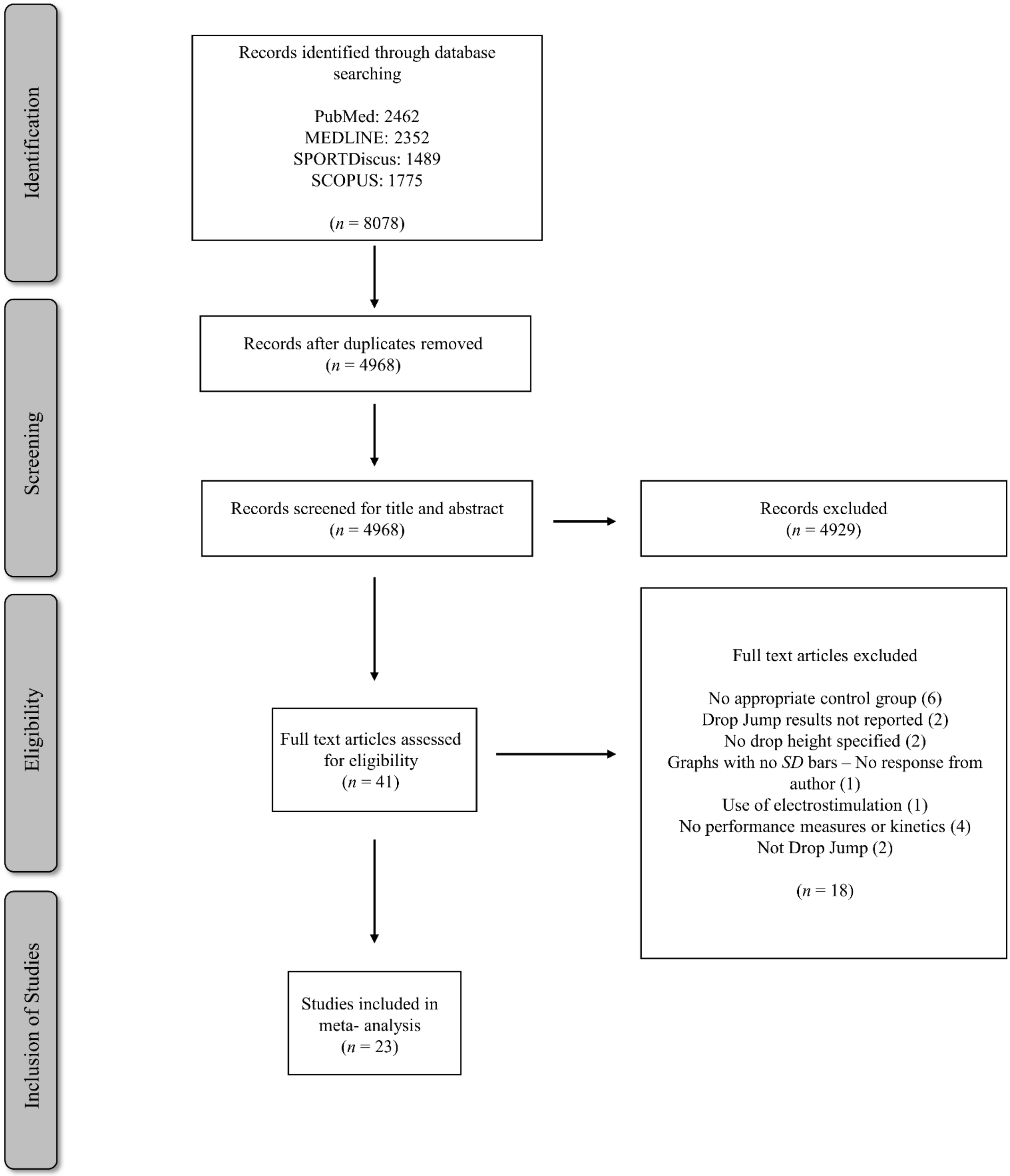


Figure 3.1 Process of study selection.

3.3.2 Risk of Quality

A summary of the methodological assessment for all the studies included within this review is presented in *table 3.1*. There was a 99.6% agreement ($\kappa = 0.940$; $p < 0.001$) between the two reviewers with one instance of disagreement. The disagreement was resolved through discussion between reviewers. The median score of the included studies was 9, and ranged from 7 to 12, out of the 15 possible points, which would suggest that the findings from the meta-analysis are based on good quality research. No study was excluded from the review on the basis of the screening outcome as all the studies were of atleast 'fair' methodological quality.

Table 3.1 Summary of TESTEX scores of the studies by the reviewers.

Authors	Eligibility criteria specified	Allocation concealment	Randomization specified	Groups similar at baseline	Blinding of assessor for at least one key outcome	Assessment of outcome measures	Intention-to-treat analysis	Between-group statistical comparisons reported	Point measures and measures of variability for all reported outcome measures	Activity monitoring in control groups	Relative exercise intensity remained constant	Exercise volume and energy expenditure reported	Total
Bogdanis et al. (2019)	1	0	0	1	0	1	1	2	1	0	1	1	9
Hernández et al. (2018)	1	1	1	1	0	0	1	2	1	0	1	1	10
Karagianni et al. (2020)	1	0	0	1	0	1	0	2	1	0	1	1	8
Katsikari et al. (2020)	1	0	0	1	0	1	1	2	1	0	1	1	9
Keiner et al. (2014a)	1	0	0	1	0	0	0	2	1	0	1	1	7
Latorre Román et al. (2018)	1	0	0	1	0	1	0	2	1	0	1	1	8
Michailidis et al. (2013)	1	0	0	1	0	0	0	2	1	0	1	1	7
Moeskops et al. (2018)	1	0	0	1	0	0	1	2	1	0	1	1	8

Negra et al. (2020)	0	1	0	1	0	2	0	2	1	0	1	1	9
Palma-Muñoz et al. (2021)	1	1	1	1	0	2	1	2	1	0	1	1	12
Panagoulis et al. (2020)	1	0	0	1	0	0	1	2	1	0	1	1	8
Ramírez-Campillo et al. (2014)	1	1	1	1	0	0	0	2	1	0	1	1	9
Ramirez-Campillo et al. (2014a)	1	1	0	1	0	1	0	2	1	0	1	1	9
Ramírez-Campillo et al. (2015a)	1	0	0	1	0	0	1	2	1	0	1	1	8
Ramírez-Campillo et al. (2015b)	1	0	0	1	0	0	1	2	1	0	1	1	8
Ramírez-Campillo et al. (2015c)	1	0	1	1	0	0	1	2	1	0	1	1	9

Ramírez-Campillo et al. (2015d)	1	0	1	1	0	1	0	2	1	0	1	1	9
Ramirez-Campillo et al. (2019)	1	1	0	1	0	1	1	2	1	0	1	1	10
Ramirez-Campillo et al. (2020)	1	1	1	1	0	1	1	2	1	0	1	1	11
Romero et al. (2021)	1	1	0	1	0	0	1	2	1	0	1	1	9
Rosas et al. (2016)	1	1	1	1	0	0	1	2	1	0	1	1	10
Santos and Janeira (2012)	1	0	0	1	0	0	0	2	1	0	1	1	7
Vera-Assaoka et al. (2020)	1	1	0	1	0	0	1	2	1	0	1	1	9

3.3.3 Description of Studies

3.3.3.1 Participant Characteristics

A summary of the included studies is presented in *table 3.2*. There was total of 1089 participants, with the median group size across all the studies was 39 participants (range = 19 to 166). The median training group size was 12 participants (range = 6 to 57), while the median CON group size was 14 participants (range = 6 to 55). Five of the studies recruited only girls, seventeen recruited only boys and one recruited both boys and girls. The total number of girls was 178 and the total number of boys was 911. The median age of the participant in the studies was 12.25 years and ranged from 8 years to 17 years. Although the participants in all the studies were youth, referring to the period of life before adulthood and categorised by individuals under 18 years of age (Lloyd et al., 2014), four of the included studies did not report the participants' maturity status. With growth rate increases suggested to reach a peak at about 12 years in girls and 14 years in boys (Beunen and Malina, 2008; Malina et al., 2004; Tanner, 1962), the average age of 13 years was considered as a cut-off when classifying individuals as children or adolescents for the sub-group analysis. Thirteen studies recruited children, eight recruited adolescents and two recruited children and adolescents. While participants in 15 of the studies had no prior resistance training experience, six studies reported that participants received no exposure to resistance training for a period of three to six months prior to the intervention and two did not report training status. For sub-group analysis, individuals who were reported as having no background in structured strength or jump training were classified as untrained. Any individuals who were reported to have not had exposure to structured resistance training within the last three to six months were considered as trained.

Table 3.2 Summary of included studies included in the review.

Authors	Participant Information					Training Intervention	Duration and Frequency	Drop Height (cm)	Variable Reported
	Numbers	Gender	Chronological Age (years)	Maturity Status	Training Age				
Bogdanis et al. (2019)	50 Participants (CON: 17; EXP 33)	Girls	8.1 ± 0.8	Maturity Offset: -4.9 ± 0.4	No background in structured plyometric training	Plyometric Training	8 Weeks 2x / Week	20	Jump Height, GCT and RSI
Hernández et al. (2018)	19 Participants (CON: 6; EXPI: 7; EXPII: 6)	Boys	10.2 ± 1.7	N/A	No regular strength or jump training in the past 3 months	Plyometric Training	7 Weeks 2x / Week	20	Jump Height
Karagianni et al. (2020)	23 Participants (CON: 11; EXP: 12)	Girls	13.2 ± 2.3	Maturity Offset: 0.6 ± 1.9	No background in structured strength or power training	Combined Training	10 Weeks 3x / Week	20	Jump Height
Katsikari et al. (2020)	24 Participants (CON: 12; EXP12)	Girls	9 to 11	Tanner Stage: 1 to 2	No background in regular strength or jump training	Plyometric Training	10 Weeks 2x / Week	20	Jump Height and GCT
Keiner et al. (2014a)	70 Participants (CONI: 16; CONII: 16; EXPI: 19; EXPII: 19)	Boys	10.5 ± 1.5	N/A	N/A	Combined Training	2 years 2x / Week	16 and 24	RSI
Latorre Román et al. (2018)	58 Participants (CON: 28; EXP: 30)	Boys and Girls	8.72 ± 0.97	Tanner Stage 1	No formal exposure to contrast training programmes	Combined Training	10 Weeks 2x / Week	20 and 40	Jump Height
Michailidis et al. (2013)	45 Participants (CON: 21; EXP: 24)	Boys	10.7 ± 0.7	Tanner Stage: 1.4 ± 0.3	No background in regular strength or jump training	Plyometric Training	12 Weeks 2x / Week	30	Jump Height

Moeskops et al. (2018)	34 Participants (CON: 17; EXP: 17)	Girls	8.2 ± 2.7	Pre – Peak Height Velocity	No background in regular strength training	Neuromuscular Training	8 Weeks 2x / Week	20	RSI
Negra et al. (2020)	24 Participants (CON: 11; EXP: 13)	Boys	12.7 ± 0.2	Maturity Offset: -1.7 ± 0.7	N/A	Plyometric Training	8 Weeks 2x / Week	20 and 40	Jump Height
Palma-Muñoz et al. (2021)	22 Participants (CON: 7; EXPI: 7; EXPII: 8)	Boys	13.5 ± 2.0	N/A	No background in regular strength or jump training	Plyometric Training	6 Weeks 2x / Week	20 and 40	Jump Height
Panagoulis et al. (2020)	28 Participants (CON: 14; EXP: 14)	Boys	12.4 ± 0.5	Tanner Stage: 2.8 ± 0.6	No background in regular strength training	Neuromuscular Training	8 Weeks 3x / Week	20	Jump Height
Ramírez-Campillo et al. (2014)	76 Participants (CON: 38; EXP: 38)	Boys	13.2 ± 1.8	Tanner Stage: 3.6 ± 1.1	No background in regular strength or jump training	Plyometric Training	7 Weeks 2x / Week	20 and 40	RSI
Ramirez-Campillo et al. (2014a)	54 Participants (CON: 15; EXPI: 13; EXPII: 14; EXPIII: 12)	Boys	10.1 ± 2.3	Tanner Stage: 2.4 ± 1.1	No background in regular strength training	Plyometric Training	7 Weeks 2x / Week	20 and 40	RSI
Ramírez-Campillo et al. (2015a)	54 Participants (CON: 14; EXPI; 12; EXPII: 16; EXPIII: 12)	Boys	11.6 ± 2.7	Maturity Offset -2.2 ± 2.4	No background in regular strength or jump training	Plyometric Training	6 Weeks 2x / Week	20	RSI
Ramírez-Campillo et al. (2015b)	40 Participant (CON: 10; EXPI: 10; EXPII: 10; EXPIII: 10)	Boys	11.4 ± 2.3	Maturity Offset: -2.2 ± 2.0	No background in regular strength or jump training	Plyometric Training	6 Weeks 2x / Week	20	RSI
Ramírez-Campillo et al. (2015c)	24 Participants (CON: 8; EXPI: 8; EXPII: 8)	Boys	13.0 ± 2.8	Maturity Offset: 0.4 ± 1.5	No background in regular strength or jump training	Plyometric Training	6 Weeks 2x / Week	20	RSI
Ramírez-Campillo et al. (2015d)	166 Participants (CON: 55; EXPI: 54; EXPII: 57)	Boys	14.1± 2.3	Tanner Stage:	No exposure to plyometric training in the past 6 months	Plyometric Training	6 Weeks	20	RSI

				3.9 ± 1.2			2x/ Week		
Ramirez-Campillo et al. (2019)	39 Participants (CON: 20; EXP: 19)	Boys	13.2 ± 1.9	Tanner Stage: 2 to 5	No background in regular strength or jump training	Plyometric Training	7 weeks 2x / Week	20 and 40	RSI
Ramirez-Campillo et al. (2020)	38 Participants (CON:12; EXPI: 12; EXPII: 14)	Boys	16.9 ± 0.5	Tanner Stage: 4 to 5	No systematic plyometric training in the past 5 months	Plyometric Training	7 Weeks 2x / Week	20	RSI
Romero et al. (2021)	27 Participants (CONI: 9; EXPI: 10; CONII: 9; EXPII: 9)	Girls	12 to 17	Tanner Stage: 2 to 5	No exposure to plyometric training in the last 4 months	Plyometric Training	6 Weeks 2x / Week	20	RSI
Rosas et al. (2016)	63 Participants (CON: 21; EXPI: 21; EXPII: 21)	Boys	12.0 ± 2.3	N/A	No resistance or jump training in the past 6 months	Plyometric Training	6 Weeks 2x / Week	20 and 40	RSI
Santos and Janeira (2012)	25 Participants (CON: 10; EXP: 15)	Boys	14.2 ± 0.6	Tanner Stage: 3 to 4	No background in regular strength or jump training	Traditional Resistance Training	10 Weeks 2x / Week	40	Jump Height
Vera-Assaoka et al. (2020)	76 Participants (CONI: 16; CONII: 22; EXPI: 16; EXPII: 22)	Boys	10 to 16	Tanner Stage: 1 to 5	No background in regular strength or jump training	Plyometric Training	7 Weeks 2x / Week	20 and 40	RSI

CON = control; EXP = experimental; GCT = ground contact time; N/A = not available; RSI = reactive strength index.

3.3.3.2 Training Intervention

Seventeen of the studies utilised a plyometric training intervention, two studies utilised a neuromuscular training intervention, three studies implemented a combined training intervention and one utilised a traditional resistance training intervention. The median duration of the interventions was seven weeks (range six weeks to two years). While seven studies employed six-week long interventions, six others employed seven-week long interventions. Four of the remaining studies utilised eight-week long interventions, four others employed 10-week long interventions, one utilised a 12-week intervention and the final remaining study implemented a two-year long intervention. The majority of the studies (n = 21) adopted a training frequency of two sessions per week, while two studies adopted a frequency of three sessions per week.

3.3.4 Effect of Resistance Training in Youth on Jump Height and RSI

Results for the effect of resistance training in youth on jump height and RSI during a DJ are presented in *figure 3.2 and 3.3*. Overall small significant effects favouring training were observed for jump height (g = 0. 44; CI: 0.20 to 0.68; $p < 0.05$) and RSI (g = 0. 52; CI: 0.41 to 0.63; $p < 0.05$). While small significant effects favouring training on jump height were observed for boys (g = 0. 55; CI: 0.23 to 0.88; $p < 0.05$), small non-significant effects for training were observed for girls (g = 0. 50; CI: -0.24 to 1.23; $p > 0.05$). Small significant effects favouring training on RSI were observed for boys (g = 0. 56; CI: 0.44 to 0.68; $p < 0.05$), with trivial non-significant effects observed for girls (g = 0. 11; CI: -0.26 to 0.47; $p > 0.05$). The study by Latorre Román et al. (2018) was excluded from the sub-group analysis as the authors did not report results separately for girls and boys. Overall, low, non-significant heterogeneity was observed across all the studies (≤ 26%; $p > 0.10$) Low non-significant heterogeneity was observed across the studies recruiting boys in sub-group analysis for jump height and RSI (≤

19%; $p > 0.10$). While low non-significant heterogeneity was observed across the studies recruiting girls for the RSI sub-group analysis (0%; $p > 0.10$), significant moderate heterogeneity was observed for the studies recruiting girls in the jump height sub group analysis (64%; $p < 0.10$).

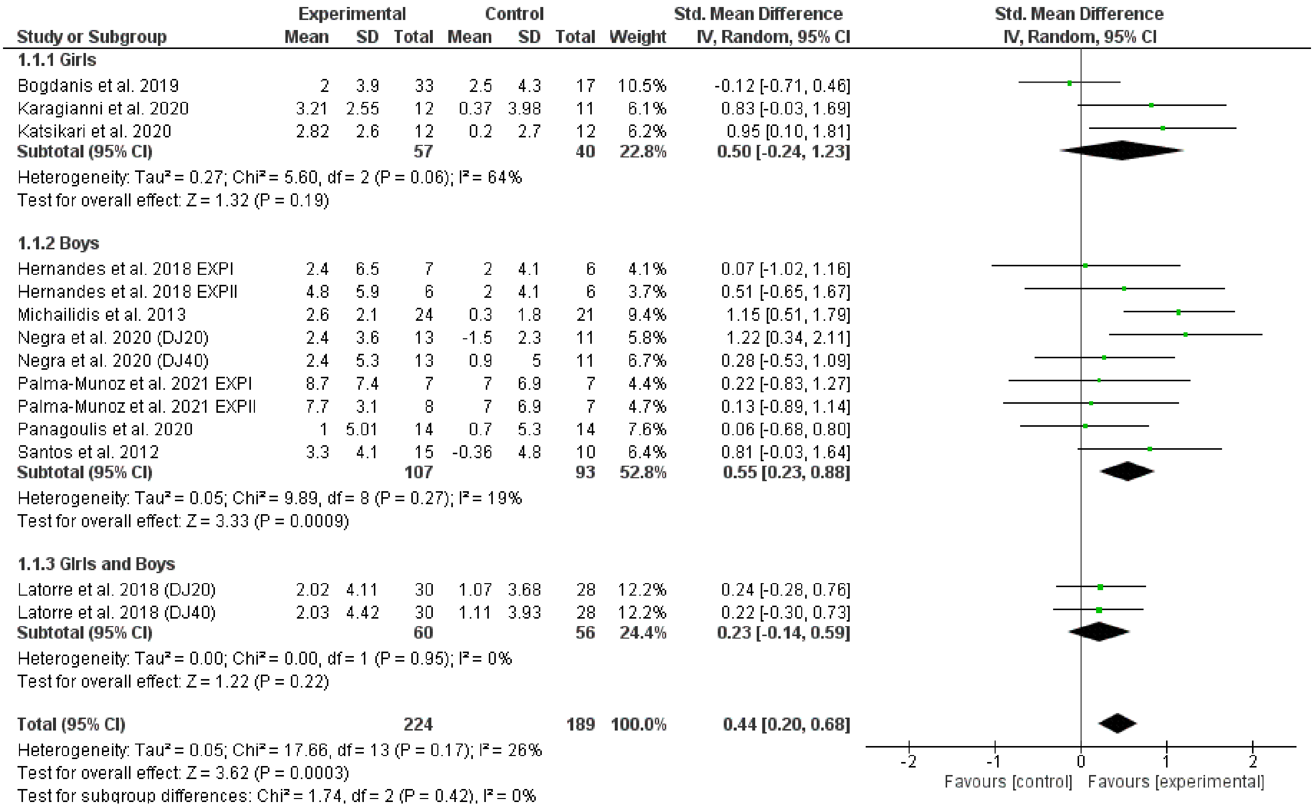


Figure 3.2 Forest plot showing the effect of resistance training in youth on jump height during a drop jump.

Study or Subgroup	Experimental Mean	Experimental SD	Experimental Total	Control Mean	Control SD	Control Total	Weight	Std. Mean Difference IV, Random, 95% CI
3.1.1 Girls								
Bogdanis et al. 2019	0.08	0.22	33	0.08	0.21	17	3.6%	0.00 [-0.59, 0.59]
Moeskops et al. 2018	0.16	0.3	17	0.11	0.38	17	2.7%	0.14 [-0.53, 0.82]
Romero et al. 2021 EXPI	0.1	0.3	10	0.1	0.2	9	1.5%	0.00 [-0.90, 0.90]
Romero et al. 2021 EXPII	0.2	0.3	9	0.1	0.1	9	1.4%	0.43 [-0.51, 1.36]
Subtotal (95% CI)			**69**			**52**	**9.3%**	**0.11 [-0.26, 0.47]**
Heterogeneity: Tau² = 0.00; Chi² = 0.64, df = 3 (P = 0.89); I² = 0%								
Test for overall effect: Z = 0.57 (P = 0.57)								
3.1.2 Boys								
Keiner et al. 2014a EXPI	0.31	0.21	19	0.18	0.39	16	2.8%	0.42 [-0.26, 1.09]
Keiner et al. 2014a EXPII (DJ16)	0.36	0.28	19	0.08	0.28	16	2.5%	0.98 [0.27, 1.69]
Keiner et al. 2014a EXPII (DJ24)	0.46	0.2	19	0.07	0.4	16	2.3%	1.24 [0.51, 1.97]
Ramirez-Campillo et al. 2014 (DJ20)	0.23	0.4	38	0.03	0.28	38	5.9%	0.57 [0.11, 1.03]
Ramirez-Campillo et al. 2014 (DJ40)	0.16	0.4	38	0.02	0.35	38	6.1%	0.37 [-0.08, 0.82]
Ramirez-Campillo et al. 2014a EXPI (DJ20)	0.26	0.2	13	0.07	0.2	15	2.0%	0.92 [0.14, 1.71]
Ramirez-Campillo et al. 2014a EXPI (DJ40)	0.29	0.3	13	0.09	0.3	15	2.1%	0.65 [-0.12, 1.41]
Ramirez-Campillo et al. 2014a EXPII (DJ20)	0.26	0.2	14	0.07	0.2	15	2.1%	0.92 [0.15, 1.70]
Ramirez-Campillo et al. 2014a EXPII (DJ40)	0.28	0.2	14	0.09	0.3	15	2.2%	0.72 [-0.04, 1.47]
Ramirez-Campillo et al. 2014a EXPIII (DJ20)	0.27	0.3	12	0.07	0.2	15	2.0%	0.78 [-0.01, 1.57]
Ramirez-Campillo et al. 2014a EXPIII (DJ40)	0.33	0.3	12	0.09	0.3	15	2.0%	0.78 [-0.02, 1.57]
Ramirez-Campillo et al. 2015a EXPI	0.19	0.5	12	0.04	0.4	14	2.1%	0.32 [-0.45, 1.10]
Ramirez-Campillo et al. 2015a EXPII	0.12	0.3	16	0.04	0.4	14	2.4%	0.22 [-0.50, 0.94]
Ramirez-Campillo et al. 2015a EXPIII	0.24	0.5	12	0.04	0.4	14	2.0%	0.43 [-0.35, 1.21]
Ramirez-Campillo et al. 2015b EXPI	0.2	0.42	10	0.05	0.41	10	1.6%	0.35 [-0.54, 1.23]
Ramirez-Campillo et al. 2015b EXPII	0.16	0.36	10	0.05	0.41	10	1.6%	0.27 [-0.61, 1.15]
Ramirez-Campillo et al. 2015b EXPIII	0.2	0.2	10	0.05	0.41	10	1.6%	0.45 [-0.44, 1.34]
Ramirez-Campillo et al. 2015c EXPI	0.25	0.34	8	-0.02	0.29	8	1.2%	0.81 [-0.22, 1.84]
Ramirez-Campillo et al. 2015c EXPII	0.09	0.22	8	-0.02	0.29	8	1.3%	0.40 [-0.59, 1.40]
Ramirez-Campillo et al. 2015d EXPI	0.16	0.4	54	0.02	0.42	55	8.7%	0.34 [-0.04, 0.72]
Ramirez-Campillo et al. 2015d EXPII	0.16	0.39	57	0.02	0.42	55	8.9%	0.34 [-0.03, 0.72]
Ramirez-Campillo et al. 2019 (DJ20)	0.17	0.43	19	-0.06	0.41	20	3.0%	0.54 [-0.10, 1.18]
Ramirez-Campillo et al. 2019 (DJ40)	0.17	0.44	19	-0.04	0.35	20	3.0%	0.52 [-0.12, 1.16]
Ramirez-Campillo et al. 2020 EXPI	0.34	0.2	12	0.02	0.28	12	1.6%	1.27 [0.38, 2.16]
Ramirez-Campillo et al. 2020 EXPII	0.09	0.32	14	0.02	0.28	12	2.1%	0.22 [-0.55, 1.00]
Rosas et al. 2016 EXPI	0.09	0.4	21	0.03	0.4	21	3.4%	0.15 [-0.46, 0.75]
Rosas et al. 2016 EXPII	0.18	0.5	21	0.03	0.4	21	3.4%	0.33 [-0.28, 0.93]
Vera-Assaoka et al. 2020 EXPI (DJ20)	0.2	0.1	16	0	0.2	16	2.1%	1.23 [0.47, 2.00]
Vera-Assaoka et al. 2020 EXPI (DJ40)	0.1	0.2	16	0	0.1	16	2.5%	0.62 [-0.09, 1.33]
Vera-Assaoka et al. 2020 EXPII (DJ20)	0.2	0.3	22	-0.1	0.3	22	3.2%	0.98 [0.35, 1.61]
Vera-Assaoka et al. 2020 EXPII (DJ40)	0.2	0.3	22	-0.1	0.3	22	3.2%	0.98 [0.35, 1.61]
Subtotal (95% CI)			**590**			**594**	**90.7%**	**0.56 [0.44, 0.68]**
Heterogeneity: Tau² = 0.00; Chi² = 24.88, df = 30 (P = 0.73); I² = 0%								
Test for overall effect: Z = 9.36 (P < 0.00001)								
Total (95% CI)			**659**			**646**	**100.0%**	**0.52 [0.41, 0.63]**
Heterogeneity: Tau² = 0.00; Chi² = 30.88, df = 34 (P = 0.62); I² = 0%								
Test for overall effect: Z = 9.08 (P < 0.00001)								
Test for subgroup differences: Chi² = 5.36, df = 1 (P = 0.02), I² = 81.3%								

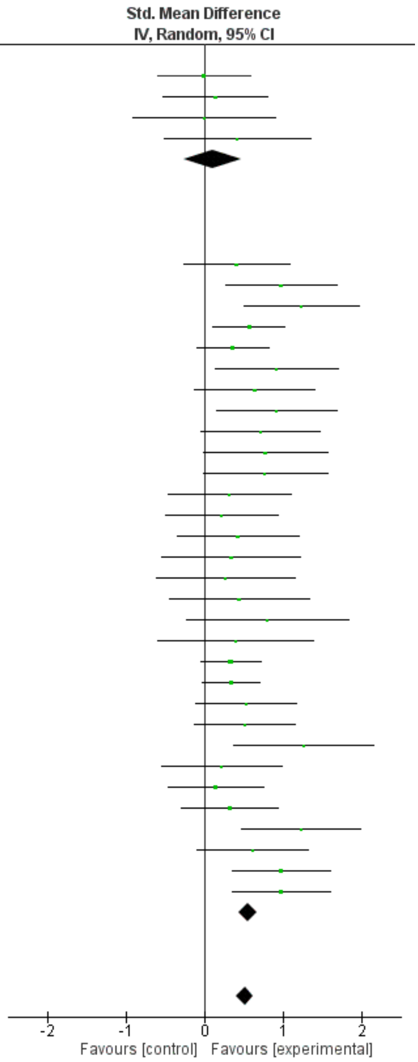


Figure 3.3 Forest plot showing the effect of resistance training in youth on RSI during a drop jump.

Only two studies, both recruiting girls, reported the effect of resistance training on ground contact time during a DJ from a 20 cm height. Although analysis revealed an overall non-significant increase in ground contact time in favour of the control groups, significantly high heterogeneity observed across the studies (96%; $p < 0.10$; *figure 3.4*), requiring caution to be exercised when interpreting the results.

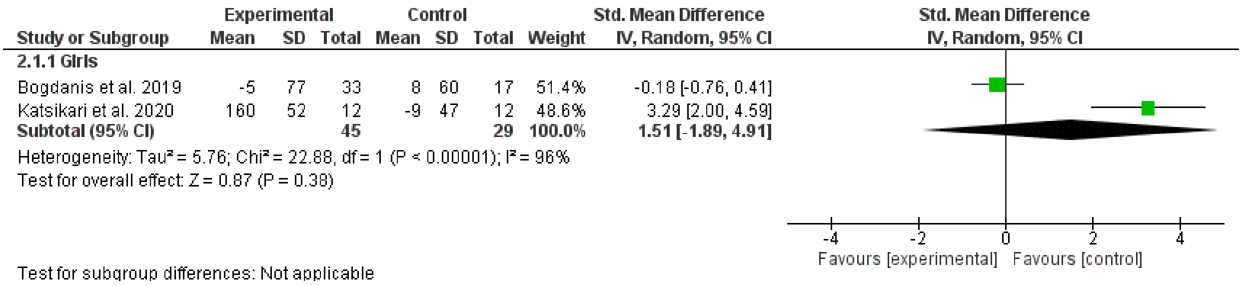


Figure 3.4 Forest plot showing the effect of resistance training on ground contact time during a drop jump from 20 cm in girls.

3.3.5 Effect of Resistance Training on Jump Height and RSI from Different Drop Heights

Results for the effect of resistance training in youth on jump height from different drop heights are presented in *figure 3.5*. Drop height of 30 cm was excluded from this sub-group analysis due to insufficient number of studies (n = 1). While a small significant effect for training was observed on jump height from a drop of 20 cm (g = 0. 36; CI: 0.08 to 0.64; $p < 0.05$), a small non-significant effect for training was observed on jump height from a drop of 40 cm (g = 0. 36; CI: -0.03 to 0.74; $p > 0.05$).

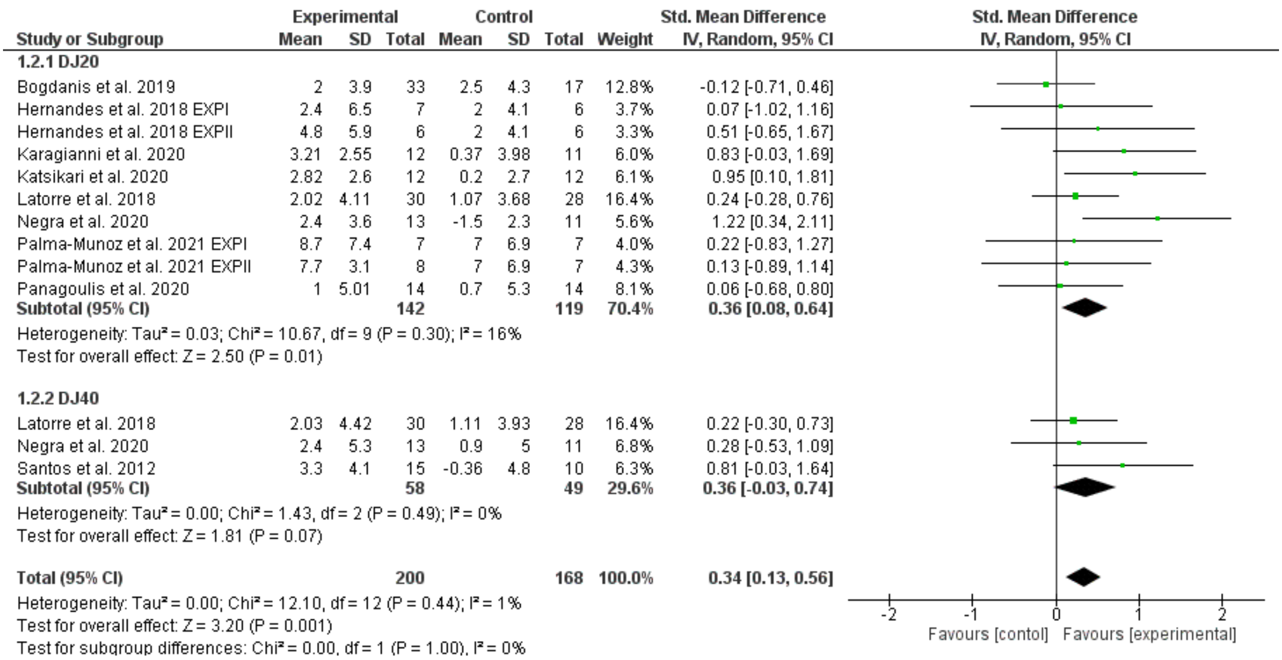


Figure 3.5 Forest plot showing the effect of resistance training in youth on jump height during a drop jump from different drop heights.

Results for the effect of resistance training in youth on RSI from different drop heights are presented in *figure 3.6*. Drop height of 24 cm was excluded from the sub-group analysis due to insufficient number of studies (n = 1). Small to moderate effects favouring training were observed on RSI from drop heights of 16 cm (g = 0. 69; CI: 0.14 to 1.23; $p < 0.05$), 20 cm (g = 0. 45; CI: 0.32 to 0.59; $p < 0.05$) and 40 cm (g = 0. 61; CI: 0.37 to 0.86; $p < 0.05$). Low non-significant heterogeneity was observed across the studies included in the drop height sub-group analysis for jump height and RSI (≤ 21%; $p > 0.10$).

Study or Subgroup	Experimental Mean	SD	Total	Control Mean	SD	Total	Weight	Std. Mean Difference IV, Random, 95% CI
3.2.1 DJ16								
Keiner et al. 2014a EXPI	0.31	0.21	19	0.18	0.39	16	2.8%	0.42 [-0.26, 1.09]
Keiner et al. 2014a EXPII	0.36	0.28	19	0.08	0.28	16	2.5%	0.98 [0.27, 1.69]
Subtotal (95% CI)			**38**			**32**	**5.4%**	**0.69 [0.14, 1.23]**
Heterogeneity: Tau² = 0.03; Chi² = 1.27, df = 1 (P = 0.26); I² = 21%								
Test for overall effect: Z = 2.45 (P = 0.01)								
3.2.2 DJ20								
Bogdanis et al. 2019	0.08	0.22	33	0.08	0.21	17	3.7%	0.00 [-0.59, 0.59]
Moeskops et al. 2018	0.16	0.3	17	0.11	0.38	17	2.8%	0.14 [-0.53, 0.82]
Ramirez-Campillo et al. 2014	0.23	0.4	38	0.03	0.28	38	6.0%	0.57 [0.11, 1.03]
Ramirez-Campillo et al. 2014a EXPI	0.26	0.2	13	0.07	0.2	15	2.1%	0.92 [0.14, 1.71]
Ramirez-Campillo et al. 2014a EXPII	0.26	0.2	14	0.07	0.2	15	2.1%	0.92 [0.15, 1.70]
Ramirez-Campillo et al. 2014a EXPIII	0.27	0.3	12	0.07	0.2	15	2.0%	0.78 [-0.01, 1.57]
Ramirez-Campillo et al. 2015a EXPI	0.19	0.5	12	0.04	0.4	14	2.1%	0.32 [-0.45, 1.10]
Ramirez-Campillo et al. 2015a EXPII	0.12	0.3	16	0.04	0.4	14	2.5%	0.22 [-0.50, 0.94]
Ramirez-Campillo et al. 2015a EXPIII	0.24	0.5	12	0.04	0.4	14	2.1%	0.43 [-0.35, 1.21]
Ramirez-Campillo et al. 2015b EXPI	0.2	0.42	10	0.05	0.41	10	1.6%	0.35 [-0.54, 1.23]
Ramirez-Campillo et al. 2015b EXPII	0.16	0.36	10	0.05	0.41	10	1.6%	0.27 [-0.61, 1.15]
Ramirez-Campillo et al. 2015b EXPIII	0.2	0.2	10	0.05	0.41	10	1.6%	0.45 [-0.44, 1.34]
Ramirez-Campillo et al. 2015c EXPI	0.25	0.34	8	-0.02	0.29	8	1.2%	0.81 [-0.22, 1.84]
Ramirez-Campillo et al. 2015c EXPII	0.09	0.22	8	-0.02	0.29	8	1.3%	0.40 [-0.59, 1.40]
Ramirez-Campillo et al. 2015d EXPI	0.16	0.4	54	0.02	0.42	55	8.9%	0.34 [-0.04, 0.72]
Ramirez-Campillo et al. 2015d EXPII	0.16	0.39	57	0.02	0.42	55	9.2%	0.34 [-0.03, 0.72]
Ramirez-Campillo et al. 2019	0.17	0.43	19	-0.06	0.41	20	3.1%	0.54 [-0.10, 1.18]
Ramirez-Campillo et al. 2020 EXPI	0.34	0.2	12	0.02	0.28	12	1.6%	1.27 [0.38, 2.16]
Ramirez-Campillo et al. 2020 EXPII	0.09	0.32	14	0.02	0.28	12	2.1%	0.22 [-0.55, 1.00]
Romero et al. 2021 EXPI	0.1	0.3	10	0.1	0.2	9	1.6%	0.00 [-0.90, 0.90]
Romero et al. 2021 EXPII	0.2	0.3	9	0.1	0.1	9	1.5%	0.43 [-0.51, 1.36]
Rosas et al. 2016 EXPI	0.09	0.4	21	0.03	0.4	21	3.5%	0.15 [-0.46, 0.75]
Rosas et al. 2016 EXPII	0.18	0.5	21	0.03	0.4	21	3.4%	0.33 [-0.28, 0.93]
Vera-Assaoka et al. 2020 EXPI	0.2	0.1	16	0	0.2	16	2.2%	1.23 [0.47, 2.00]
Vera-Assaoka et al. 2020 EXPII	0.2	0.3	22	-0.1	0.3	22	3.2%	0.98 [0.35, 1.61]
Subtotal (95% CI)			**468**			**457**	**73.1%**	**0.45 [0.32, 0.59]**
Heterogeneity: Tau² = 0.00; Chi² = 21.16, df = 24 (P = 0.63); I² = 0%								
Test for overall effect: Z = 6.73 (P < 0.00001)								
3.2.4 DJ40								
Ramirez-Campillo et al. 2014	0.16	0.4	38	0.02	0.35	38	6.2%	0.37 [-0.08, 0.82]
Ramirez-Campillo et al. 2014a EXPI	0.29	0.3	13	0.09	0.3	15	2.2%	0.65 [-0.12, 1.41]
Ramirez-Campillo et al. 2014a EXPII	0.28	0.2	14	0.09	0.3	15	2.2%	0.72 [-0.04, 1.47]
Ramirez-Campillo et al. 2014a EXPIII	0.33	0.3	12	0.09	0.3	15	2.0%	0.78 [-0.02, 1.57]
Ramirez-Campillo et al. 2019	0.17	0.44	19	-0.04	0.35	20	3.1%	0.52 [-0.12, 1.16]
Vera-Assaoka et al. 2020 EXPI	0.1	0.2	16	0	0.1	16	2.5%	0.62 [-0.09, 1.33]
Vera-Assaoka et al. 2020 EXPII	0.2	0.3	22	-0.1	0.3	22	3.2%	0.98 [0.35, 1.61]
Subtotal (95% CI)			**134**			**141**	**21.5%**	**0.61 [0.37, 0.86]**
Heterogeneity: Tau² = 0.00; Chi² = 2.77, df = 6 (P = 0.84); I² = 0%								
Test for overall effect: Z = 4.95 (P < 0.00001)								
Total (95% CI)			**640**			**630**	**100.0%**	**0.50 [0.39, 0.61]**
Heterogeneity: Tau² = 0.00; Chi² = 27.06, df = 33 (P = 0.76); I² = 0%								
Test for overall effect: Z = 8.68 (P < 0.00001)								
Test for subgroup differences: Chi² = 1.77, df = 2 (P = 0.41), I² = 0%								

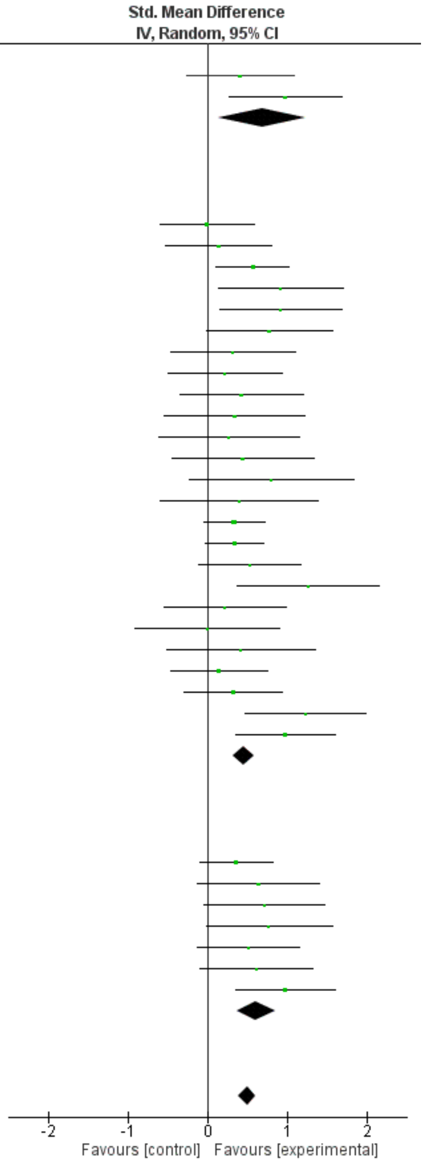


Figure 3.6 Forest plot showing the effect of resistance training in youth on RSI during a drop jump from different drop heights.

3.3.6 Effect of Different Resistance Training Interventions on Jump Height and RSI

Results for the effect of different types of resistance training interventions on jump height and RSI during a DJ in youth are presented in *figure 3.7 and 3.8*. Neuromuscular training and traditional resistance training were excluded from the sub-group analysis due to insufficient number of studies. While a small significant effect favouring plyometric training on jump height was observed (g = 0. 51; CI: 0.13 to 0.88; $p < 0.05$), a small non-significant effect was observed for combined training (g = 0. 32; CI: -0.02 to 0.66; $p > 0.05$). Small significant effects favouring plyometric training were also observed for RSI (g = 0. 50; CI: 0.38 to 0.62; $p < 0.05$), with moderate significant effects being observed for combined training (g = 0. 86; CI: 0.38 to 1.34; $p < 0.05$). While the studies implementing combined training in the jump height sub-group analysis exhibited low non-significant heterogeneity (0%; $p > 0.10$), the studies utilising plyometric training exhibited low significant heterogeneity (41%; $p < 0.10$). Low to moderate non-significant heterogeneity was observed in the studies included for RSI intervention sub-group analysis (≤ 29%; $p > 0.10$).

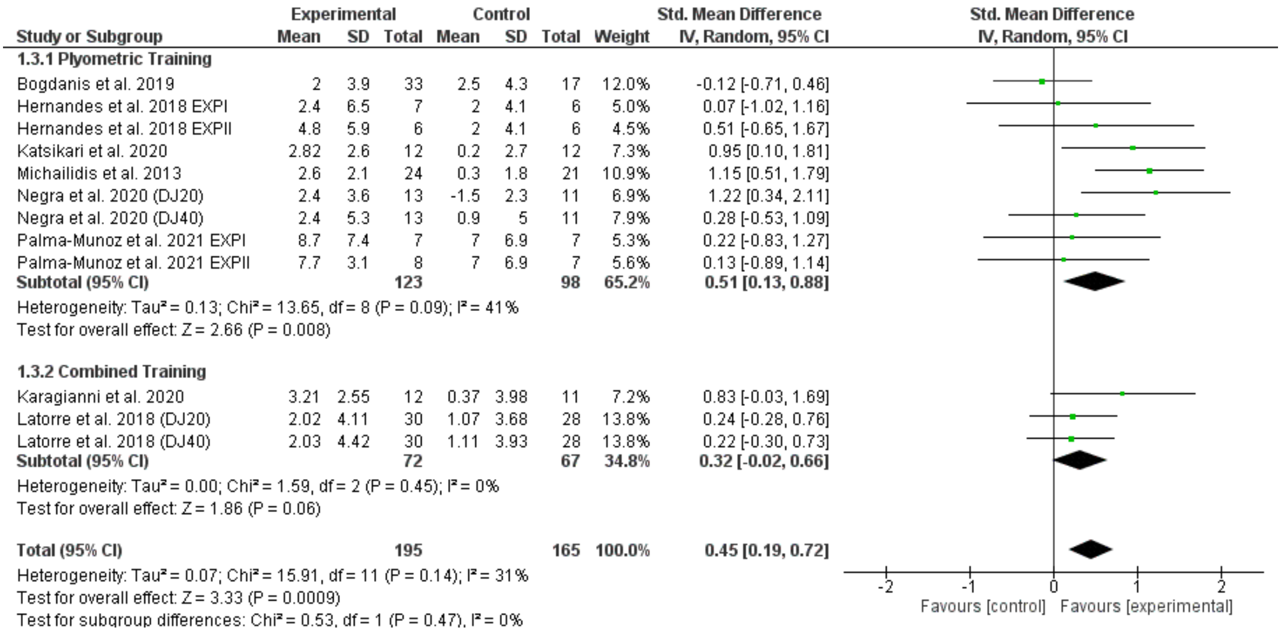


Figure 3.7 Forest plot showing the effect of plyometric and combined resistance training in youth on jump height during a drop jump.

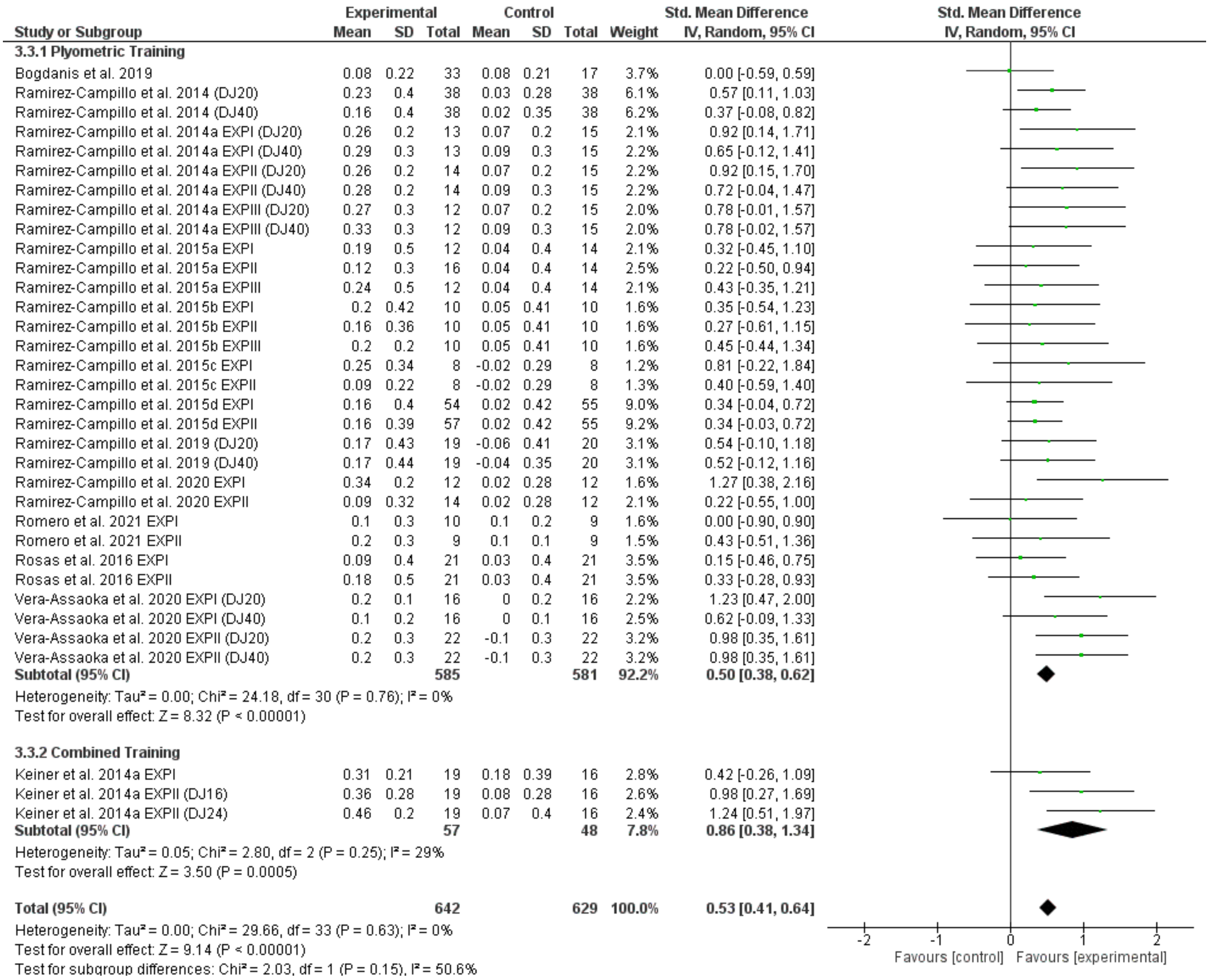


Figure 3.8 Forest plot showing the effect of plyometric and combined resistance training in youth on RSI during a drop jump.

3.3.7 Effect of Resistance Training on Untrained and Trained Youth

Results for the effect of resistance training on jump height and RSI during a DJ on untrained and trained youth are presented in *figure 3.9 and 3.10*. The studies by Keiner et al. (2014a) and Negra et al. (2020) were excluded from the sub-group analysis due to participants' training status not being reported. Small significant effects favouring training on jump height were observed for the untrained individuals ($g = 0.42$; CI: 0.14 to 0.70; $p < 0.05$), with small non-significant effects being observed for trained individuals ($g = 0.27$; CI: -0.52 to 1.07; $p > 0.05$). While moderate significant effects for training were observed on RSI for untrained individuals

(g = 0. 63; CI: 0.47 to 0.80; $p < 0.05$), small significant effects favouring training were observed for trained individuals (g = 0. 38; CI: 0.21 to 0.55; $p < 0.05$). Low non-significant heterogeneity was observed across all studies included in the sub-group analysis for jump height and RSI (≤ 35%; $p > 0.10$).

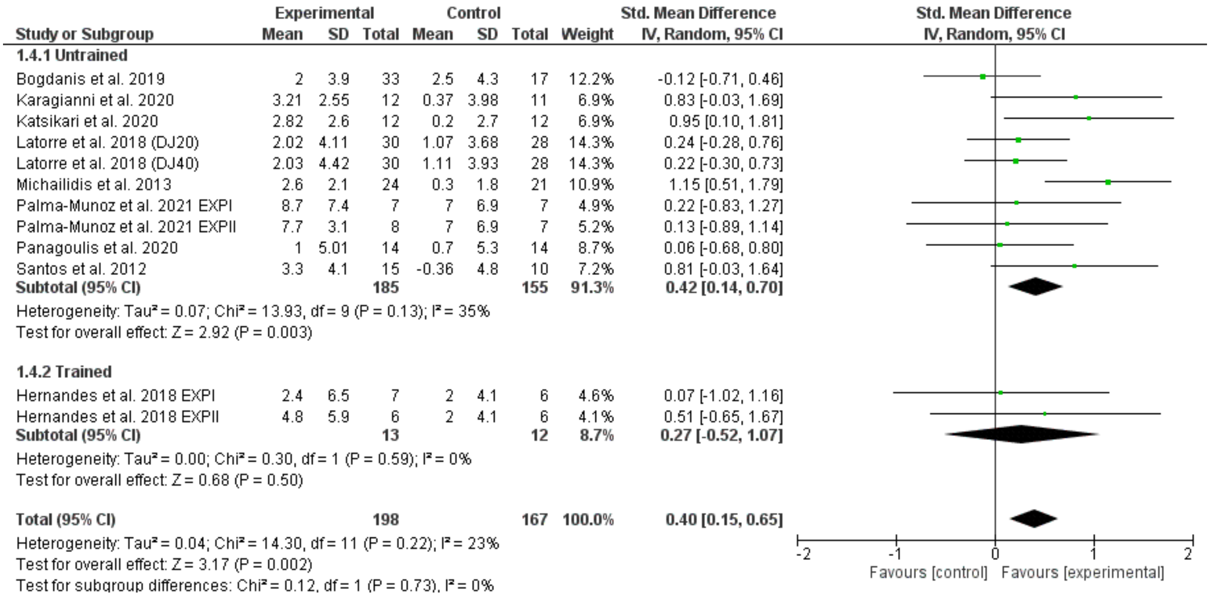


Figure 3.9 Forest plot showing the effect of resistance training on jump height during a drop jump in untrained and trained youth.

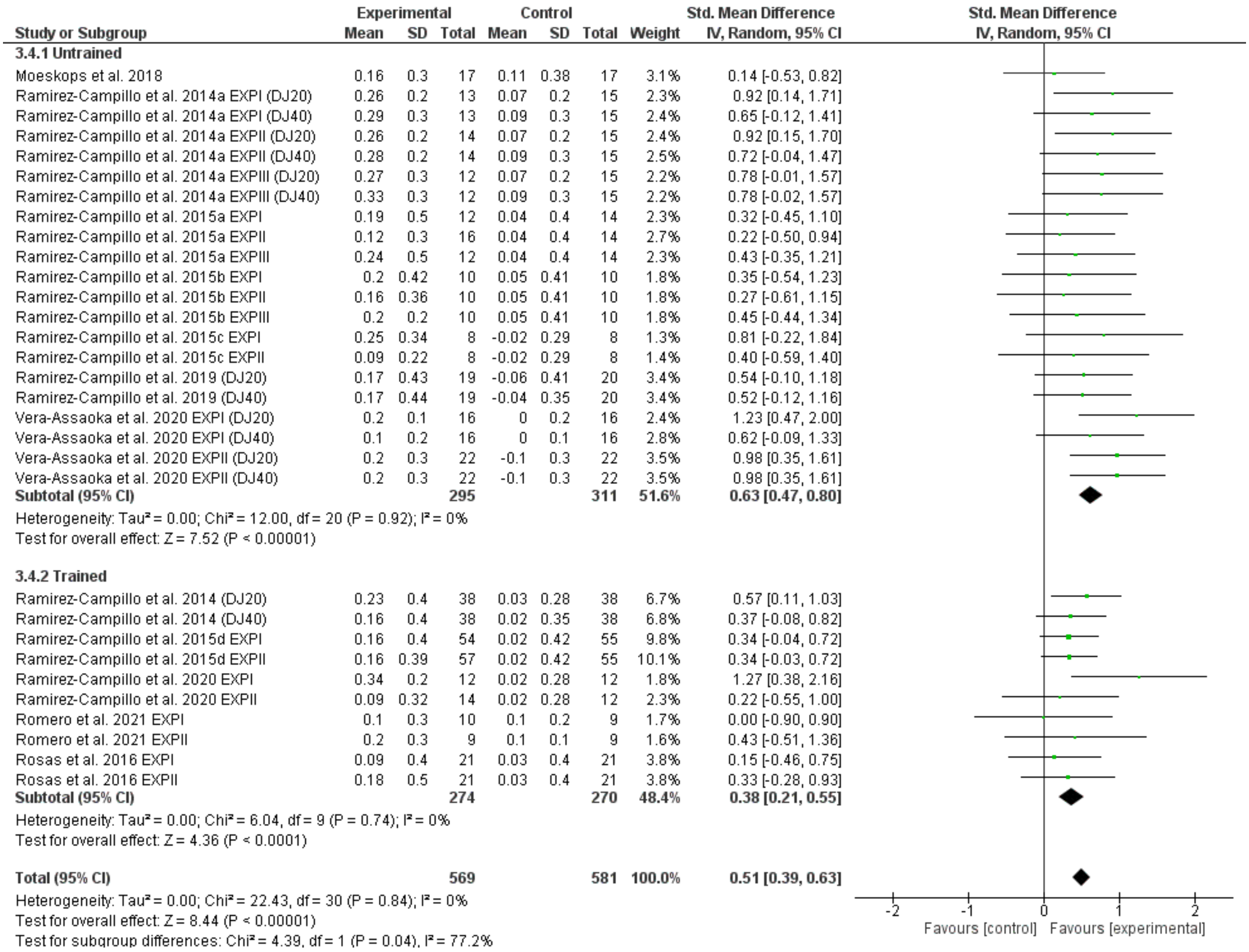


Figure 3.10 Forest plot showing the effect of resistance training on RSI during a drop jump in untrained and trained youth.

3.3.8 Effect of Resistance Training on Jump Height and RSI in Children and Adolescents

Results for the effect of resistance training on jump height and RSI during a DJ on children and adolescents are presented in *figure 3.11 and 3.12*. Small significant effects favouring training on jump height were observed for children (g = 0.42; CI: 0.12 to 0.73; $p < 0.05$) and adolescents (g = 0.56; CI: 0.09 to 1.02; $p < 0.05$). Similarly, small significant effects for training on RSI were observed for children (g = 0.52; CI: 0.36 to 0.68; $p < 0.05$) and adolescents (g = 0.52; CI: 0.36 to 0.67; $p < 0.05$). While low non-significant heterogeneity was observed across the studies recruiting adolescents within the jump height sub-group analysis (0%; $p > 0.10$), low significant heterogeneity was observed across the studies recruiting children (42%; $p < 0.10$). Low non-significant heterogeneity was observed across all the studies included within the RSI subgroup analysis (0%; $p > 0.10$). A summary of the findings from the meta-analysis is presented in *table 3.3*.

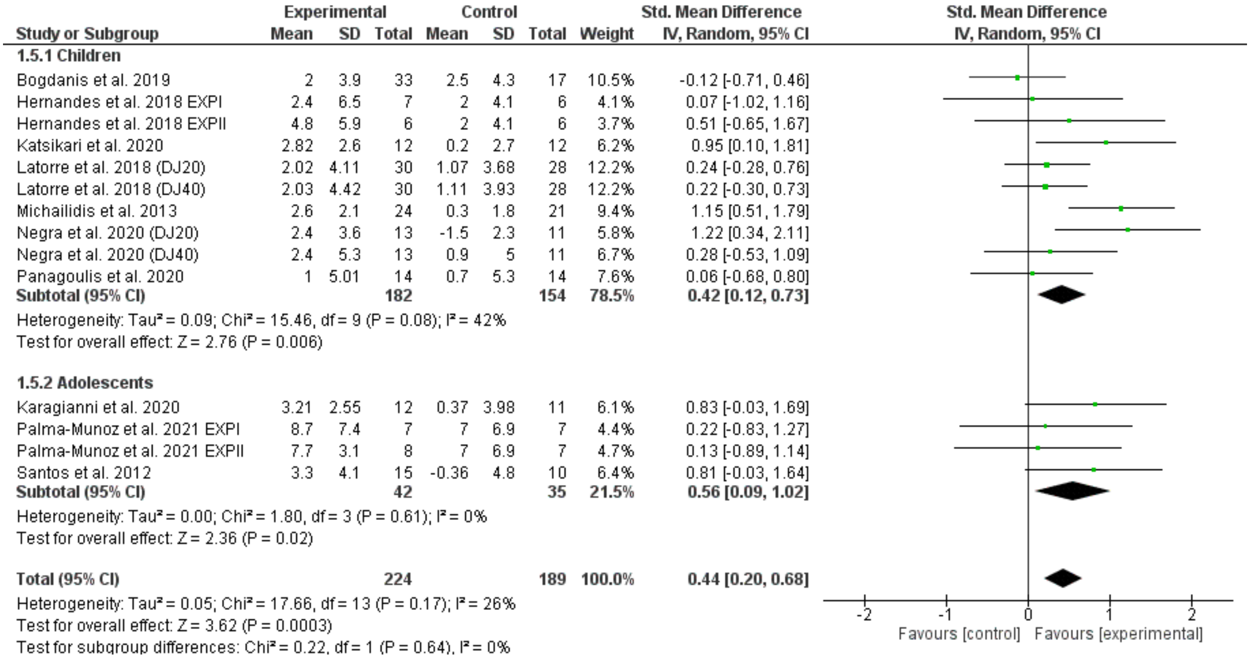


Figure 3.11 Forest plot showing the effect of resistance training on jump height during a drop jump in children and adolescents.

Study or Subgroup	Experimental Mean	Experimental SD	Experimental Total	Control Mean	Control SD	Control Total	Weight	Std. Mean Difference IV, Random, 95% CI
3.5.1 Children								
Bogdanis et al. 2019	0.08	0.22	33	0.08	0.21	17	3.6%	0.00 [-0.59, 0.59]
Keiner et al. 2014a EXPI	0.31	0.21	19	0.18	0.39	16	2.8%	0.42 [-0.26, 1.09]
Keiner et al. 2014a EXPII (DJ16)	0.36	0.28	19	0.08	0.28	16	2.5%	0.98 [0.27, 1.69]
Keiner et al. 2014a EXPII (DJ24)	0.46	0.2	19	0.07	0.4	16	2.3%	1.24 [0.51, 1.97]
Moeskops et al. 2018	0.16	0.3	17	0.11	0.38	17	2.7%	0.14 [-0.53, 0.82]
Ramirez-Campillo et al. 2014a EXPI (DJ20)	0.26	0.2	13	0.07	0.2	15	2.0%	0.92 [0.14, 1.71]
Ramirez-Campillo et al. 2014a EXPI (DJ40)	0.29	0.3	13	0.09	0.3	15	2.1%	0.65 [-0.12, 1.41]
Ramirez-Campillo et al. 2014a EXPII (DJ20)	0.26	0.2	14	0.07	0.2	15	2.1%	0.92 [0.15, 1.70]
Ramirez-Campillo et al. 2014a EXPII (DJ40)	0.28	0.2	14	0.09	0.3	15	2.2%	0.72 [-0.04, 1.47]
Ramirez-Campillo et al. 2014a EXPIII (DJ20)	0.27	0.3	12	0.07	0.2	15	2.0%	0.78 [-0.01, 1.57]
Ramirez-Campillo et al. 2014a EXPIII (DJ40)	0.33	0.3	12	0.09	0.3	15	2.0%	0.78 [-0.02, 1.57]
Ramirez-Campillo et al. 2015a EXPI	0.19	0.5	12	0.04	0.4	14	2.1%	0.32 [-0.45, 1.10]
Ramirez-Campillo et al. 2015a EXPII	0.12	0.3	16	0.04	0.4	14	2.4%	0.22 [-0.50, 0.94]
Ramirez-Campillo et al. 2015a EXPIII	0.24	0.5	12	0.04	0.4	14	2.0%	0.43 [-0.35, 1.21]
Ramirez-Campillo et al. 2015b EXPI	0.2	0.42	10	0.05	0.41	10	1.6%	0.35 [-0.54, 1.23]
Ramirez-Campillo et al. 2015b EXPII	0.16	0.36	10	0.05	0.41	10	1.6%	0.27 [-0.61, 1.15]
Ramirez-Campillo et al. 2015b EXPIII	0.2	0.2	10	0.05	0.41	10	1.6%	0.45 [-0.44, 1.34]
Romero et al. 2021 EXPI	0.1	0.3	10	0.1	0.2	9	1.5%	0.00 [-0.90, 0.90]
Rosas et al. 2016 EXPI	0.09	0.4	21	0.03	0.4	21	3.4%	0.15 [-0.46, 0.75]
Rosas et al. 2016 EXPII	0.18	0.5	21	0.03	0.4	21	3.4%	0.33 [-0.28, 0.93]
Vera-Assaoka et al. 2020 EXPI (DJ20)	0.2	0.1	16	0	0.2	16	2.1%	1.23 [0.47, 2.00]
Vera-Assaoka et al. 2020 EXPI (DJ40)	0.1	0.2	16	0	0.1	16	2.5%	0.62 [-0.09, 1.33]
Subtotal (95% CI)			**339**			**327**	**50.5%**	**0.52 [0.36, 0.68]**
Heterogeneity: Tau² = 0.00; Chi² = 20.84, df = 21 (P = 0.47); I² = 0%								
Test for overall effect: Z = 6.47 (P < 0.00001)								
3.5.2 Adolescents								
Ramirez-Campillo et al. 2014 (DJ20)	0.23	0.4	38	0.03	0.28	38	5.9%	0.57 [0.11, 1.03]
Ramirez-Campillo et al. 2014 (DJ40)	0.16	0.4	38	0.02	0.35	38	6.1%	0.37 [-0.08, 0.82]
Ramirez-Campillo et al. 2015c EXPI	0.25	0.34	8	-0.02	0.29	8	1.2%	0.81 [-0.22, 1.84]
Ramirez-Campillo et al. 2015c EXPII	0.09	0.22	8	-0.02	0.29	8	1.3%	0.40 [-0.59, 1.40]
Ramirez-Campillo et al. 2015d EXPI	0.16	0.4	54	0.02	0.42	55	8.7%	0.34 [-0.04, 0.72]
Ramirez-Campillo et al. 2015d EXPII	0.16	0.39	57	0.02	0.42	55	8.9%	0.34 [-0.03, 0.72]
Ramirez-Campillo et al. 2019 (DJ20)	0.17	0.43	19	-0.06	0.41	20	3.0%	0.54 [-0.10, 1.18]
Ramirez-Campillo et al. 2019 (DJ40)	0.17	0.44	19	-0.04	0.35	20	3.0%	0.52 [-0.12, 1.16]
Ramirez-Campillo et al. 2020 EXPI	0.34	0.2	12	0.02	0.28	12	1.6%	1.27 [0.38, 2.16]
Ramirez-Campillo et al. 2020 EXPII	0.09	0.32	14	0.02	0.28	12	2.1%	0.22 [-0.55, 1.00]
Romero et al. 2021 EXPII	0.2	0.3	9	0.1	0.1	9	1.4%	0.43 [-0.51, 1.36]
Vera-Assaoka et al. 2020 EXPII (DJ20)	0.2	0.3	22	-0.1	0.3	22	3.2%	0.98 [0.35, 1.61]
Vera-Assaoka et al. 2020 EXPII (DJ40)	0.2	0.3	22	-0.1	0.3	22	3.2%	0.98 [0.35, 1.61]
Subtotal (95% CI)			**320**			**319**	**49.5%**	**0.52 [0.36, 0.67]**
Heterogeneity: Tau² = 0.00; Chi² = 10.04, df = 12 (P = 0.61); I² = 0%								
Test for overall effect: Z = 6.38 (P < 0.00001)								
Total (95% CI)			**659**			**646**	**100.0%**	**0.52 [0.41, 0.63]**
Heterogeneity: Tau² = 0.00; Chi² = 30.88, df = 34 (P = 0.62); I² = 0%								
Test for overall effect: Z = 9.08 (P < 0.00001)								
Test for subgroup differences: Chi² = 0.00, df = 1 (P = 0.99), I² = 0%								

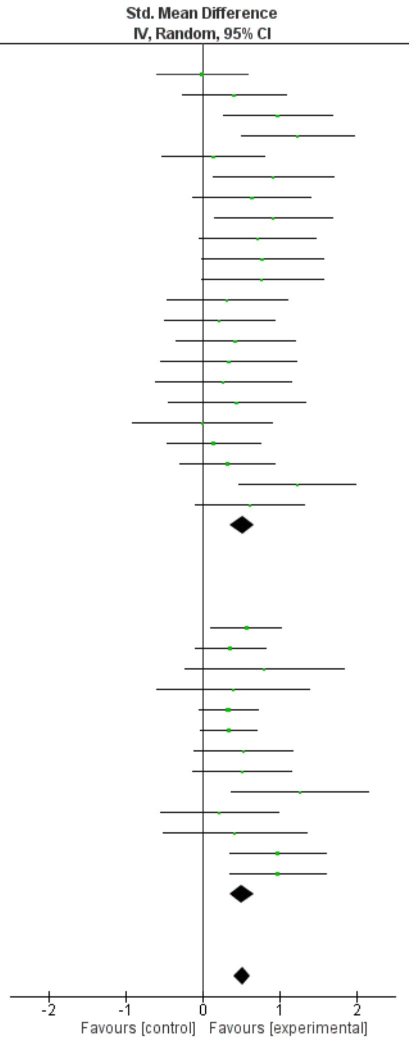


Figure 3.12 Forest plot showing the effect of resistance training on RSI during a drop jump in children and adolescents.

Table 3.3 Summary of findings from the meta-analysis quantifying the effect of resistance training on drop jump performance variables in youth.

Performance Variable	**Subgroups**	**Overall**	**Subgroup Analysis**		
			I	**vs II**	**vs III**
Jump Height	Girls vs Boys	0.44*	0.50#	0.55*	-
	20 cm vs 40 cm	0.34*	0.36*	0.36	-
	Plyometric vs Combined	0.45*	0.51*	0.32	-
	Untrained vs Trained	0.40*	0.42*	0.27	-
	Children vs Adolescents	0.44*	0.42*	0.56*	-
Ground Contact Time	Girls	-	1.51Ŧ	-	-
Reactive Strength Index	Girls vs Boys ¥	0.52*	0.11	0.56*	-
	16 cm vs 20 cm vs 40 cm	0.50*	0.69*	0.45*	0.61*
	Plyometric vs Combined	0.53*	0.50*	0.86*	-
	Untrained vs Trained ¥	0.51*	0.63*	0.38*	-
	Children vs Adolescents	0.52*	0.52*	0.52*	-

* significant effect ($p < 0.05$)

¥ significant difference between subgroups ($p < 0.05$)

moderate significant heterogeneity

Ŧ large significant heterogeneity

3.4 DISCUSSION

The study aimed to quantify the effects of resistance training on DJ performance variables in youth. Overall, the findings indicate that resistance training in youth can have small significant positive effects on jump height and RSI during DJs. Small significant effects favouring training on jump height and RSI were observed for boys, with trivial to small non-significant effects being observed for girls. The results suggest that resistance training can have small to moderate significant effects on jump height and RSI during DJs from different drop heights, with the only non-significant effect being observed on jump height from a 40 cm drop. Both plyometric and combined training were observed to have small to moderate positive effects on jump height and RSI during DJs, although the effect of combined training on jump height was non-significant. Although jump height and RSI in both untrained and trained youth were observed to be positively influenced by resistance training, comparatively larger effects were observed in untrained youth. Finally, resistance training in both children and adolescents elicited small significant positive effects on jump height and RSI during a DJ. The only significant differences between subgroups were observed for RSI in girls vs boys and untrained vs trained youth. Although two studies did report ground contact time, the results were excluded from the discussion due to the high significant levels of heterogeneity. No kinetic measures were included in the analysis as an insufficient number of studies reported changes in kinetic qualities in youth during DJs, following resistance training.

Jump Height vs RSI

While the current study observed small significant effects favouring resistance training on jump height and RSI during DJs in youth, slightly larger effects were observed on RSI compared to jump height (g = 0.52 vs 0.44). With RSI being calculated as the ratio of jump height and ground contact time (Flanagan and Comyns, 2008), this calculation assumes that if ground contact time increases, jump height would also increase proportionately, potentially leaving RSI unchanged (Healy et al., 2018). The greater effects favouring training observed on RSI compared to jump height might suggest a decrease in ground contact time following the training interventions, but unfortunately ground contact time was often not reported in the studies included. The interaction of force development and its manipulation over time is referred to as impulse, calculated as the product of force and time (Xu et al., 2020), and this vertical impulse underpins jump height (Winter, 2005). A decrease in ground contact time coupled with an increased force production could result in trivial to small increases in jump height but comparatively larger increases in RSI. However, the majority of the studies within the meta-analysis that reported RSI failed to provide measures for jump height and ground contact time, thereby leaving the changes underpinning the outcome unclear.

Gender-Related Differences

A meta-analysis by Lesinski et al. (2016) reported similar magnitudes of improvement in strength and vertical jump performance in boys and girls following resistance training. Similarly, a meta-analysis by Peitz et al. (2018) reported that resistance training induced similar magnitudes of adaptations in boys and girls of the same age group. However, the current study observed small significant effects favouring training on jump height and RSI in boys, with trivial to small non-significant effects being observed for jump height and RSI in girls. Prior research has documented that the natural development of strength differs between boys and girls due to differences in growth and maturation-related neuromuscular changes (Lloyd et al., 2014; O'Brien et al., 2010a). Research comparing training responsiveness of boys and girls across different maturity groups is scarce (Lesinski et al., 2016), and while the differences in natural development do not necessarily suggest differences in trainability, it could suggest varied responsiveness to different types of resistance training. The studies included in the current analysis primarily utilised plyometric and combined training interventions. Given the sex based differences in maturation-related neuromuscular changes, such as greater increases in lean muscle mass in boys in addition to the continued neural adaptations (Lloyd and Oliver, 2013b; Malina et al., 2004), it could be speculated that boys would respond better to combined resistance training than girls due to the process of synergistic adaptation. Further research is needed to compare training responsiveness between girls and boys across maturity groups. Additionally, with the studies failing to report any kinetic measures it is unclear what changes underpinned the observed outcome.

Drop Height

Analysis in the current study revealed small to moderate significant effects favouring resistance training in youth on jump height and RSI during DJs from various drop heights. The only non-significant effect observed was on jump height from a 40 cm drop. Drop jumps involve a high amount of braking loading (Bobbert et al., 1986), with increased drop heights being associated with greater braking loads (Bobbert et al., 1987b). Increases in braking loading often results in high stretch loads, and a subsequent neuromuscular inhibition prior to reflex activation (Bobbert et al., 1987a; Komi and Gollhofer, 1997). The inhibited stretch reflex is suggested to make performance during the propulsive phase of the DJ highly dependent on the force producing capabilities of the individual (Bobbert et al., 1987b). The three studies reporting jump height during DJs from a 40 cm drop height implemented combined, plyometric and traditional resistance training (Latorre Román et al., 2018; Negra et al., 2020; Santos and Janeira, 2012). While exposure to strength training elicits improvements in force producing capabilities (Cormie et al., 2011b), sufficient exposure to high-velocity movements is required for these improved force producing capabilities to transfer to DJ performance (Cronin et al., 2002; McBride et al., 2002).

It is worth noting that while the studies by Latorre Román et al. (2018), Negra et al. (2020) and Santos and Janeira (2012) all reported significant training-related improvements in jump height in their respective training groups. However, the study by Latorre Román et al. (2018) also reported a significant increase in jump height in the control group at the post-intervention testing, which could have affected the observed effect in the current meta-analysis. The authors did report a significantly greater pre- to post-intervention change in the training group compared to the control, suggesting that the training intervention elicited a positive effect beyond that of solely playing the sport (Latorre Román et al., 2018). The improvements exhibited by the control group could be attributed to their basketball sessions, with recent data reported by Reina et al. (2020) suggesting that during a match youth basketball players can perform up to two jumps per minute. This would suggest that between training and matches, participants in the control group were exposed to a high amount of neuromuscular stimulus, underpinning improvements at post-testing (Buchheit and Simpson, 2017). However, the lack of kinetic measures leaves the changes underpinning the improved jump height in the experimental and control group unclear.

Plyometric vs Combined Resistance Training

The current study observed small significant effects favouring plyometric training vs control in youth on jump height and RSI during a DJ. While moderate significant effects favouring combined training in youth were observed for RSI during a DJ, small non-significant effects were observed for jump height. While prior research has shown that youth of different maturity status respond positively to both plyometric and combined training interventions (Lloyd et al., 2016; Radnor et al., 2017), Radnor et al. (2017) suggested that youth would benefit more from combined training programmes. The authors suggested that this would positively influence the performance of tasks that placed a high demand on concentric strength as well tasks placing requiring a high level of reactive strength. The high amount of braking loading during drop jumps (Bobbert et al., 1986) can often result in an inhibition of the stretch reflex (Bobbert et al., 1987a; Komi and Gollhofer, 1997), thereby making execution of the propulsive phase strongly dependent on the strength of the individual (Bobbert et al., 1987b). The majority of studies (n = 2) in the current analysis that implemented combined resistance training programmes recruited pre-pubertal children. Although prior research has demonstrated that pre-PHV youth can make improvements in performance following combined training they have been shown to exhibit comparatively greater responsiveness to plyometric training (Lloyd et al., 2016; Radnor et al., 2017), which could explain the current findings.

Trained vs Untrained

The findings in the current study revealed moderate and small significant effects favouring training on RSI in untrained and trained youth, respectively. While small significant effects favouring training on jump height were observed for untrained youth, a small non-significant effect was observed for trained youth. The greater magnitude of the effect of training on jump performance in untrained compared to trained youth is similar to the findings of the review by Behm et al. (2017). The authors suggested that this observation stemmed from the untrained individuals having a lower baseline of performance compared to the trained individuals, resulting in a degree of initial improvement greater than trained individuals whose capacities have already progressed beyond their initial baseline. The review by Behringer et al. (2011) suggested that untrained individuals might experience greater learning effects than the trained individuals, resulting in this trend of the untrained exhibiting a comparatively greater magnitude of improvement following a training intervention.

Children vs Adolescents

The current study reported small significant effects for training on jump height and RSI during a DJ in children and adolescents. The magnitude of these effects was greater in adolescents compared to children for jump height (g = 0.56 vs 0.42, respectively), and similar between the two for RSI (g = 0.52 vs 0.52, respectively). The findings in the current study are unlike those in the reviews by Behm et al. (2017) and Behringer et al. (2011), who reported greater improvements in children than adolescents following training. Behringer et al. (2011) suggested that the greater responsiveness to training observed in children compared to adolescents could be due to the training-related neural adaptations that children experience and the significant neural adaptions occurring at the beginning of a resistance training intervention. However, Lloyd et al. (2016) suggested that the level of responsiveness to resistance training amongst children of different maturity status might also depend on the type of resistance training implemented. The authors reported that pre-PHV youth responded better to plyometric training, with post-PHV youth responding better to combined training and attributed this to the process of synergistic adaptation. However, most of the studies included in the current analysis utilised plyometric training interventions and yet greater improvements in DJ jump height were observed in the adolescents compared to children. These findings could potentially be attributed to the performance of DJs being strongly dependent on the individual's force producing capabilities (Bobbert et al., 1987b), and more mature individuals possessing greater force producing capabilities than their younger counterparts (Lloyd and Oliver, 2013b; Tumkur Anil Kumar et al., 2021). The examination of augmentations in kinetic qualities in response to resistance training will provide a better understanding of the changes that underpin training-related differences in DJ performance in youth of different maturity status.

3.5 LIMITATIONS

The authors acknowledge the risk of systematic and random errors associated with using a single reviewer for the screening process (McDonagh and Raina, 2013). However, in an attempt to reduce these risks, all studies were dually screened and all study exclusion and data extraction was verified by a second reviewer. Additionally, although a single reviewer approach could result in wider confidence intervals, the direction of the findings would most likely not differ (Pham et al., 2016). It should also be acknowledged that several studies were excluded from the review due to insufficient data for extraction. Another limitation is that the analyses in the current study are based on a variety of studies using different combinations of training parameters such as training volume and intensity. Despite these limitations, this was the first study to quantify the effects of resistance training on DJ performance in youth.

3.6 SUMMARY

The study aimed to quantify the effects of resistance training on DJ performance in youth. Overall, the findings suggest that resistance training in youth can have small significant positive effects on jump height and RSI during DJs. While there exists a large body of research examining the effects of training in youth, relatively few have measured DJ performance in response to training. The majority of the studies that have reported DJ performance have implemented plyometric training programmes and have primarily reported simple field-based metrics of jump height and RSI. The lack of kinetic measures reported leaves the changes underpinning training-related performance outcomes unclear. A better understanding of how resistance training influences the kinetic qualities that underpin DJ performance in youth can help better inform resistance training programme design.

Chapter 4 Prelude

Chapter 3 was a systematic review with meta-analysis that quantified the effects of resistance training on DJ performance in youth. Although very few studies have measured drop jump performance outcomes in response to training in youth, the findings suggest that resistance training can positively affect drop jump performance in youth. However, with majority of the existing research primarily reporting field-based metrics such as jump height and RSI, it remains unclear what changes in kinetic outcomes underpinned the training-related improvements in drop jump performance. Based on these observations, it was deemed important to determine the relative importance of the variables (jump height and ground contact time) utilised in the calculation of RSI and understand the associations between these performance variables and kinetic outcomes measured during the braking and propulsive phases of a DJ. Such information would provide practitioners a with a better understanding of the kinetic qualities represented by these commonly used field-based metrics.

Chapter 4 – Reactive Strength Index: An Indicator of Absolute and Relative Power?

4.1. INTRODUCTION

Reactive strength index (RSI) is a commonly utilised measure when assessing an individual's stretch shortening cycle (SSC) function (Healy et al., 2018). It is derived as the ratio of jump height by ground contact time (Flanagan and Comyns, 2008), typically measured during a drop jump (DJ) or multiple vertical rebound jumps (Flanagan and Comyns, 2008; Lloyd et al., 2012c; Young, 1995). RSI is suggested to evaluate the individual's ability to efficiently brake and absorb forces, before subsequently and rapidly generating a propulsive force (Comyns et al., 2019). However, it was proposed by Healy et al. (2018) that there were certain limitations with the calculations of RSI, primarily that the calculation of RSI assumed that jump height would increase in direct proportion to increases in ground contact time. This would result in a longer amortization phase, thereby ignoring what is considered as efficient SSC function i.e., a short and fast eccentric phase followed by a quick transition to the concentric phase (Healy et al., 2018; Komi, 2000), and potentially failing to elicit a stretch reflex (Schmidtbleicher, 1992). Additionally, the authors demonstrated that similar RSI scores can be achieved through different ground contact times, suggesting that the assumptions within the calculation of these outcome measures fail to account for the utilisation of different jump strategies (Healy et al., 2018). Prior research has demonstrated that varying strategies, such as greater centre of mass (COM) displacement or higher braking peak velocity can influence the resultant jump performance (Meylan et al., 2010; Struzik et al., 2016) and relying solely on RSI would not reflect the kinetic measures that underpin SSC function.

Prior research has reported very large negative correlations for ground contact time and near perfect correlations for jump height with RSI (Ball and Zanetti, 2012; Healy et al., 2018). However, the relative importance of the variables utilised in the calculation of RSI unclear. Additionally, while jump height has been shown to be strongly related to net vertical impulse ($r > 0.93$) albeit from countermovement jumps and squat jumps (Kirby et al., 2011), it is unclear which kinetic qualities are reflected by reactive strength measures collected during a DJ. It is yet to be determined if these reactive measures provide any additional insight beyond their component parts. An understanding of the kinetic measures represented by RSI, would better inform the design of training programmes to target the improvement specific qualities. Therefore, the aim of the current study was to (i) determine the relative importance of jump height and ground contact time in the calculation of RSI; (ii) understand the associations between the performance measures and kinetic outcomes. It was hypothesised that while RSI might be a strong predictor of several kinetic variables, stronger relationships might be observed for several of those kinetic variables with the components of RSI i.e., jump height and ground contact time.

4.2 METHODS

4.2.1 Participants

Two hundred and fifty-nine young male athletes from soccer and cricket academies volunteered to participate in the study. The average age of the participants was 13.3 ± 2.2 years of age, with standing height of 50.4 ± 14.0 cm, body mass of 159.4 ± 14.9 kg and maturity offset of -0.6 ± 1.19 years from PHV. Participants reported no injuries at the familiarisation or testing sessions. At the time of testing, all participants were taking part regularly in their sport training two to four times per week depending on the age group. While participants had been introduced to formal strength and conditioning support, they had not been exposed any structured resistance training. Upon receiving ethical approval from the University Research Ethics Committee for the study, informed parental consent and participant assent were obtained, and physical activity readiness questionnaires completed.

4.2.2 Procedures

4.2.2.1 Anthropometrics

Body mass was recorded to the nearest 0.1 kg on a weighing scale (SECA, 321, Vogel & Halke, Hamburg, Germany). Standing height and sitting height were collected to the nearest 0.1 cm using a stadiometer (SECA, 321, Vogel & Halke, Hamburg, Germany). Maturity offset (years from peak height velocity [PHV]) was calculated by entering anthropometric data into a sex-specific regression equation (*Equation 1*).

Maturity Offset (± 0.59 yrs) = -9.236 + [0.0002708 x Leg Length and Sitting Height Interaction] - [0.001663 x Age and Leg Length Interaction] + [0.007216 x Age and Sitting Height Interaction] + [0.02292 x Weight by Height Ratio]

(*Equation 1*)

4.2.2.2 Drop Jump Assessment

Participants completed a 10-minute progressive warmup, inclusive of light mobilisation and activation exercises targeting the main muscle groups of the upper and lower extremities, followed by increasing intensity running drills. During the first session, subjects were familiarised with the DJ movement. Specifically, feedback was provided to participants during this familiarisation session and subjects were allowed to practise the movement until they demonstrated consistent technical competency over multiple trials, as established by the lead researcher. Formal testing was conducted during the second session. Participants positioned themselves on top of a 30 cm box and were instructed to stand with toes on the edge, with feet hip width apart and with their hands on their hips (Pedley et al., 2017) . On the lead researcher's command, the participants were instructed to step out from the box onto two force plates (Pasco, Roseville, CA, USA) which were positioned 12 cm in front of the box and separated by 8 cm, housed within a custom-built frame. Each foot was required to land on an individual force plate. Upon landing, participants were instructed to "jump as high and as fast as possible" and then to "stick" the second landing on the force plates. Hands were required to remain on the hips through the entire movement to avoid upper body interference (Lees et al., 2004), with legs remaining straight while airborne (Markwick et al., 2015). Failure to fulfil all of these requirements resulted in that trial being discounted and another attempt being performed. Vertical ground reaction force data were collected at a rate of 1000 Hz. Three maximal effort trials were completed, separated by a rest period of 1 minute between each trial. Raw ground reaction force data were smoothed using a fourth order recursive low-pass Butterworth filter with a cut-off of 30 Hz and using a bespoke Microsoft Excel® Spreadsheet (Microsoft Corporation, 2016). The variables were automatically calculated from the force data of the first ground contact period and grouped into subcategories depending on the qualities they represented; performance variables, peak force variables, work rate variables, impulse variables and movement strategy variables (*see table 4.1*).

The absolute variables were allometrically scaled to obtain relative values (see *table 4.1).* Allometric scaling provides a normalised methodological approach for performance tests (Jaric et al., 2005), and has previously been used to scale measurements of full body strength in youth of difference body size (Brownlee et al., 2018). Allometric normalisation involves dividing the absolute force from a performance test by body mass in $kg^{0.67}$ (Comfort and Pearson, 2014). However, given the limitations of allometrically scaling separate groups using a fitted exponent (Suchomel et al., 2018), all relative variables in the current study were calculated by allometric scaling using a population specific exponent.

Table 4.1 List of variables investigated and the method of calculation.

VARIABLE	**METHOD OF CALCULATION**
Performance Variables	
Ground Contact Time (s)	The duration of ground contact time of the first landing was established by determining the time interval between the first (initial contact) and final (take-off) data point using the threshold of 5 x SD of noise.
Jump Height (m)	Defined as the largest vertical displacement of the body's centre of mass during the flight time between the first and second ground contact, calculated using the method of Leard (Leard et al., 2007), $= TOV^2 / 2g$ (TOV = vertical velocity of the centre of mass at take-off; g = acceleration due to gravity)
Flight Time (s)	Calculated as the time interval (s) between take-off and the next chronological time frame where the force reading exceeded 15 N.
Reactive Strength Index	Calculated as the ratio of jump height (mm) and first ground contact time (ms) as proposed by McClymont and Hore (McClymont, 2003)

Peak Force Variables	
Braking Peak Force (N)	Calculated as the highest force value, which was followed by a decline in force, during the braking phase of the first ground contact period. The braking phase was identified as the phase that followed the timing of initial contact up until the peak centre of mass displacement.
Propulsive Peak Force (N)	Calculated as the highest force value recorded during the propulsive phase of the movement. The propulsive phase was identified as the phase that followed the timing of the peak centre of mass displacement up until take-off.
Force at Peak Centre of Mass Displacement (N)	Determined by dividing the vertical component of the ground reaction force by the participant's body mass to determine acceleration. Double integration of acceleration was then performed to calculate displacement of centre of mass, and then the force value at this point was recorded.
Braking Rate of Force Development (N/s)	Defined as the 0.001 s interval that had the greatest change in force between initial ground contact and the occurrence of the first peak.
Impulse Variables	
Net Impulse (N.s)	Net impulse was measured by subtracting body mass impulse from total vertical impulse.

Braking Impulse (Ns)	Braking impulse is the total vertical impulse applied to the ground during the landing phase of ground contact and is calculated by summing the instantaneous impulse values between initial ground contact and peak centre of mass displacement.
Propulsive Impulse (Ns)	Propulsive impulse is calculated by summing the instantaneous impulse values between peak centre of mass displacement and take-off phase of ground contact.
Work Rate Variables	
Mean Braking Power (W)	Velocity of the centre of mass was multiplied by the ground reaction force at each timing sample to derive power. Mean braking power was calculated as the average power between initial ground contact and the timing of the maximal displacement of centre of mass.
Mean Propulsive Power (W)	Velocity of the centre of mass was multiplied by the ground reaction force at each timing sample to derive power. Mean propulsive power was calculated as the average power from the timing of lowest point of the centre of mass and the point of take-off.
Braking Work Done (J)	Calculated as the braking force multiplied by centre of mass displacement.
Propulsive Work Done (J)	Calculated as the propulsive force multiplied by centre of mass displacement.
Movement Strategy Variables	

Spring like Correlation	Determined by calculating a Pearson's product-moment correlation coefficient using centre of mass displacement and absolute vertical force throughout the initial ground contact period.
Stiffness (N/m)	Vertical stiffness was calculated as the ratio of peak vertical ground reaction force (BW) to maximal vertical displacement of the centre of mass (m) in accordance with the method of (McMahon and Cheng, 1990). In the event of maximal vertical force also being peak landing force, the proceeding force peak following the peak landing force was used for the calculation of leg stiffness.
Peak Centre of Mass Displacement (m)	Determined by dividing the vertical component of the ground reaction force by the participant's body mass to determine acceleration. Double integration of acceleration was then performed to calculate displacement of centre of mass and the peak was then obtained by identifying the minimum value.
Braking Mean Centre of Mass Velocity (m/s)	Calculated by dividing mean braking power by mean braking force.
Propulsive Mean Centre of Mass Velocity (m/s)	Calculated by dividing mean propulsive power by mean propulsive force.
Relative Variables	
Relative Braking Peak Force ($N/kg^{0.74}$) Relative Propulsive Peak Force ($N/kg^{1.09}$)	The absolute variables were normalised using allometric scaling (P/BM^b; where *P* represents the variable, *BM* is body mass in kilograms and *b* is the power exponent. The power exponent for

Relative Force at Peak COM Displacement ($N/kg^{1.12}$)	allometric scaling was derived from the data collected, by plotting log transformed data of each variable and body mass on a scale and then using the slope of the linear regression line (Atkins, 2004; Crewther et al., 2009).
Relative Net Impulse ($N.s/kg^{1.03}$)	
Relative Braking Impulse ($N.s/kg^{1.05}$)	
Relative Propulsive Impulse ($N.s/kg^{0.96}$)	
Relative Mean Braking Power ($W/kg^{1.04}$)	
Relative Mean Propulsive Power ($W/Kg^{1.12}$)	

4.2.3 Statistical Analysis

Relationships between the variables used to calculate RSI (jump height, and ground contact time) were assessed using Pearson's correlation coefficients. Subsequently, multiple step-wise regression analysis was used to examine the degree of influence that jump height and ground contact time had on RSI. Similarly, the relationship between all kinetic variables and RSI, jump height and ground contact time was assessed using Pearson's correlation coefficient. Following this, stepwise multiple regression analyses were utilised to establish the influence of the various kinetic variables on RSI. The strength of relationships were categorised using the following thresholds: no relationship, < 0.20; weak, 0.21 – 0.45; moderate, 0.46 – 0.70; strong, ≥ 0.71, based on previous recommendations (O'Donoghue, 2013). The assumption of independent errors in multiple regression analyses was tested using a Durbin-Watson test and multicollinearity was tested using a variance inflation factor (VIF) and tolerance (Field, 2009) diagnostics. All significance values were accepted at $p < 0.05$ and all statistical procedures were conducted using SPSS v.27 for Windows.

4.3 RESULTS

4.3.1 Influence of jump height and ground contact time on RSI

All the variables were found to be normally distributed. Within the whole cohort, there were significant moderate correlations between both jump height and ground contact time with RSI (r = 0.68 and -0.61, respectively; $p < 0.05$). However, analysis revealed that jump height was the key determinant of RSI (adjusted $R^2 = 0.46$; *figure 4.1*).

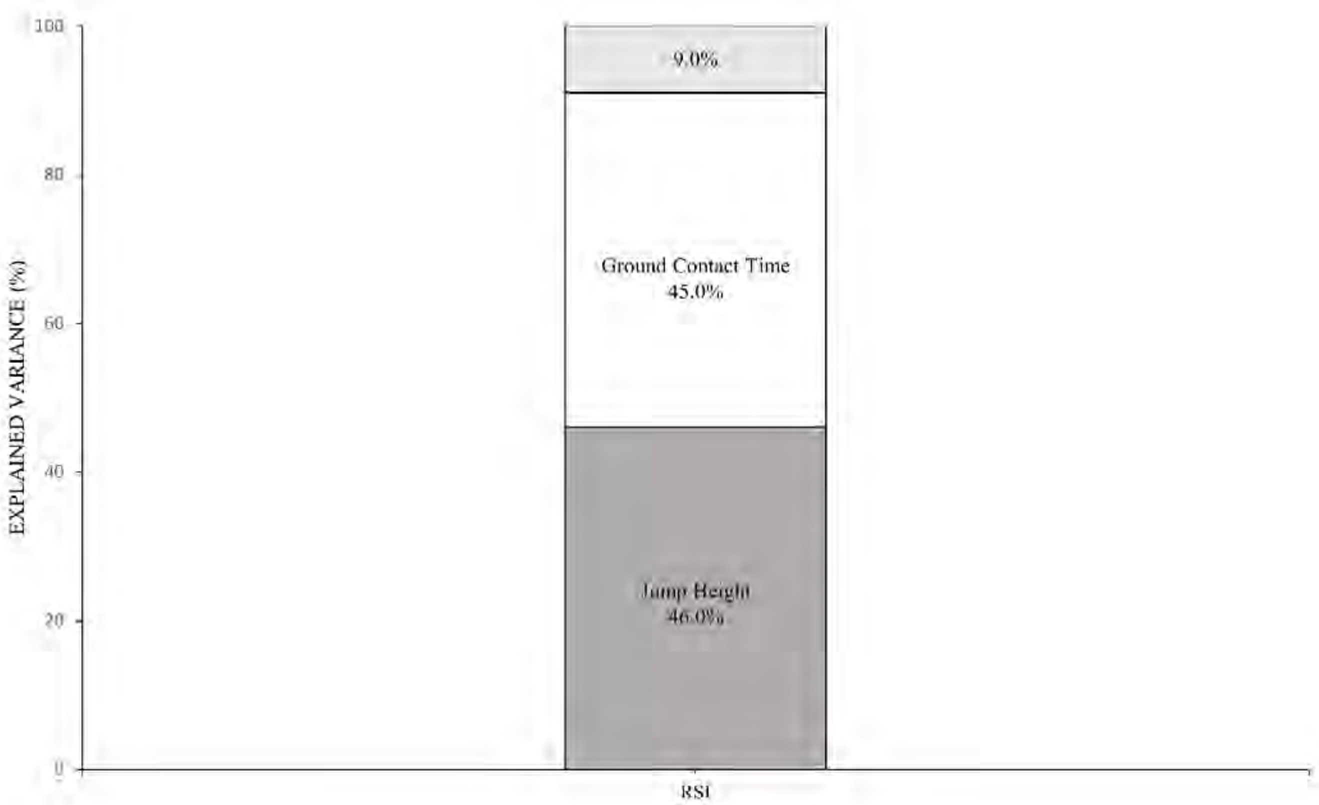


Figure 4.1 Degree of influence of jump height and ground contact time on RSI.

4.3.2 Relationships between the kinetic and performance variables

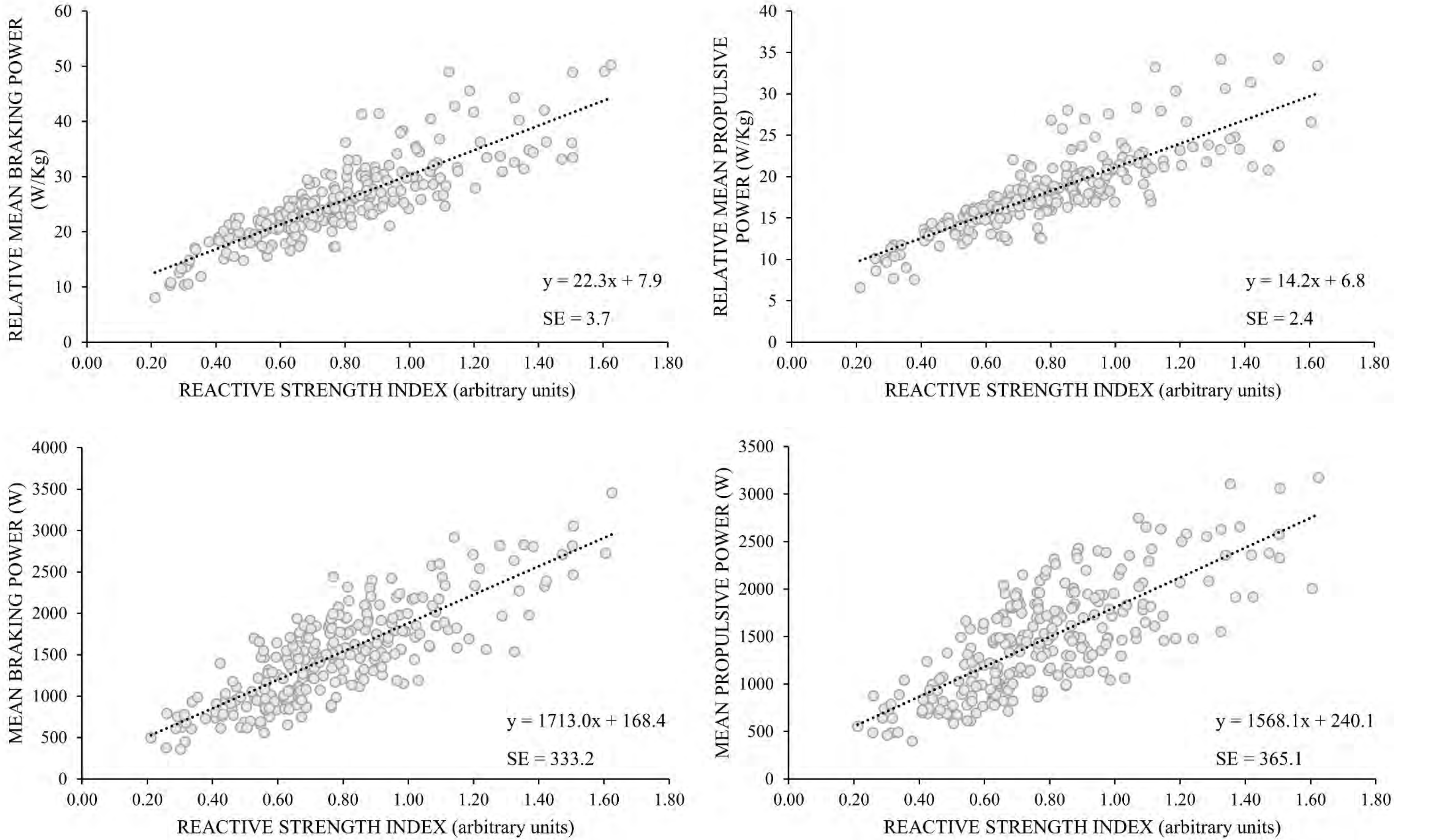
Analysis revealed significant weak to strong correlations (*r* = -0.14 to 0.85; $p < 0.05$; *table 4.2*) for most of the kinetic variables with RSI, except for peak COM displacement and braking RFD ($p > 0.05$). The strongest relationships for RSI were with absolute and relative mean braking and propulsive power as well as absolute propulsive peak forces ($r = \geq 0.69$; $p < 0.05$; *figure 4.2*). Although RSI did exhibit strong relationships with relative propulsive peak force measures ($r = 0.75$; $p < 0.05$), ground contact time exhibited stronger relationships with those relative propulsive peak forces ($r = 0.83$; $p < 0.05$). Jump height was found to be most strongly related to mean COM velocity and relative net impulse ($r = \geq 0.79$; $p < 0.05$).

Table 4.2 Results of correlation analysis between the kinetic and outcome variables.

Kinetic Variables	Jump Height	Ground Contact Time	RSI
Braking Peak Force (N)	0.12* (0.00 - 0.24)	-0.53* (-0.62 to -0.44)	0.52 (0.43 to 0.61)
Propulsive Peak Force (N)	0.34* (0.22 - 0.44)	-0.55* (-0.63 to -0.46)	0.69* (0.63 to 0.75)
Force at Peak COM Displacement (N)	0.33* (0.21 to 0.43)	-0.58* (-0.65 to -0.49)	0.71* (0.64 to 0.76)
Braking Rate of Force Development (N/s)	-0.12 (-0.24 to ?)	-0.23* (-0.34 to -0.11)	0.07 (-0.05 to 0.19)
Net Impulse (N.s)	0.70* (0.63 to 0.76)	-0.01 (-0.13 to 0.12)	0.51* (0.41 to 0.49
Braking Impulse (N.s)	0.69* (0.51 to 0.67)	0.33* (0.22 to 0.43)	0.20* (0.08 to 0.31)
Propulsive Impulse (N.s)	0.53* (0.44 to 0.62)	0.31* (0.20 to 0.42)	0.17* (0.05 to 0.29)
Mean Braking Power (W)	0.63* (0.55 to 0.70)	-0.44* (-0.53 t0 -0.33)	0.81* (0.76 to 0.85)
Mean Propulsive Power (W)	0.69* (0.62 to 0.75)	-0.31* (-0.42 to -0.20)	0.75* (0.70 to 0.80)
Braking Work Done (J)	0.59* (0.51 to 0.67)	0.33* (0.22 to 0.43)	0.20* (0.08 to 0.31)
Propulsive Work Done (J)	0.53* (0.44 to 0.62)	0.31* (0.20 to 0.42)	0.17* (0.05 to 0.29)
Spring-like Correlation	0.22* (0.11 to 0.34)	-0.69* (-0.74 to -0.61)	0.60* (0.51 to 0.67)
Stiffness (N/m)	-0.14* (-0.26 to -0.02)	-0.73* (-0.79 to -0.67)	0.49* (0.39 to 0.58)
Peak COM Displacement (m)	0.66* (0.58 to 0.72)	0.65* (0.57 to 0.71)	0.00 (-0.12 to 0.12)
Mean Braking COM Velocity (m/s)	0.88* (0.85 to 0.91)	-0.05 (-0.17 to 0.97)	0.65* (0.57 to 0.71)
Mean Propulsive COM Velocity (m/s)	0.79* (0.74 to 0.83)	-0.09 (-0.21 to .03)	0.60* (0.51 to 0.67)
Relative Braking Peak Force ($N/kg^{0.74}$)	-0.11 (-0.23 to 0.02)	-0.65* (-0.71 to -0.57)	0.43* (0.33 to 0.53)
Relative Propulsive Peak Force ($N/kg^{1.09}$)	0.14* (0.02 to 0.26)	-0.83* (-0.86 to -0.78)	0.75* (0.70 to 0.80)
Relative Force at Peak COM Displacement ($N/kg^{1.12}$)	0.14* (0.01 to 0.25)	-0.83* (-0.86 to -0.79)	0.75* (0.70 to 0.80)
Relative Net Impulse ($N.s/kg^{1.03}$)	0.85* (0.81 to 0.88)	0.01 (-0.12 to 0.13)	0.59* (0.50 to 0.66)
Relative Braking Impulse ($N.s/kg^{1.05}$)	0.62* (0.54 to 0.69)	0.74* (0.67 to 0.79)	-0.06 (-0.18 to 0.06)
Relative Propulsive Impulse ($N.s/kg^{0.96}$)	0.50* (0.41 to 0.59)	0.73* (0.67 to 0.78)	-0.14* (-0.25 to -0.02)
Relative Braking Power ($W/kg^{1.04}$)	0.54* (0.45 to 0.62)	-0.59* (-0.67 to -0.51)	0.85* (0.81 to 0.88)
Relative Propulsive Power ($W/kg^{1.12}$)	0.67* (0.60 to 0.73)	-0.47* (-0.56 to -0.37)	0.84* (0.80 to 0.88)

* $p < 0.05$; Grey scale highlights which performance measures relate most strongly to the corresponding kinetic variable.

COM – centre of mass; RSI – reactive strength index.



RELATIVE MEAN BRAKING POWER (W/Kg)
REACTIVE STRENGTH INDEX (arbitrary units)
y = 22.3x + 7.9
SE = 3.7
RELATIVE MEAN PROPULSIVE POWER (W/Kg)
REACTIVE STRENGTH INDEX (arbitrary units)
y = 14.2x + 6.8
SE = 2.4
MEAN BRAKING POWER (W)
REACTIVE STRENGTH INDEX (arbitrary units)
y = 1713.0x + 168.4
SE = 333.2
MEAN PROPULSIVE POWER (W)
REACTIVE STRENGTH INDEX (arbitrary units)
y = 1568.1x + 240.1
SE = 365.1

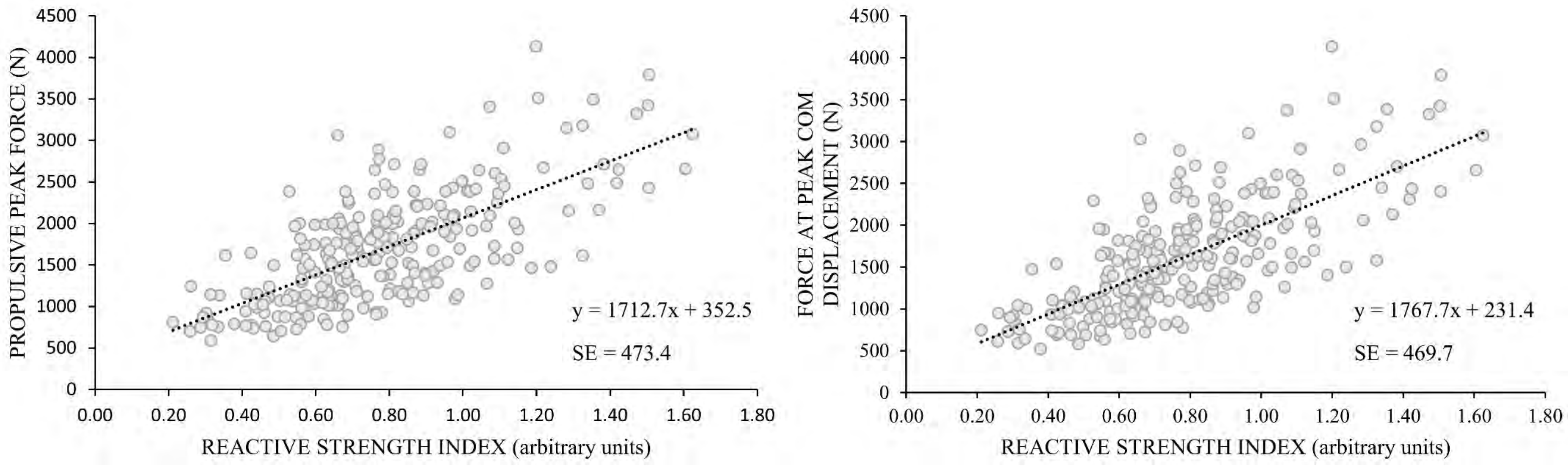


Figure 4.2 Strongest relationships between RSI and the kinetic variables.

The regression analyses demonstrated that relative mean braking power was the primary determinant of RSI, accounting for more than three-quarters of the variance (adjusted R^2 = 0.78). No other variables significantly contributed to the model ($p > 0.05$).

4.4 DISCUSSION

The aim of the current study was to (i) determine the relative importance of jump height and ground contact time in the calculation of RSI; (ii) to understand the associations between performance measures and kinetic outcomes. The hypothesis was satisfied, with RSI exhibiting strong relationships with several kinetic variables such as absolute propulsive peak forces, as well as absolute and relative power. However, ground contact time and jump height did exhibit stronger relationships with a number of the kinetic variables such as relative peak forces and impulse, compared to RSI. The main findings of the current study were as follows. *First*, jump height was observed to have a greater influence than ground contact time on RSI. *Second*, the strongest relationships observed for RSI were with absolute and relative mean braking and propulsive power as well as absolute propulsive peak forces. *Third*, the relative peak force variables, relative braking and propulsive impulse, stiffness and spring-like correlation exhibited stronger relationships with ground contact time than RSI. *Fourth*, the absolute impulse variables and relative net impulse exhibited stronger relationships with jump height than RSI. *Finally*, when all kinetic variables were entered into the regression analyses, relative mean braking power explained the most variance in RSI performance. The findings from the current study suggest that RSI might be a strong indicator of absolute force producing capabilities as well as absolute and relative power.

The findings from the current study suggest that out of the two components of RSI, jump height serves as the primary determinant. Although this was the first study to examine the relative importance of jump height and ground contact time on RSI during a DJ, the findings are similar to those of Beckham et al. (2019) who reported a stronger contribution of jump height than time to take-off on RSI-modified in males. When examining depth jump performance, where the focus is on maximal height with no restriction placed on ground contact time (Pedley et al., 2017), Beattie et al. (2017) reported greater RSI and jump height in the stronger athletes compared to the weaker counterparts with no significant differences between groups for ground contact time. The findings of Beattie et al. (2017) suggests that the difference in RSI between the groups was derived from differences in jump height. Similarly, Birat et al. (2020) reported no significant differences in ground contact time between pre- and post-pubertal boys during DJs from various drop heights, but reported higher RSI scores in the post-pubertal boys compared to their less mature counterparts with this being attributed to the comparatively greater jump height of the more mature boys. The findings of Beattie et al. (2017) and Birat et al. (2020) could explain the observations in the current study, wherein trivial differences in ground contact time between participants would result in RSI being more strongly influenced by jump height. With jump height being underpinned by the preceding impulse (Kirby et al., 2011; Ruddock and Winter, 2015), the findings in the current study suggest that when attempting to improve RSI during a DJ practitioners would benefit more by improving force producing capabilities and subsequently jump height, rather than focusing on decreasing ground contact times.

While the findings of the regression analysis suggest that RSI might best represent relative mean braking power, it is important to note the strong significant relationships observed for absolute and relative mean braking, and propulsive power with RSI. Although, this provides practitioners with an understanding of the kinetic qualities being assessed when utilising such a field-based metric, it is important consider the reasonable amount of error when predicting these qualities. Mean power is calculated as the product of mean force and COM velocity. Changes in power can result from either a change in mean force, COM velocity or both variables simultaneously. While increases in mean force would positively influence absolute and relative net impulse, which underpin jump height (Kirby et al., 2011; Ruddock and Winter, 2015), the current study also observed strong significant relationships between mean COM velocity and jump height suggesting that an increase or decrease in these variables would positively or negatively influence jump height which is the primary determinant of RSI during a DJ.

While jump height, in accordance with earlier research, exhibited strongest relationships with absolute and relative net impulse (Kirby et al., 2011; McBride et al., 2010; Ruddock and Winter, 2015), ground contact time exhibited strongest relationships with the relative propulsive peak force variables. This relationship between ground contact time and the relative peak force variables suggests that the shortening of ground contact time during jump requires high levels of relative force. The current study provides novel insight regarding the kinetic qualities that might be reflected when assessing DJ performance through common field-based metrics such as jump height, ground contact time and RSI. Based on the current findings it would appear that when assessing DJ performance, jump height might be a suitable measure to reflect relative net impulse and ground contact time a suitable measure to reflect relative propulsive force.

4.5 CONCLUSION

The findings of the current study revealed jump height had a greater influence than ground contact time on RSI during a DJ. The findings also suggest that RSI might best represent absolute and relative power, while jump height and ground contact time might best reflect relative net impulse and relative propulsive force, respectively. The examination of kinetic qualities requires access to appropriate equipment such as force plates and practitioners might not always have access to such equipment. The findings of the study provide some clarity to practitioners about kinetic qualities that are being measured by these commonly utilised outcome variables. However, there is still a reasonable amount of error when predicting these kinetic qualities from the outcome variables which makes direct examination of the kinetics important. Despite this, such an understanding of the kinetic qualities being assessed would help inform the design of more appropriate training programmes. It is also equally important to note what kinetic measures RSI is not good representation of, such as spring-like correlation, COM displacement, braking and propulsive impulse, as well as braking and propulsive work done. Therefore, developing an understanding what underpins differences and changes in DJ performance requires the examination of kinetic qualities and not just outcomes variables.

Chapter 5 Prelude

Chapter 4 provided an understanding of the associations between drop jump performance variables and kinetic outcomes. The findings suggested that jump height, ground contact time and RSI might best represent relative net impulse, relative propulsive force, and absolute and relative power respectively. The study also highlighted the error associated with the prediction of these kinetic qualities, suggesting that direct examination of kinetics was required rather than solely reporting simple field-based metrics. With the addition of this novel data, and considering the various growth and maturity-related neuromuscular changes that youth experience, it was considered important to (i) determine the reliability of the DJ kinetic outcomes in youth of different maturity status, due to the variability in jump performance in youth; and (ii) understand how these kinetic qualities develop amongst youth of different maturity status. This information would also provide a more detailed understanding of the maturity-related development of SSC function in youth during a drop jump.

Chapter 5 – The Influence of Maturity Status on Drop Jump Kinetics in Male Youth

5.1 INTRODUCTION

Research that has described the development of SSC function through childhood and adolescence has tended to focus on countermovement jumps (CMJ) and squat jumps (SJ), or simple field-based metrics from rebound jumps (Harrison and Gaffney, 2001; Lloyd et al., 2011b; Sahrom et al., 2013). However, it has been suggested that the CMJ and SJ may have a longer amortization phase than other rebound based activities (Komi and Gollhofer, 1997), which would result in the stretch reflex not being activated and therefore they would not appropriately represent SSC function (Lloyd et al., 2011a; Schmidtbleicher, 1992). To ensure that SSC function is being appropriately assessed, researchers have utilised rebound based exercises to elicit pre-activation and a stretch reflex in the lower limb (Barr and Nolte, 2011; Bassa et al., 2012; Gillen et al., 2019; Komi, 2000). The drop jump (DJ) is an example of such a rebound exercise that has been utilised in prior research to examine SSC function in youth (Bassa et al., 2012; Birat et al., 2020; Gillen et al., 2019; Pedley et al., 2020). The DJ involves a SSC action with an emphasis on eccentric overload during a phase of triple flexion of the lower limb on landing, followed by subsequent triple extension to drive the body into the air (Pedley et al., 2017). This sequence of movements replicates those in human locomotive tasks such as sprinting, thereby making it a suitable tool to evaluate SSC function (Bobbert et al., 1987b; Marshall and Moran, 2013).

During DJ protocols, jump height, ground contact time and reactive strength index (RSI), calculated as the ratio of jump height to ground contact time (Flanagan and Comyns, 2008;

McClymont, 2003), are commonly reported measures to evaluate SSC function (Barr and Nolte, 2011; Flanagan and Comyns, 2008; Laffaye et al., 2016). C*hapter 4* provided an understanding of the kinetic outcomes that jump height, ground contact time and RSI might reflect. However, relying solely on these simple field-based metrics may not reflect all the kinetic qualities underpinning SSC function (Healy et al., 2018), since different jump strategies can affect outcome measures such as jump height (Jidovtseff et al., 2014). Researchers have demonstrated that different strategies can be used in the braking phase, such as greater braking displacement or higher braking peak velocity, to influence the resultant jump performance (Meylan et al., 2010). Given the influence that the braking phase of the SSC has on the propulsive phase (Bosco et al., 1987; Komi, 2000) and therefore on the final outcome (Fukashiro et al., 2005; Jones and Caldwell, 2003), it may be necessary to examine multiple braking and propulsive kinetic measures such as peak and mean force, impulse, peak and mean power, peak velocity, stiffness and maximum displacement to truly understand the determinants of SSC function (Meylan et al., 2012). A more thorough understanding of how kinetic measures influence subsequent performance can help better inform future training prescription (Jidovtseff et al., 2014).

Previous research has examined the effect of increased drop height on subsequent jump performance in youth, and while their findings indicated that older youth performed better than their younger counterparts when dropping from greater heights, the study failed to explain how maturity status affects the kinetic variables that drive this performance (Gillen et al., 2019). Recently, a novel method to categorise SSC function in youth has been proposed, and while the authors were able to classify youth into poor, moderate or good categories based on SSC function (Pedley et al., 2020), the variables investigated were limited to mean and peak forces, centre of mass displacement and power in the concentric phase, and failed to examine important measures such as impulse which has been suggested to significantly influence jump performance (Kirby et al., 2011; McBride et al., 2010). Given the sequence of different muscle actions involved during the SSC (Sahrom et al., 2013) and the changes in motor co-ordination associated with maturation (Dotan et al., 2012), it is important to have a more granular understanding of the development of SSC function in youth.

Although prior research has reported extremely good reliability for landing and take-off force in youth during DJs (Quatman et al., 2006), the study included only 5 participants of mixed maturity status. This has left the reliability of these kinetic measures within the two phases of the DJ uncertain, and given the greater jump variability that youth display in comparison to adults (Gerodimos et al., 2008) this warrants further investigation. Therefore, the aim of the current study is to determine the reliability of the kinetic variables, measured during the braking and propulsive phases of a DJ, at different stages of maturation and to use these variables to examine the influence of maturity status on DJ kinetics in youth. Additionally, the study utilised a chi-squared analysis to examine the interaction between maturity status and SSC function categories, as assessed through the DJ kinetics. It was hypothesized that the more mature participants would exhibit better DJ kinetics and SSC function compared to their less mature counterparts.

5.2 METHODS

5.2.1 Participants

Three-hundred and forty-one young male athletes participating in academy soccer and cricket volunteered to participate in the study. Participants reported no injuries at the familiarisation or testing sessions. All participants took part regularly in their sport training and matches. While participants had been introduced to formal strength and conditioning support, they had not been exposed any structured resistance training. Upon receiving ethical approval from the

University Research Ethics Committee for the study, informed parental consent and participant assent were obtained, and physical readiness questionnaires completed.

5.2.2 Procedures

5.2.2.1 Anthropometrics

Anthropometrics and maturity status were assessed using the same method as Chapter 4 (refer to section 4.2.2.1).

A maturity offset value of < -2.51 years was classified as early-pre-PHV, -1.99 to -1.00 years indicated that the individual was late-pre-PHV, -0.50 to 0.50 indicated that the individual was circa-PHV, and a score of > 1.00 years indicated that the individual was post-PHV (Mirwald et al., 2002). A 6-month boundary between maturity groups was chosen to prevent an individual being incorrectly classified due to the error associated with the prediction model (Mirwald et al., 2002). Eighty-two participants were categorised between maturity groups and therefore excluded from further analysis, leaving 259 participants for the final analysis (n = 57 early-pre, n = 80 late-pre, n = 49 circa and n = 73 post). Descriptive statistics for the various maturity groups can be found in *table 5.1*.

Table 5.1 Mean (± SD) values for descriptive details of each maturity group's anthropometric data.

MATURITY GROUP	*n*	STANDING HEIGHT (cm)	MASS (kg)	AGE (years)	MATURITY OFFSET (years from PHV)
Early-pre-PHV	57	139.91± 4.75*	34.2 ± 3.7*	10.54 ± 0.72*	-2.99 ± 0.29*
Late-Pre-PHV	80	153.29 ± 6.05*	43.9 ± 6.9*	12.39 ± 0.93*	-1.55 ± 0.28*
Circa-PHV	49	165.23 ± 6.01*	54.7 ± 7.4*	14.16 ± 0.90*	-0.05 ± 0.31*
Post-PHV	73	177.26 ± 5.13*	67.2 ± 7.1*	15.87 ± 0.86*	1.84 ± 0.65*

PHV – peak height velocity

* Significant between group difference with all other maturity groups ($p < 0.05$)

5.2.2.2 Drop Jump Assessment

Drop Jump was assessed using the same procedures as Chapter 4 (refer to section 4.2.2.2).

Participants were categorised based on presentation of an impact peak in their force-time profile (the highest transient, visible force peak during the braking phase of ground contact and occurring within the first 20% of ground contact) (Hreljac, 2004; Nicol et al., 1991), and whether they display spring-like behaviour (Pearson product-moment correlation between vertical ground reaction force and vertical centre of mass displacement through the entire contact phase being < -0.80) (Padua et al., 2005; Pedley et al., 2020). As in Pedley et al. (2020), participants were then classified into GOOD (no impact peak and still spring-like), MODERATE (impact peak and still spring-like), or POOR (impact peak and not spring-like). Individual force traces were time-normalised to 101 data points utilising a custom Microsoft Excel spreadsheet. Mean ± standard deviations of the vertical forces were calculated for each time point to derive average force traces for each SSC category.

5.2.3 Statistical Analyses

5.2.3.1 Within-Session Reliability

For the assessment of within-session reliability, a sub-group of 25 early-pre-PHV, 25 pre-PHV, 26 circa-PHV and 23 post-PHV were used. Reliability was assessed using a one-way, repeated measures, analysis of variance (ANOVA) to test for any systematic bias, intraclass correlation coefficients (ICC) was used for relative reliability, and mean coefficients of variation (CV) used for random error. Magnitudes of ICC were classified as: < 0.49 indicate poor reliability, 0.50 - 0.74 indicate moderate reliability, 0.75 to 0.89 indicate good reliability, and values >0.90 indicate excellent reliability (Koo and Li, 2016). A CV threshold of < 10% has been suggested to identify acceptable random variation (Augustsson et al., 2006; Cormack et al., 2008; Cronin et al., 2004), however, this may ignore the issue of sensitivity and kinetic data can often display large differences between groups in youth (Cronin et al., 2004).

5.2.3.2 Between Group Comparisons

Data was assessed for normality using the Shapiro-Wilk test. A one-way ANOVA was used to determine differences for all DJ kinetic variables across maturity groups. Homogeneity of variance was assessed using Levene's Test and where violated, Welch's adjustment was used to calculate the *F*-ratio. In the event of a significant *F*-ratio, a Bonferroni post hoc test was used to determine pairwise differences when equal variances were assumed. In the event of a significant Levine's outcome, Games-Howell post-hoc tests were used to identify pairwise differences. A Kruskal-Wallis test was performed to identify differences between maturity groups when variables were not normally distributed. Dunn's pairwise test adjustment with the Bonferroni correction were applied post-hoc to determine where significant differences occurred. The level of significance was set at alpha level $p < 0.05$. Cohen's *d* effect sizes were calculated to determine the magnitude of between-group differences that were observed (Cohen, 2013) and were categorised as < 0.19: trivial, 0.20 - 0.59: small, 0.60 - 1.19: moderate, 1.20 - 1.99: large, 2.00 – 3.99: very large and greater than 4.00 as extremely large (Hopkins et al., 2009).

5.2.3.3 Chi-squared Analysis

Chi-squared (χ^2) analysis was used to investigate between-group differences for the number of individuals within each SSC function category (POOR, MODERATE and GOOD). In the Chi-squared test, analysis of the adjusted standardized residuals was completed to identify frequencies that were > 1.96 z-scores ($p < 0.05$) different to the whole group distribution. Adjusted residuals were converted into Chi-squared values and subsequently into *p* values. The Bonferroni correction was used to produce an adjusted alpha level of $p < 0.05$ in order to reduce the potential for a type I error as a result of multiple comparisons (Beasley and Schumacker, 1995).

All ANOVA, Chi-squared and post hoc analysis were processed using SPSS® (v24.0.0.2. Chicago, Illinois), while descriptive statistics and effect sizes were computed using Microsoft Excel®. ICC, CV% and typical error were calculated using an online spreadsheet run through Microsoft Excel® (Hopkins, 2017).

5.3 RESULTS

5.3.1 Reliability

No significant differences in any of the variables were observed between the means across all the DJ trials for the four maturity groups ($p > 0.05$), thereby showing no evidence of learning effect for any of the maturity groups. Net impulse, and mean braking and propulsive COM velocities showed moderate to excellent relative reliability (ICC = 0.59 – 0.90) for all maturity groups and acceptable absolute reliability (CV < 10%) across all maturity groups. All other variables displayed moderate to excellent relative reliability (ICC = 0.62 – 0.91), but for some maturity groups they exceeded the acceptance threshold for random variation (CV > 10%; refer *table 5.2*).

Table 5.2 Coefficient of variation, intraclass correlation coefficient and typical error for the drop jump variables.

VARIABLE	MATURITY GROUP	ICC	CV%	TE	VARIABLE	MATURITY GROUP	ICC	CV%	TE
Performance Variables									
Ground Contact Time (s)	Early-Pre	0.82	12.7	0.04	Jump Height (m)	Early-Pre	0.85	15.4	0.03
	Pre	0.78	16.5	0.06		Pre	0.81	13.4	0.02
	Circa	0.77	13.0	0.04		Circa	0.85	11.5	0.02
	Post	0.79	10.6	0.03		Post	0.63	12.2	0.03
Reactive Strength Index	Early-Pre	0.88	18.4	0.12					
	Pre	0.81	13.4	0.02					
	Circa	0.64	18.8	0.14					
	Post	0.68	17.0	0.13					
Force Variables									
Mean Braking Force (N)	Early-Pre	0.79	17.6	144	Mean Propulsive Force (N)	Early-Pre	0.69	15.0	114
	Pre	0.82	15.3	172		Pre	0.86	10.4	91
	Circa	0.79	10.9	161		Circa	0.83	7.9	108
	Post	0.79	9.0	151		Post	0.87	6.2	95

Braking Peak (N)	Early-Pre	0.89	13.7	186	Propulsive Peak (N)	Early-Pre	0.83	13.1	129
	Pre	0.88	14.6	310		Pre	0.88	14.4	198
	Circa	0.75	16.1	351		Circa	0.81	12.6	259
	Post	0.62	16.4	386		Post	0.86	9.6	213
Force at Peak COM Displacement (N)	Early-Pre	0.82	15.0	134	Braking RFD (KN/s)	Early-Pre	0.78	30.7	16.8
	Pre	0.88	15.3	209		Pre	0.66	34.3	27.0
	Circa	0.75	16.0	304		Circa	0.72	33.7	26.8
	Post	0.88	9.9	215		Post	0.69	28.8	24.3
Impulse Variables									
Net Impulse (Ns)	Early-Pre	0.90	9.3	14.7	Braking Impulse (Ns)	Early-Pre	0.80	10.7	13.0
	Pre	0.89	5.7	9.3		Pre	0.78	8.9	12.4
	Circa	0.88	5.2	11.9		Circa	0.91	6.3	11.9
	Post	0.73	6.8	18.3		Post	0.79	6.7	15.2
Propulsive Impulse (Ns)	Early-Pre	0.90	7.9	10.5					
	Pre	0.73	10.4	19.0					
	Circa	0.90	4.9	9.9					
	Post	0.78	6.3	14.7					

Work Rate Variables									
Mean Braking Power (W)	Early-Pre	0.90	16.2	192	Mean Propulsive Power (W)	Early-Pre	0.88	14.7	171
	Pre	0.90	11.1	162		Pre	0.91	9.3	104
	Circa	0.62	13.8	226		Circa	0.73	10.5	172
	Post	0.71	12.4	228		Post	0.75	10.5	197
Braking Work Done (KJ)	Early-Pre	0.80	10.6	1.30	Propulsive work Done (KJ)	Early-Pre	0.90	7.9	10.49
	Pre	0.78	8.9	12.44		Pre	0.73	10.4	19.04
	Circa	0.91	6.3	11.94		Circa	0.90	4.9	9.89
	Post	0.79	6.7	15.23		Post	0.78	6.3	14.77
Movement Strategy Variables									
Spring-like-Correlation	Early-Pre	0.92	26.9	0.13	Braking COM Velocity (m/s)	Early-Pre	0.84	9.2	0.12
	Pre	0.69	13.4	0.09		Pre	0.89	5.2	0.05
	Circa	0.72	7.8	0.06		Circa	0.87	4.9	0.05
	Post	0.78	4.2	0.04		Post	0.75	6.1	0.07
Peak COM Displacement (m)	Early-Pre	0.76	21.2	0.04					
	Pre	0.78	20.4	0.03					
	Circa	0.88	14.7	0.03					

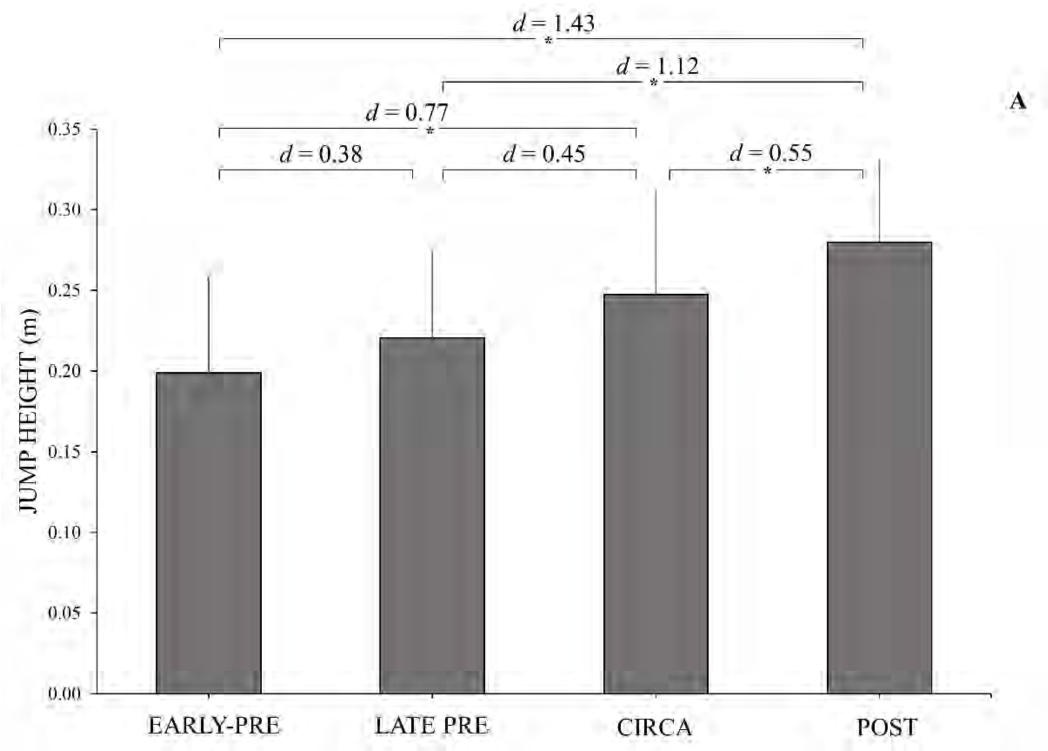
	Post	0.75	15.7	0.03
Propulsive COM Velocity (m/s)	Early-Pre	0.87	8.3	0.11
	Pre	0.82	5.3	0.06
	Circa	0.86	3.9	0.05
	Post	0.59	6.0	0.07

CV% - coefficient of variation; ICC – intraclass correlation coefficient; TE – typical error; RFD – rate of force development; COM – centre of mass.

5.3.2 Between Group Comparisons

5.3.2.1 Drop Jump Performance Variables

The performance variables for the four maturity groups are shown in *Figure 5.1*. No significant differences were observed between groups for ground contact time ($p > 0.05$). In terms of jump height, no differences were observed from early-pre- to late-pre-PHV and late-pre- to circa-PHV ($p > 0.05$), however, the post-PHV group displayed significantly greater jump heights than early-pre-, late-pre- and circa-PHV ($d = 1.43$, 1.12 and 0.55; $p < 0.05$). The circa-PHV exhibited greater jump height that early-pre-PHV ($d = 0.77$; $p < 0.05$). Late-pre-, circa- and post-PHV groups all had a greater RSI than the early-pre-PHV group ($d = 0.53$, 0.92, and 1.08, respectively; $p < 0.05$), while the post-PHV cohort also had a greater RSI than the late-pre-PHV group ($d = 0.51$; $p < 0.05$). The changes observed from early-pre to late-pre-PHV, late-pre- to circa-PHV and circa- to post-PHV for jump height and RSI appear to be similar in magnitude (*Figure 5.1*). No significant differences were observed between late-pre- and circa-PHV, and between circa- and post-PHV for RSI ($p > 0.05$).



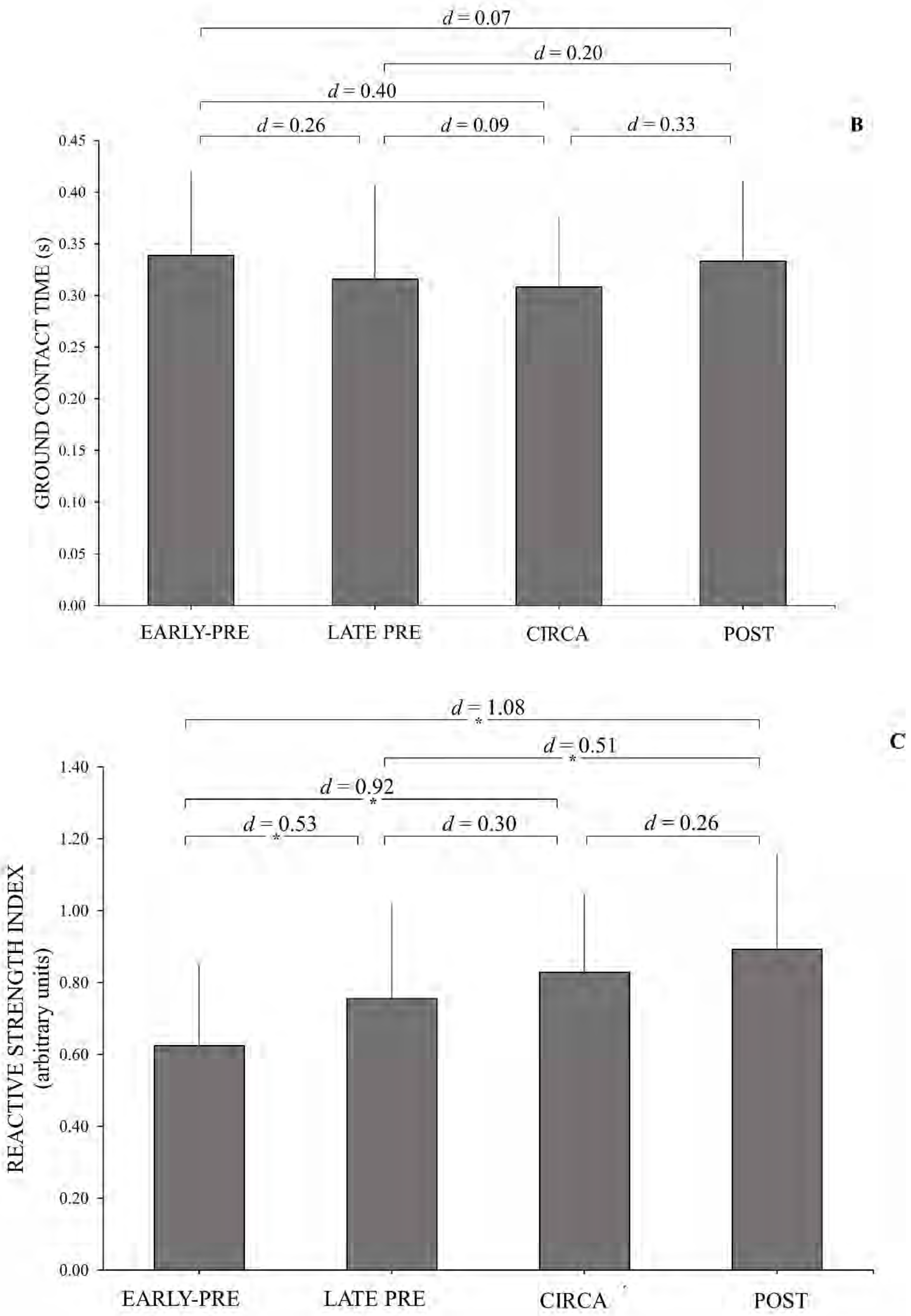


Figure 5.1 Effect of maturity status on (a) jump height, (b) ground contact time and (c) RSI.

d = between group effect size.

* Significant difference between maturity groups ($p < 0.05$).

5.3.2.2 Force Variables

Table 5.3 shows the force variables for the four maturity groups. Late-pre-, circa- and post-PHV all had significantly greater mean braking force ($d = 1.21$, 2.29 and 2.92, respectively; $p < 0.05$), braking peak force ($d = 0.99$, 1.43 and 1.94, respectively; $p < 0.05$), mean propulsive force ($d = 1.58$, 3.21 and 3.92, respectively; $p < 0.05$) propulsive peak force ($d = 1.16$, 2.38 and 2.75, respectively; $p < 0.05$), and force at peak COM displacement ($d = 1.07$, 2.24 and 2.49, respectively; $p < 0.05$), compared to the early-pre-PHV cohort. The circa- and post-PHV groups exhibited a significantly greater mean braking force ($d = 0.83$ and 1.47, respectively; $p < 0.05$), mean propulsive force ($d = 1.29$ and 2.33, respectively; $p < 0.05$), propulsive peak ($d = 0.84$ and 1.39, respectively; $p < 0.05$), and force at peak COM displacement ($d = 0.81$ and 1.29, respectively; $p < 0.05$) than late-pre-PHV. However, only the post-PHV group displayed a significantly greater braking peak force than late-pre-PHV ($d = 0.77$; $p < 0.05$). The post-PHV cohort also had significantly greater mean braking force, mean propulsive force, propulsive peak force and force at peak COM displacement compared to circa-PHV ($d = 0.72$, 1.28, 0.68 and 0.61, respectively; $p < 0.05$). The changes observed from early-pre to late-pre-PHV for peak braking force, peak propulsive force and force at peak COM displacement, appear to be larger in magnitude compared to the changes from late-pre to circa-PHV and circa- to post-PHV (*table 5.3*). The late-pre-PHV group presented significantly greater relative braking peak force compared to post-PHV ($d = 0.49$; $p < 0.05$; *table 5.3*). No significant differences were observed between maturity groups for braking rate of force development, relative propulsive peak and relative force at peak COM displacement ($p > 0.05$).

Table 5.3 Effect of maturity status on absolute and relative force, impulse, power and movement strategy variables.

VARIABLE	MATURITY GROUP				BETWEEN GROUP EFFECT SIZES (*d*)					
	Early-Pre (I)	**Late-Pre (II)**	**Circa (III)**	**Post (IV)**	**I – II**	**I – III**	**I – IV**	**II – III**	**II – IV**	**III – IV**
Force Variables										
Mean Braking Force (N)	850 ± 194	1166 ± 312*	1413 ± 288* #	1633 ± 326 Ŧ	1.21	2.29	2.92	0.83	1.47	0.72
Braking Peak Force (N)	1490 ± 408	1988 ± 583*	2219 ± 599*	2425 ± 548* #	0.99	1.43	1.94	0.39	0.77	0.36
Relative Braking Peak ($N/kg^{0.74}$)	108.3 ± 26.6	120.8 ± 30.6	114.4 ± 27.9	107.4 ± 23.3#	0.44	0.23	0.04	0.22	0.49	0.27
Mean Propulsive Force (N)	730 ± 123	1006 ± 214*	1277 ± 206* #	1595 ± 286 Ŧ	1.58	3.21	3.92	1.29	2.33	1.28
Propulsive Peak Force (N)	1033 ± 254	1499 ± 510*	1904 ± 452* #	2258 ± 577 Ŧ	1.16	2.38	2.75	0.84	1.39	0.68
Relative Propulsive Peak ($N/kg^{1.09}$)	21.8 ± 5.3	24.1 ± 7.0	24.0 ± 5.0	22.6 ± 5.3	0.38	0.43	0.17	0.01	0.23	0.26
Force at Peak COMD	978 ± 260	1421 ± 524*	1825 ± 468* #	2162 ± 621Ŧ	1.07	2.24	2.49	0.81	1.29	0.61
Relative Force at Peak COMD ($N/kg^{1.11}$)	19.3 ± 5.1	21.2 ± 6.8	21.3 4.9	20.0 ± 5.3	0.33	0.42	0.14	0.02	0.20	0.26
Braking RFD (KN/sec)	75. 9 ± 32.7	88.3 ± 37.9	85.6 ± 39.8	79.2 ± 33.2	0.35	0.26	0.10	0.07	0.26	0.17

Impulse Variables										
Net Impulse (N.s)	140 ± 30	186 ± 31*	233 ± 32* #	296 ± 43Ŧ	1.47	2.94	4.18	1.49	2.95	1.66
Relative Net Impulse (N.s/kg$^{1.03}$)	3.66 ± 0.70	3.78 ± 0.52	3.78 ± 0.54	3.86 ± 0.51	0.20	0.20	0.34	0.01	0.16	0.15
Braking Impulse (N.s)	121 ± 24	154 ± 30*	194 ± 31* #	258 ± 42Ŧ	1.17	2.56	3.93	1.28	2.80	1.70
Relative Braking Impulse (N.s/kg$^{1.05}$)	2.96 ± 0.50	2.90 ± 0.43	2.91 ± 0.50	3.09 ± 0.47	0.13	0.10	0.28	0.02	0.43	0.37
Propulsive Impulse (N.s)	134 ± 27	169 ± 32*	205 ± 27* #	259 ± 37 Ŧ	1.21	2.64	3.93	1.22	2.64	1.68
Relative Propulsive Impulse (N.s/kg$^{0.96}$)	4.46 ± 0.66	4.48 ± 0.60	4.41 ± 0.54	4.56 ± 0.58	0.03	0.09	0.16	0.12	0.14	0.27
Work Rate Variables										
Mean Braking Power (W)	943 ± 335	1341 ± 415*	1664 ± 351* #	2009 ± 477 Ŧ	1.05	2.10	2.58	0.84	1.49	0.82
Relative Braking Power (W/kg$^{1.04}$)	23.8 ± 8.4	26.3 ± 7.4	26.0 ± 5.6	25.1 ± 6.2*	0.32	0.31	0.18	0.04	0.17	0.14
Mean Propulsive Power (W)	889 ± 280	1259 ± 343*	1609 ± 320* #	2032 ± 437 Ŧ	1.18	2.40	3.11	1.05	1.97	1.10
Relative Propulsive Power (W/kg$^{1.21}$)	16.9 ± 5.2	18.3 ± 4.9	18.3 ± 3.8	18.2 ± 3.9	0.28	0.30	0.27	0.01	0.03	0.03
Mean Braking Work Done (KJ)	121 ± 24	154 ± 30*	194 ± 31* #	257 ± 42 Ŧ	1.17	2.56	3.93	1.28	2.80	1.70
Mean Propulsive Work Done (KJ)	134 ± 26	169 ± 31*	205 ± 27* #	259 ± 37 Ŧ	1.21	2.64	3.93	1.22	2.64	1.68

Movement Strategy Variables										
Spring-like-correlation	0.74 ± 0.15	0.81 ± 0.15 *	0.88 ± 0.09 * #	0.87 ± 0.13 * #	0.51	1.18	0.98	0.55	0.43	0.08
Peak COMD (m)	0.18 ± 0.6	0.18 ± 0.06	0.20 ± 0.07	0.24 ± 0.07 Ŧ	0.06	0.35	0.90	0.30	0.86	0.49
Mean Braking COM Velocity (m/s)	1.09 ± 0.20	1.15 ± 0.16	1.19 ± 0.16 *	1.23 ± 0.15 * #	0.33	0.54	0.80	0.24	0.51	0.26
Mean Propulsive COM Velocity (m/s)	1.20 ± 0.18	1.24 ± 0.15	1.26 ± 0.14	1.27 ± 0.14	0.26	0.38	0.43	0.13	0.20	0.07

COM = centre of mass; COMD = centre of mass displacement; RFD = rate of force development

* Significant between group difference with Early-pre-PHV ($p < 0.05$)

Significant between group difference with Pre-PHV ($p < 0.05$)

Ŧ Significant between group difference with all other maturity groups ($p < 0.05$)

5.3.2.3 Impulse Variables

The effect of maturity status on impulse variables is shown in *table 5.3*. Late-pre-, circa- and post-PHV groups displayed significantly greater net impulse (*d* = 1.47, 2.94 and 4.18, respectively; $p < 0.05$), braking impulse (*d* = 1.17, 2.56 and 3.93, respectively; $p < 0.05$) and propulsive impulse (*d* = 1.21, 2.64 and 3.93, respectively; $p < 0.05$) compared to early-pre-PHV. The post-PHV group exhibited significantly greater net impulse (*d* = 2.95 and 1.66 $p < 0.05$), braking impulse (*d* = 2.80 and 1.70 $p < 0.05$) and propulsive impulse (*d* = 2.64 and 1.68 $p < 0.05$) compared to the late-pre- and circa-PHV cohorts. The circa PHV group displayed significantly greater net, braking and propulsive impulse compared to late-pre-PHV (*d* = 1.49, 1.28 and 1.22 respectively; $p < 0.05$). The changes observed in all the absolute impulse variables from early-pre- to late-pre-PHV, late-pre- to circa-PHV and circa- to post-PHV appear to be similar in magnitude (*table 5.3*). No significant differences were observed between groups for any of the relative impulse variables ($p > 0.05$; *table 5.3*).

5.3.2.4 Work Rate Variables

Table 5.3 shows the work rate variables for the four maturity groups. Analysis revealed that the late-pre-, circa- and post-PHV groups displayed significantly greater mean braking power (*d* = 1.05, 2.10 and 2.58; $p < 0.05$), mean propulsive power (*d* = 1.18, 2.40 and 3.11; $p < 0.05$), mean braking work done (*d* = 1.17, 2.56 and 3.93; $p < 0.05$) and mean propulsive work done (*d* = 1.21, 2.64 and 3.93; $p < 0.05$) than the early-pre-PHV group. The post-PHV group presented significantly greater mean braking power (*d* =1.49 and 0.82; $p < 0.05$), mean propulsive power (*d* = 1.97 and 1.10; $p < 0.05$), mean braking work done (*d* = 2.80 and 1.70; $p < 0.05$) and mean propulsive work done (*d* = 2.64 and 1.68; $p < 0.05$) than late-pre- and circa-PHV. The circa-PHV cohort exhibited significantly greater mean braking and propulsive power, as well as mean braking and propulsive work done than the late-pre-PHV group (*d* =

0.84, 1.05, 1.28 and 1.22 respectively; $p < 0.05$). The changes observed in the work rate variables from early-pre- to late-pre-PHV, late-pre- to circa-PHV and circa- to post-PHV appear to be similar in magnitude (*see table 5.3*). No significant differences across maturity groups were observed for relative braking power and relative propulsive power ($p > 0.05$; *table 5.3*).

5.3.2.5 Landing Strategy Variables

The landing strategy variables for the maturity groups are shown in *table 5.3*. Analysis revealed that the late-pre-, circa- and post-PHV groups displayed significantly greater spring-like-correlation ($d = 0.51$, 1.18 and 0.98, respectively; $p < 0.05$) compared to the early-pre-PHV. The post-PHV exhibited a greater peak COM displacement than early-pre-, late-pre- and circa-PHV ($d = 0.90$, 0.86 and 0.49, respectively; $p < 0.05$), and significantly greater spring-like-correlation than late-pre-PHV ($d = 0.43$; $p < 0.05$). The only significant difference between late-pre- and circa-PHV was for spring-like-correlation ($d = 0.55$; $p < 0.05$), with the circa-PHV exhibiting a greater value. While the circa- and post-PHV groups displayed a significantly greater eccentric COM velocity ($d = 0.54$ and 0.80, respectively; $p < 0.05$) compared to early-pre-PHV, only the post-PHV had a greater eccentric COM velocity than late-pre-PHV ($d = 0.51$; $p < 0.05$). No other differences were observed between groups ($p > 0.05$) for the movement strategy variables.

5.3.3 Stretch Shortening Cycle Categories

When analysing the whole group, 49.0% (n = 127) of the participants were categorised as having GOOD SSC function, 20.5% (n = 53) as MODERATE function and 30.5% (n = 79) as POOR function (*Figure 5.2*). This is also reflected in the distribution of SSC categories, with analysis revealing a significant interaction between SSC function and maturity status, with more early-pre-PHV displaying POOR SSC function ($p < 0.05$) and proportionately less early-pre-PHV exhibiting GOOD SSC function ($p < 0.05$) when compared to the whole group. The opposite was observed for the post-PHV group with proportionately lower number of participants displaying POOR SSC function ($p < 0.05$), and a greater number of participants presenting GOOD SSC function ($p < 0.05$) than the whole group. While the circa-PHV group had lower number of participants displaying POOR SSC function in comparison to the entire sample ($p < 0.05$), they showed no significantly different distribution amongst the other two SSC categories compared to the whole group ($p > 0.05$). The late-pre-PHV group showed no significantly different distribution amongst any of the SSC categories when compared to the entire sample ($p > 0.05$).

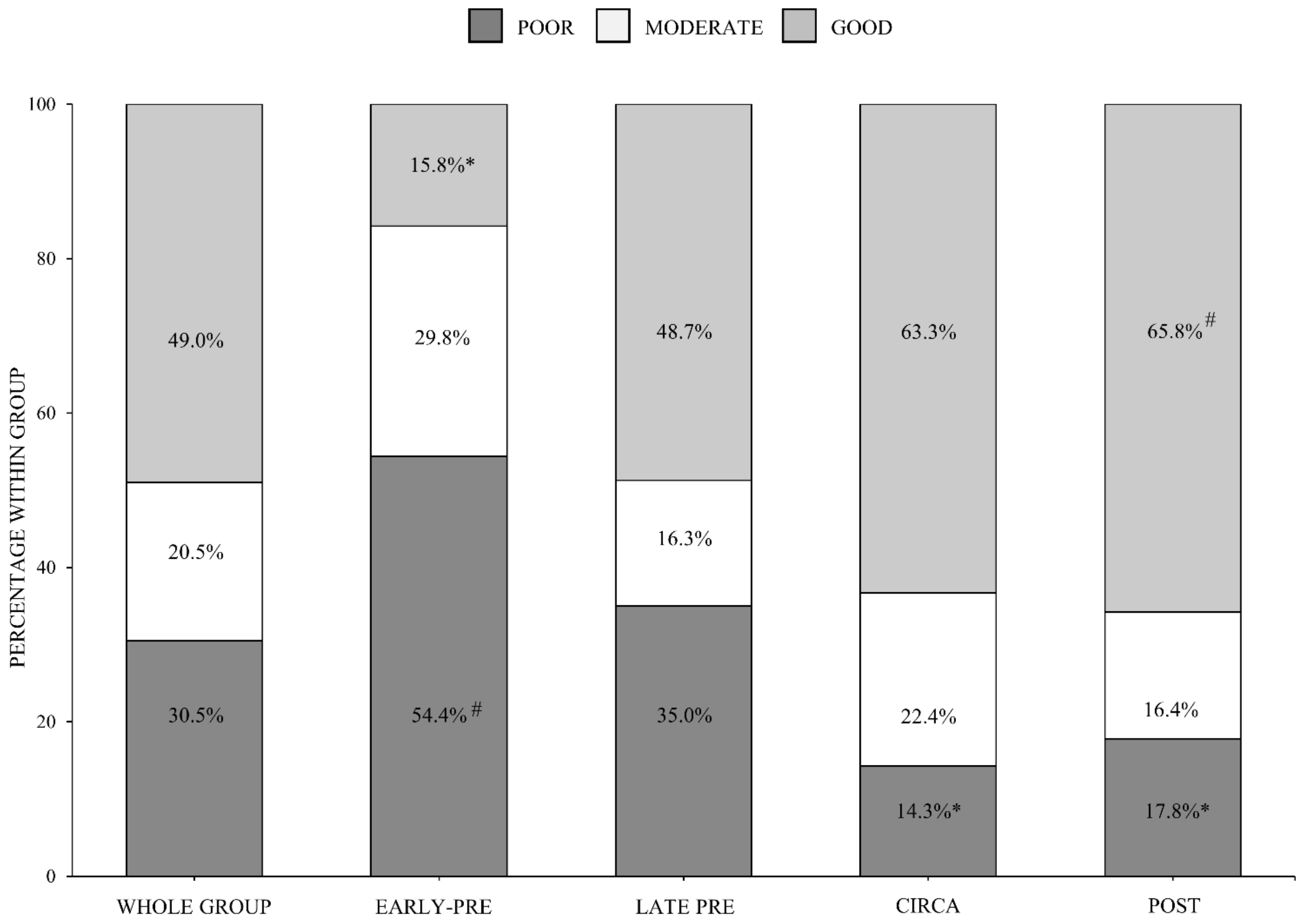


Figure 5.2 Proportion of stretch shortening cycle function categories within and between different stages of maturation (pre-PHV, n = 185; circa-PHV, n = 49; post-PHV, n = 73).

Significantly more in proportion to whole group ($p < 0.05$).

*Significantly less in proportion to whole group ($p < 0.05$).

5.4 DISCUSSION

The aim of the current study was to examine the effect of maturity status on DJ kinetics in young males, by assessing several kinetic variables during the braking and propulsive phases of a DJ. The main finding of the current study was that the post-PHV group exhibited greater values for most absolute kinetic variables, such as mean and peak propulsive forces, impulse and power compared to early-pre, late-pre- and circa-PHV. The differences observed between early-pre to late-pre-PHV, late-pre- to circa-PHV and circa- to post-PHV were similar in magnitude for most variables. SSC function appears to improve with maturity status, as demonstrated by a greater number of post-PHV displaying GOOD SSC function and greater number of early-pre-PHV displaying POOR SSC function, when compared to the whole group.

The findings of the study revealed that there was no systematic bias, relative reliability was acceptable in most instances, and although CV was > 10% in some cases, the differences observed in the cross-sectional analysis were greater than the typical error. The significant differences between groups in the performance variables, except for the difference in jump height between early-pre- and late-pre-PHV, were larger than the typical error for the respective groups. All significant differences in the peak force, impulse and work rate variables observed between maturity groups were greater than the typical error for the groups being examined. In the movement strategy variables being assessed, only the differences between early-pre- and post-PHV for peak COM displacement and braking COM velocity, late-pre- and post-PHV for peak COM displacement and braking COM velocity, circa- and post-PHV for peak COM displacement were greater than the typical error reported for each group. Caution needs to be exercised when reporting variables like spring-like correlation and mean braking

COM velocity as some of the differences observed were smaller than the typical error reported to the groups.

In accordance with prior research, the current study observed greater jump height and RSI, with no change in ground contact time, in the more mature participants compared to their younger cohorts. The findings suggest that as boys mature their performance during vertical jumping and rebound activities improves (Laffaye et al., 2016; Pääsuke et al., 2001; Quatman et al., 2006; Taylor et al., 2010), but with limited changes in ground contact time (Birat et al., 2020). The performance in the propulsive phase of the DJ has been suggested to be strongly influenced by the force producing capabilities of the muscle (Bobbert et al., 1987b; van Ingen Schenau et al., 1997b). Based on this, the greater jump height and RSI in the more mature participants compared to their less mature counterparts, can be explained by their greater absolute propulsive mean and peak force, force at peak COM displacement, net impulse, propulsive impulse, and propulsive power. Such improvements in force producing capabilities with maturity have been associated with increases in muscle mass (Radnor et al., 2021), with maturity-related increases in vastus lateralis muscle thickness being suggested to underpin vertical jump performance (Radnor et al., 2021; Secomb et al., 2015). This suggested influence of muscle mass is further reinforced by the lack of differences between the maturity groups for propulsive peak force and force at peak COM displacement relative to body mass, which is in congruence with the findings of Radnor et al. (2021).

The more mature participants exhibited significantly greater absolute mean and peak braking forces compared to other cohorts, with the post-PHV group displaying significantly greater braking peak forces than late-pre-PHV even when normalised to body mass. The large amounts of preceding braking loading during DJs (Bobbert et al., 1986) have been suggest to result in high stretch loads (Bobbert et al., 1987a; Komi and Gollhofer, 1997), and result in long ground contact times (Ball et al., 2010). While increased braking pre-loading has been linked to improved jump performance in adults (Bobbert et al., 1987a; Bobbert et al., 1987b; Turner and Jeffreys, 2010), it has been suggested that youth might not respond the same way due to their under developed skeletal musculature and the pre-loading potentially exceeding the SSC capabilities of their lower limb musculature (Bassa et al., 2012; Gillen et al., 2019; Lazaridis et al., 2010; McKay et al., 2005; Suchomel et al., 2016). Although the ground contact times remained unchanged between maturity groups, the more mature boys appear to accommodate their greater absolute breaking peak force and impulse by displacing more during ground contact, with a greater braking COM velocity thereby resulting in greater mean braking power and work done. While this is indicative of an increased and faster pre-stretch, suggestive of storage of a greater amount of elastic energy (Edman et al., 1978), the greater displacement also allows for a greater distance over which force can be developed (Hunter and Marshall, 2002). These mechanisms are reflected by the maturity status-related increases in absolute mean and peak forces, power and more importantly net impulse, which is indicative of change in momentum (Rosengrant, 2011). Jump performance has been evidenced to be strongly influenced by velocity at take-off and this velocity is determined by the preceding impulse (Ruddock and Winter, 2015).

Based on Padua et al. (2005), who suggested a cut-off of >0.80 to describe whether or not an individual is displaying spring-like behaviour, the higher spring-like correlation observed in the more mature participants in the current study indicates that spring-like-behaviour might improve with maturation, and this is further supported by the results of the reliability analysis. While it has been suggested that stiffness is a pre-requisite to spring-like-behaviour (Blickhan, 1989), the current study did not enumerate vertical stiffness as the calculation assumes that the an individual displays springlike behaviour and prior research has applied a threshold of >0.80 to ensure the calculation is valid (Padua et al., 2005). Although the greater spring-like correlation in the more mature participants might be indicative of greater levels of stiffness, they also displayed greater levels of peak COM displacement than their cohorts. With the absolute mean and peak braking forces being greater in the more mature participants, their greater COM displacement might be a movement strategy to attenuate the ground reaction forces, with it being suggested that greater flexion of the ankles, knees and hips allows for more time to distribute impact forces and allow for the absorption of these forces by the musculature (McNitt-Gray, 1993; Viitasalo et al., 1998). Neural mechanisms such as pre-activation, as well as amplitude and timing of stretch-reflex have also been suggested to influence lower limb stiffness during rebound activities (Hobara et al., 2008; Jones and Watt, 1971; McMahon et al., 2012; Oliver and Smith, 2010). Prior research has reported growth and maturity-related improvements of these feed-forward and feed-back mechanisms (Grosset et al., 2007; Hobara et al., 2008; Lazaridis et al., 2010; Lloyd et al., 2012b; Oliver and Smith, 2010), with it being suggested that stiffness resulting from maturation stays constant post the onset of puberty (Korff et al., 2009). Additionally, lower levels of pre-activation have been suggested to result in peak vertical ground reaction forces that manifest as impact peaks during the early phase of ground contact (Hreljac, 2004; Nicol et al., 1991). In the current study, the distribution within the SSC categories appears to become stable between pre- and circa-PHV, which could potentially be explained by the maturity related improvements in neural mechanisms, however this requires further examination. The findings of the current study are consistent with previous research showing an improvement in SSC function associated with maturity status (Hewett et al., 2006; Pedley et al., 2020; Quatman et al., 2006), reflected by a greater proportion of individuals in the post-PHV group having GOOD SSC function and greater proportion in the pre-PHV group having POOR SSC function, when compared to the whole group. However, similar to the findings of Pedley et al. (2020), while several pre-PHV participants displayed GOOD SSC function, a small proportion of the post-PHV group displayed POOR SSC function suggesting that SSC development was not exclusively a function of maturation.

5.5 CONCLUSION

The study aimed to determine the reliability of the kinetic variables, measured during the braking and propulsive phases of a DJ, at different stages of maturation and to use these variables to examine the influence of maturity status on DJ kinetics in youth. Most of the examined variables highlighted an improved performance with increasing maturity, and these improvements may be attributed to the growth and maturity-related structural and motor control strategy changes that occur in youth. The findings of the study reinforce the need for the examination of SSC function to move beyond just measures of jump height and RSI. While prior research has frequently utilised RSI and jump height to assess SSC function, the current study showed no significant differences for RSI from late-pre- to circa-PHV and circa- to post-PHV and no difference in jump height from late-pre- to circa-PHV. However, small to moderate significant differences were observed in absolute peak forces, power, work done and impulse from late-pre to circa-PHV and circa- to post-PHV. Different jump strategies have been suggested to affect outcome measures such as jump height and RSI, and the differences observed in measures such as mean and peak forces, impulse and work rate provide a better understanding of the varying kinetic and movement strategies driving performance in the different maturity groups. It is important for practitioners to refrain from relying solely on outcome measures when assessing performance or the efficiency of a training programme, as they might not reflect the underlying mechanisms. While the current study highlights the development of physical qualities with maturation, several mature individuals displayed POOR SSC function suggesting that development of SSC function is not exclusively related to maturation.

Chapter 6 Prelude

Chapter 5 established the reliability of the drop jump kinetic variables in youth of different maturity status, and highlighted how these kinetic qualities differ across youth of various maturity status. While more mature athletes had a better performance in the majority of kinetic measures, demonstrating that SSC performance may increase with maturation, it is still unclear how resistance training may influence the development of drop jump kinetics in youth of different maturity status. *Chapter 6* sought to examine this interaction of maturation and short-term resistance training on the development of kinetic outcomes from a drop jump. An understanding of how this interaction between maturation and training influences changes in these drop jump kinetic qualities would better inform programme design and exercise prescription for youth of different maturity status.

Chapter 6 – Effects of a 12-Week Combined Strength and Plyometric Training Programme on Drop Jump Kinetics in Young Male Athletes

6.1 INTRODUCTION

Resistance training is aimed at increasing an individual's ability to exert or resist force using the individual's own bodyweight, or external resistance in the form of free weights, machines or resistance bands and medicine balls (Benjamin and Glow, 2003). When examining resistance training in youth, prior research has highlighted the positive effects on health and fitness (Faigenbaum, 2007; Faigenbaum and Myer, 2010; Faigenbaum et al., 1999; Sander et al., 2013; Thomas et al., 2009), as well sport-based movements such as jump height (Chelly et al., 2009; Chelly et al., 2015; Lloyd et al., 2016; Matavulj et al., 2001; Uzelac-Sciran et al., 2020), change of direction speed (Meylan and Malatesta, 2009; Thomas et al., 2009) and running velocities (Chelly et al., 2015; Lloyd et al., 2016). However, it is unclear how the stretch shortening cycle (SSC) muscle action, which underpins these movements, develops as a result of resistance training.

Research examining the responsiveness of youth to resistance training has suggested that pre-PHV youth may respond better to plyometric training programmes while post-PHV youth respond better to combined training (Lloyd et al., 2016). The authors attributed the findings to a process of "synergistic adaptation", suggesting a symbiotic relationship between specific adaptations of an imposed training demand with accompanying growth and maturity-related adaptations. However, Radnor et al. (2017) suggested that irrespective of maturity status, all youth would benefit more from combined training programmes. This was attributed to strength training being essential for addressing tasks that place a high demand on concentric strength and plyometric training being beneficial for tasks that require high levels of reactive strength (Radnor et al., 2017). While these studies examined maturity-related responsiveness using sprints, repeated vertical jumping and squat jumps, it is unclear how DJ performance would be affected. *Chapter 3* highlighted that adolescents made greater improvements in DJ performance following resistance training. However, the interventions implemented in the studies included plyometric and combined training and an insufficient number of studies reporting maturity-related responses.

While previous studies have examined the effect of training interventions on children and adolescents, the majority have failed to report the maturity status-related development (Lesinski et al., 2016). In a meta-analysis examining training responsiveness in youth, Lesinski et al. (2016) concluded that further research was needed to explicate maturity-specific effects of resistance training on performance measures in youth. Similar findings were observed in *Chapter 3*, where most of the studies examining the effect of resistance training on drop jump (DJ) performance failed to report maturity status-related responses. Such an understanding is vital for practitioners as the response to resistance training could vary based on maturity status. Furthermore, *chapter 3* highlighted the fact that most of the research examining the effect of resistance training on DJ performance failed to report the development of the underpinning kinetic qualities. There is currently a scarcity of paediatric research investigating the training-related development of SSC function in youth of varying maturity status through a range of underpinning kinetics assessed during a DJ (Radnor et al., 2018). Therefore, the aim of the current study was to examine the development of DJ kinetics in pre- and post-PHV boys, in response to a 12-week combined strength and plyometric training programme. It was hypothesized that both pre- and post-PHV EXP groups would experience improvements in the kinetic measures following the training intervention.

6.2 METHODS

6.2.1 Participants

Participants included 40 young male athletes (*n* = 25 pre-PHV, *n* = 15 post-PHV), aged 9-17 years, from a sports academy in the United Kingdom, who were allocated to a CON or EXP groups based on their ability to attend the training sessions. Descriptive statistics for the pre- and post-PHV, EXP and CON groups, can be found in *table 6.1*. Participants reported no injuries at baseline testing or during post-intervention testing and were informed of the risks and benefits of taking part in the study. There were also no drop outs at any point due to injury. Participants had no previous experience with regular structured strength and conditioning. Parents and participants were informed that participation in the study was voluntary, and that they could withdraw from the study at any point in time. Informed parental consent and participant assent were obtained and physical readiness questionnaires completed after ethical approval was granted by the University Research Ethics Committee for the study.

Table 6.1 Mean (± SD) values for descriptive characteristics of each group

Group	N	Standing height(cm)	Mass(kg)	Age(years)	Maturity offset (years from phv)
Pre-PHV EXP	15	151.0 ± 8.0	47.3 ± 16.2	11.34 ± 0.75	-2.10 ± 0.83
Pre-PHV CON	10	146.8 ± 9.3	41.6 ± 7.0	11.24 ± 0.78	-2.29 ± 0.67
Post-PHV EXP	7	174.4 ± 9.2*	70.3 ± 13.4*	15.78 ± 0.99*	1.88 ± 1.28*
Post-PHV CON	8	173.1 ± 6.1*	61.2 ± 6.1*	14.73 ± 0.92*	1.52 ± 0.32*

PHV = peak height velocity; EXP = experimental group; CON = control group.

* Significantly different from pre-PHV participants ($p < 0.05$)

6.2.2 Procedures

6.2.2.1 Anthropometrics

Anthropometrics and maturity status were assessed using the same method as Chapter 4 (refer to section 4.2.2.1).

Participants were determined to be either pre-PHV (maturity offset < 0.00) or post-PHV (maturity offset > 0.00).

6.2.2.2 Drop Jump Assessment

Drop Jump was assessed using the same procedures as Chapter 4 (refer to section 4.2.2.2).

6.2.2.3 Training Intervention

Baseline testing for all groups was conducted one week before the start of the intervention. Following baseline testing, both pre- and post-PHV EXP groups participated in 12 weeks of 1-hour-long combined strength and plyometric training, twice weekly, in addition to their regular sport training sessions. Participants needed to attend at least 85% of the sessions to be included in the final analyses, and all participants made this cut off. The CON group however, only participated in their sport-specific training with no exposure to any sort of neuromuscular training. All sessions were led and supervised by a National Strength and Conditioning Association Certified Strength and Conditioning Specialist (*tables 6.2* and *6.3*), and each group had similar, but maturity appropriate programmes. The first 4-week mesocycle of the 12-week intervention was primarily a skill development phase to improve movement competency. Rest periods during the first 4 weeks were ~90 seconds due to low training loads and high rep ranges. Upon completion of the fourth week, the training volume and intensity were manipulated by increasing the number of sets and decreasing the number of repetitions, thereby allowing for an increase in training intensity. When participants displayed satisfactory technique, they were instructed to increase load by ~5% the following week (Ratamess et al., 2009). If participants displayed poor technique during multiple repetitions, assessed subjectively by the lead coach, the load was appropriately reduced.

The objective of the second 4-week training block was to begin to address maximal strength and force production at a higher velocity. The multi-joint exercises ranged between 5-8 repetitions so as to allow the participants to be exposed to the appropriate training stimulus (Lesinski et al., 2016). The final training block of the intervention continued to prioritise the development of maximal strength and force production at high velocity, with the number of repetitions decreased to 3-5, allowing for further increase in training load. Heavy training loads innervate type 2 muscle fibres, which are recruited during exercise requiring near maximal force production, and are prescribed with the primary goal of improving maximal strength and eventually influencing maximal power production (Cormie et al., 2011b). Rest periods between sets, during the final two training blocks, ranged from 2-3 minutes to ensure adequate recovery. Prior to every session, participants were asked to complete a 10 minute progressive RAMP warmup (Jeffreys, 2006). Throughout the training intervention, participants completed a minimum of two warmup sets prior to their working sets.

Despite the difference in exercise selection, both EXP groups followed similar training regimens in terms of targeted movements patterns. The first weekly session primarily involved plyometric training, with the intensity being progressed over the duration of the intervention by increasing drop height or cueing for shorter ground contact times. The second session of the week was designed to reinforce the technical competency developed over the first 4-week mesocycle and develop maximal strength using heavier training loads compared to the first two mesocycles.

Table 6.2 Structure of 12-week training intervention for pre-PHV EXP.

TRAINING BLOCK	WEEKS	SESSION 1			SESSION 2		
		EXERCISE	**SETS**	**REPETITIONS**	**EXERCISE**	**SETS**	**REPETITIONS**
1	1-2	Pogo Hop	3	10	Bear Crawl Hold	3	30 Seconds
		Standing Long Jump	3	5	Drop Landing	3	5
		Single Leg Hop and Stick	3	5 Each Leg	Barbell Back Squat	3	10
		Side Plank	3	30 Seconds Each Side	Banded Overhead Press	3	10
		Medball Slam	3	10	Banded Horizontal Pull	3	10
	3-4	Pogo Hop	3	10	Bear Crawl Hold	3	30 Seconds
		Split Jump	3	10	Drop Landing	3	5
		Box Jump	3	5	Barbell Deadlift	3	6-8
		Glute Bridge	3	10	Banded Overhead Press	3	10
		Medball Side Toss	3	5 Each Side	Single Arm Banded Row	3	10 Each Arm
2	5-6	Pogo Hop	4	10	Plank Holds	4	30 Seconds

		Standing Long Jump	4	5	Kettlebell Squat Jump	4	5
		Deadbug	4	20	Barbell Back Squat	4	6-8
		Medball Vertical Throw	4	5	Press Up	4	8
		Side Plank	4	30 Seconds Each Side	TRX Row	4	8
	7-8	Box Jump	4	5	Plank Hold	4	30 Seconds
		Drop Jump	4	5	Kettlebell Squat Jump	4	5
		Deadbug	4	5	Barbell Deadlift	4	5
		Glute Bridge	4	15	Press Up	4	6-8
		Medball Horizontal Throw	4	5	TRX Row	4	8
3	9-10	Multidirectional Hurdle Jump	4	6	Shoulder Tap	4	20
		Drop Jump to 10 m Sprint	4	3	Barbell Back Squat	4	3-5
		20 m Sprint	4	2	Kettlebell Swing	4	8
		Medball Overhead Throw	4	5	Dumbbell Overhead Press	4	5
		Single Leg Glute Bridge	4	10 Each Leg	Horizontal Row	4	5
	11-12	Multi-directional Hurdle Jump	4	6	Shoulder Tap	4	20

Drop Jump to Standing Long Jump	4	3	Barbell Deadlift	4	3-5
20 m Sprint	4	2	Kettlebell Swing	4	8
Medball Vertical Throw	4	5	Single Arm Dumbbell Overhead Press	4	5 Each Arm
Medball Horizontal Throw	4	3 Each Side	Single Arm Dumbbell Rows	4	5 Each Arm

PHV = peak height velocity; EXP = experimental group.

Table 6.3 Structure of 12-week training intervention for post-PHV EXP

TRAINING BLOCK	WEEKS	SESSION 1			SESSION 2		
		EXERCISE	SETS	REPETITIONS	EXERCISE	SETS	REPETITIONS
1	1-2	Standing Long Jump	3	4	Box Jump	3	5
		Pogo Hop	3	10	Barbell Back Squat	3	10
		Single Leg Hop and Stick	3	5 Each Leg	Horizontal Row	3	6-10
		Barbell Hip Thrust	3	10	Romanian Deadlift	3	10
		Chest Supported Dumbbell Row	3	10	Kneeling Landmine Press	3	8 Each Side
	3-4	Multidirectional Hurdle Jump	3	3	Box Jump	3	5
		Split Jump	3	10	Barbell Deadlift	3	6-10
		Single Leg Hop and Stick	3	5 Each Leg	Horizontal Row	3	6-10
		Kettlebell Split Squat	3	10 Each Leg	Barbell Step Up	3	5 Each Leg
		Dumbbell Bench Press	3	10	Kneeling Landmine Press	3	8 Each Side
2	5-6	Pogo Hop	4	10	Single Leg Bounding	4	3 Each Leg
		Drop Jump	4	3	Barbell Back Squat	4	5-8

		Kettlebell Squat Jump	4	3	Bent Over Row	4	8
		Chest Supported Dumbbell Row	4	10	Romanian Deadlift	4	6
		Barbell Bench Press	4	6-8	Weighted Deadbug	4	10
	7-8	Multidirectional Hurdle Jump	4	3	Single Leg Bounding	4	4 Each Leg
		Drop Jump to 10 m Sprint	4	3	Hex Bar Deadlift	4	5
		Standing Long Jump	4	4	Bent Over Row	4	6-8
		Barbell Hip Thrust	4	6-8	Barbell Step Up	4	5 Each Side
		Barbell Bench Press	4	5	Weighted Deadbug	4	10
3	9-10	Drop Jump to Standing Long Jump	4	3	20 m Sprint	4	2
		Single Leg Box Jump	4	2 Each Leg	Barbell Back Squat	4	3
		Rear Foot Elevated Dumbbell Squat	4	8 Each Leg	Pull Ups	4	5
		KB Swing	4	10	Barbell Overhead Press	4	5-8
		Single Arm Dumbbell Row	4	8 Each Arm	Weighted Plank Hold	4	30 Seconds
	11-12	Multidirectional Hurdle Jump	4	3	20 m Sprint	4	2
		Standing Long Jump	4	3	Hex Bar Deadlift	4	3

Dumbbell Lunge	4	2 Each Leg	Pull Up	4	AMRAP
Barbell Hip Thrust	4	5	Single Arm Dumbbell Overhead Press	4	5 Each Arm
Barbell Bench Press	4	5	Weighted Plank Hold	4	30 Seconds

PHV = peak height velocity; EXP = experimental group.

6.2.3 Statistical Analyses

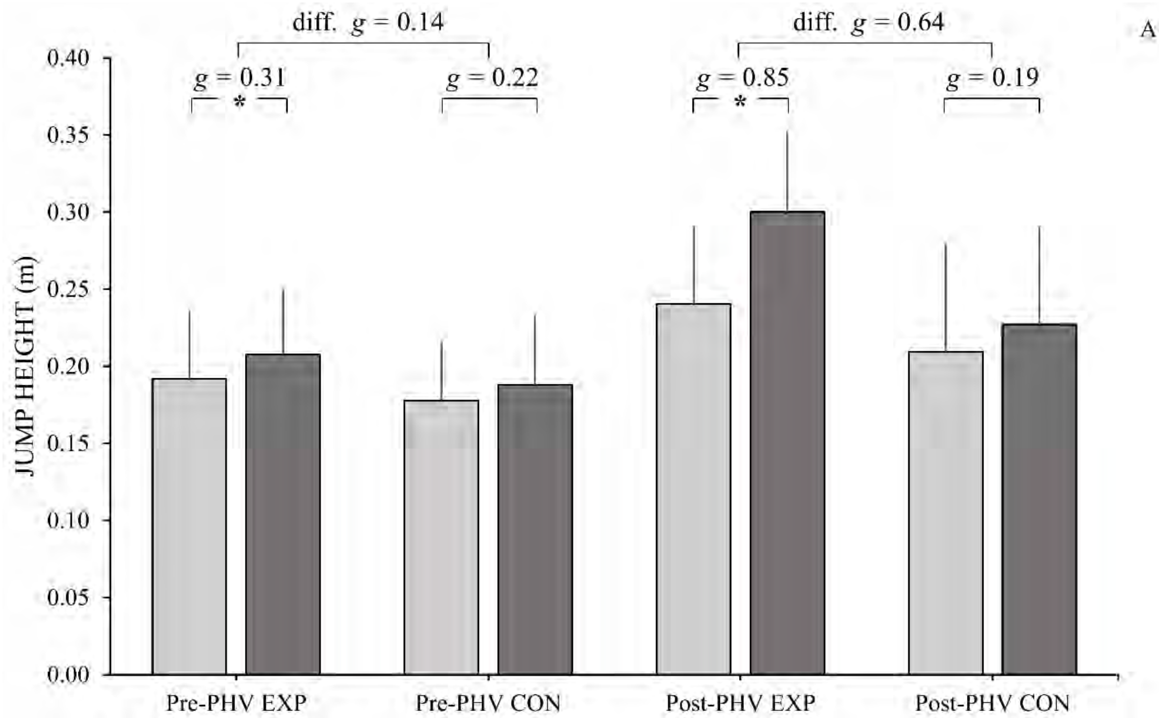
Normal distribution of data was assessed using the Shapiro-Wilk test. Descriptive statistics (means ± *SD*) were calculated for all normally distributed variables for each group at both baseline and post-intervention testing sessions. Paired sample t-tests were used to examine statistical differences within each group from baseline to post-intervention, and Hedge's *g* was calculated to interpret the magnitude of within group effects using the following thresholds trivial: <0.20; small: 0.20 – 0.59; moderate: 0.60 – 1.19; large: 1.20- 1.69; and very large: > 1.70 (Sullivan and Feinn, 2012). Separate one-way analysis of variance (ANOVA) tests were then employed to examine significant differences in the change from baseline to post-intervention between the four groups (pre-PHV EXP and CON, post-PHV EXP and CON), and when significance was observed, post-hoc analyses was carried out using a Bonferroni test. Finally, the magnitude of change from baseline to post-intervention in the training group relative to the change in the control group was calculated for each maturity group (diff. *g*).

For the variables that were deemed as non-parametric, median scores were reported. To mirror the approach adopted for the normally distributed variables, Wilcoxon signed rank tests were used to examine statistical differences within group from baseline to post-intervention. Wilcoxon *r* effect sizes were subsequently reported, and categorised as small: 0.10-0.29; moderate: 0.30-0.49; and large: > 0.50 (Fritz et al., 2012). Kruskal Wallis H-test was used to examine differences in the change from baseline to post-intervention between the four groups (pre-PHV EXP and CON, post-PHV EXP and CON), and when significance was observed a post-hoc analyses was carried out using a Games-Howell test.

6.3 RESULTS

6.3.1 Drop Jump Performance Variables

All the DJ performance variables were found to be normally distributed. Following the 12-week intervention, both pre- and post-PHV EXP groups exhibited significant increases from baseline to post-intervention for jump height ($g = 0.31$ and 0.85, respectively; $p < 0.05$), while the post-PHV EXP exhibited a significantly greater increase in jump height compared to pre-PHV EXP and pre-PHV CON ($p < 0.05$). Furthermore, the pre- and post-PHV EXP showed trivial and moderate changes in jump height relative to their CON counterparts (diff. $g = 0.14$ and 0.64, respectively; *figure 6.1*). No significant within or between group differences were observed for ground contact time ($p > 0.05$). The post-PHV EXP was the only group to exhibit a significant increase in RSI ($g = 0.48$; $p < 0.05$), exhibiting small changes relative to post-PHV CON (diff. $g = 0.55$; *figure 6.1*). No other significant within or between group differences were observed ($p > 0.05$).



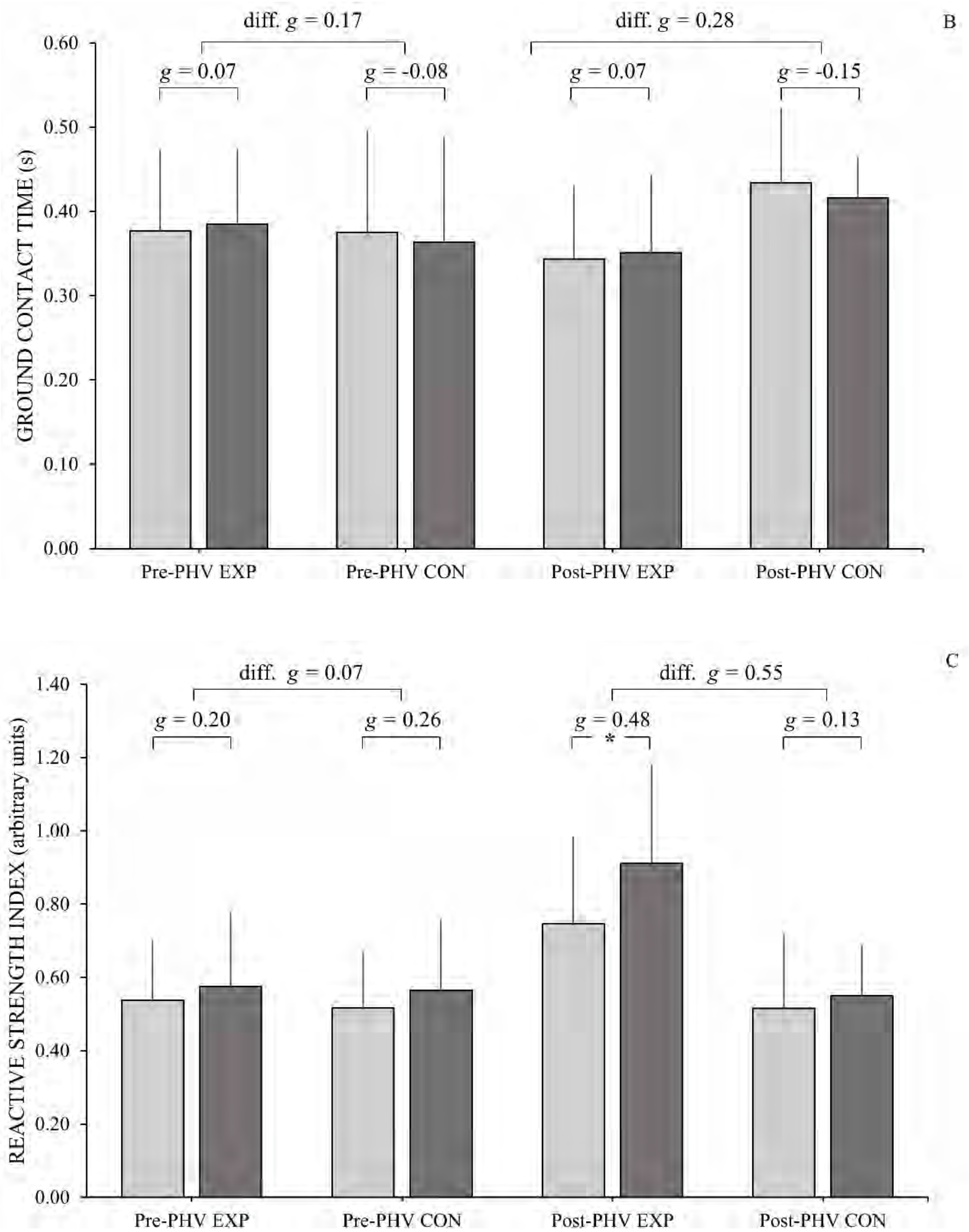


Figure 6.1 Effect of training intervention on (a) jump height, (b) ground contact time, and (c) reactive strength index.

g = within group effect size for parametric data

r = Wilcoxon *r* within-group effect size for non-parametric data

diff. *g* = change from pre- to post-intervention in EXP relative to CON

* Significant difference from baseline to post-intervention ($p < 0.05$)

6.3.2 Force Variables

Braking RFD and relative braking peak force were the only force variables deemed normally distributed. The post-PHV EXP was the only group to show a significant increase in absolute mean braking and propulsive force (r = 0.89 and 0.83, respectively; $p < 0.05$; *table 6.4*). They were also the only group to exhibit significant increases in absolute and relative propulsive peak force from baseline to post-intervention (r = 0.89 and 0.89, respectively; $p < 0.05$; *table 6.4*). No groups exhibited any significant changes in braking RFD from baseline to post-intervention ($p > 0.05$; *table 6.4*). However, pre- and post-PHV EXP exhibited small changes in braking RFD relative to pre- and post-PHV CON (diff. g = 0.42 and 0.47, respectively). While there were no significant differences within or between group for relative braking peak force ($p > 0.05$; *table 6.4*), pre- and post-PHV EXP showed small and moderate changes relative to pre- and post-PHV CON (diff. g = 0.57 and 0.83, respectively). No significant within or between group differences were observed for any other force variables ($p > 0.05$).

Table 6.4 Group means (± std dev) and medians for the kinetic variables with effect sizes for change from baseline to post-intervention.

Variables	**Pre-PHV EXP**			**Pre-PHV CON**			**Post-PHV EXP**			**Post-PHV CON**		
	Baseline	**Post**	**ES**	**Baseline**	**Post**	**ES**	**Baseline**	**Post**	**ES**	**Baseline**	**Post**	**ES**
Force Variables												
Mean Braking Force (N)	864.5	876.5	*r* = 0.03	893.7	922.3	*r* = 0.21	1530.1	1812.2*	*r* = 0.89	1173.3	1243.1	*r* = 0.40
Braking Peak Force (N)	1576.7	1429.2	*r* = -0.40	1525.1	1568.8	*r* = 0.14	2370.4	2722.9	*r* = 0.51	2011.2	1893.6	*r* = -0.25
R Braking Peak Force (N/Kg$^{0.84}$)	72.4 ± 13.9	66.8 ± 16.5	*g* = -0.35	71.1 ± 11.7	73.2 ± 16.8	*g* = 0.15	72.9 ± 16.9	80.97 ± 18.3	*g* = 0.34	66.4 ± 13.5	61.1 ± 10.5	*g* = -0.29
Mean Propulsive Force (N)	755.5	778.1	*r* = 0.21	775.2	810.1	*r* = 0.30	1486.8	1521.3*	*r* = 0.82	1219.7	1221.1	*r* = 0.25
Propulsive Peak Force (N)	1134.1	1050.2	*r* = -0.01	993.4	1149.6	*r* = 0.34	1997.6	2164.9*	*r* = 0.89	1587.5	1576.3	*r* = -0.49
R Propulsive Peak Force (N/Kg$^{0.99}$)	25.3	25.8	*r* = 0.00	28.1	28.7	*r* = 0.34	30.7	33.6*	*r* = 0.89	25.9	26.4	*r* = 0.54
Force at Peak COMD (N)	1130.7	1050.2	*r* = 0.12	995.0	1122.1	*r* = 0.27	1959.1	2137.0	*r* = 0.70	1308.5	1510.7	*r* = 0.49
R Force at Peak COMD (N/Kg$^{0.97}$)	24.7	24.8	*r* = 0.12	26.7	27.0	*r* = 0.27	27.5	33.1	*r* = 0.70	21.6	24.8	*r* = 0.49
Braking RFD (KN/s)	78.1 ± 25.8	69.7 ± 26.5	*g* = -0.29	75.5 ± 24.3	75.8 ± 34.3	*g* = 0.01	105.4 ± 39.2	107.4 ± 50.4	*g* = 0.04	85.4 ± 34.5	69.1 ± 29.7	*g* = -0.36
Impulse Variables												
Net Impulse (N.s)	152.4	166.5*	*r* = 0.67	157.6	161.6*	*r* = 0.82	285.8	343.4*	*r* = 0.89	250.3	251.5	*r* = 0.59
R Net Impulse (N.s/Kg$^{0.89}$)	5.87	6.13*	*r* = 0.64	5.83	6.14*	*r* = 0.82	6.48	7.60*	*r* = 0.89	6.33	6.37	*r* = 0.59

Braking Impulse (N.s)	132.5	145.7*	*r* = 0.57	147.8	148.0	*r* = 0.18	240.9	265.5*	*r* = 0.89	236.0	234.2	*r* = -0.10
R Braking Impulse (N.s/Kg$^{0.98}$)	3.85 ± 0.56	4.09 ± 0.62*	*g* = 0.36	3.79 ± 0.64	3.89 ± 0.80	*g* = 0.11	3.96 ± 0.64	4.44 ± 0.63*	*g* = 0.53	4.22 ± 0.79	4.39 ± 0.64	*g* = 0.17
Propulsive Impulse (N.s)	155.5	154.7	*r* = 0.13	166.7	170.2	*r* = 0.08	267.3	295.2*	*r* = 0.89	251.1	251.3	*r* = 0.25
R Propulsive Impulse (N.s/Kg$^{0.91}$)	5.80 ± 0.88	5.86 ± 0.70	*g* = 0.06	5.54 ± 0.90	5.55 ± 1.01	*g* = 0.09	5.64 ± 0.78	6.32 ± 0.67*	*g* = 0.63	6.01 ± 0.53	6.08 ± 0.66	*g* = 0.00
Work Rate Variables												
Mean Braking Power (W)	984.9	988.5	*r* = 0.29	943.8	1024.4	*r* = 0.53	1818.3	2432.3*	*r* = 0.89	1348.5	1545.9	*r* = 0.49
R Mean Braking Power (W/Kg$^{0.84}$)	45.0 ± 9.4	47.6 ± 11.9	*g* = 0.24	41.1 ± 9.9	46.1 ± 13.2	*g* = 0.41	53.1 ± 12.2	70.0 ± 12.9*	*g* = 0.98	39.2 ± 15.6	45.3 ± 10.6	*g* = 0.29
Mean Propulsive Power (W)	943.5	973.8	*r* = 0.44	928.6	1029.5*	*r* = 0.66	1809.6	2143.0*	*r* = 0.89	1507.7	1564.9	*r* = 0.49
R Mean Propulsive Power (W/Kg$^{0.91}$)	32.5 ± 6.1	34.6 ± 6.7	*g* = 0.30	31.3 ± 6.6	34.6 ± 8.7	*g* = 0.40	38.1 ± 5.8	48.6 ± 6.6*	*g* = 1.29	31.1 ± 11.7	35.0 ± 7.9	*g* = 0.25
Braking Word Done (KJ)	132.4	145.6*	*r* = 0.57	147.8	148.0	*r* = 0.18	240.9	265.4*	*r* = 0.89	236.0	234.2	*r* = -0.10
Propulsive Work Done (KJ)	155.4	154.7	*r* = 0.13	166.7	170.1	*r* = 0.08	267.3	295.2*	*r* = 0.89	251.1	251.3	*r* = 0.25
Landing Strategy Variables												
Spring-like Correlation	0.79	0.83	*r* = 0.23	0.80	0.82	*r* = 0.36	0.89	0.89	*r* = 0.00	0.70	0.84	*r* = 0.64
Peak COMD (m)	0.18	0.21*	*r* = 0.57	0.18	0.16	*r* = 0.24	0.19	0.24*	*r* = 0.89	0.21	0.25	*r* = 0.45
Mean Braking COM Velocity (m/s)	1.06	1.13*	*r* = 0.70	1.04	1.13*	*r* = 0.79	1.19	1.34*	*r* = 0.89	1.07	1.16	*r* = 0.69
Mean Propulsive COM Velocity (m/s)	1.18	1.27*	*r* = 0.54	1.18	1.24*	*r* = 0.79	1.20	1.40*	*r* = 0.89	1.18	1.28*	*r* = 0.84

Braking Duration (s)	0.16 ± 0.04	0.17 ± 0.05	*g* = 0.27	0.16 ± 0.06	0.16 ± 0.05	*g* = -0.03	0.16 ± 0.05	0.16 ± 0.06	*g* = 0.03	0.20 ± 0.04	0.19 ± 0.04	*g* = -0.05
Propulsive Duration (s)	0.22 ± 0.06	0.21 ± 0.04	*g* = -0.08	0.21 ± 0.07	0.20 ± 0.06	*g* = -0.12	0.18 ± 0.04	0.19 ± 0.04	*g* = 0.11	0.23 ± 0.07	0.22 ± 0.02	*g* = -0.16

COM = centre of mass; COMD = centre of mass displacement; ES = effect size; PHV = peak height velocity; R = relative; RFD = rate of force development.

r = Wilcoxon *r* within-group effect size for non-parametric data

g = within group effect size for parametric data

* Significant difference from baseline to post-intervention ($p < 0.05$)

6.3.3 Impulse Variables

Relative braking and propulsive impulse were the only impulse variables observed to be normally distributed. The post-PHV EXP group exhibited significant increases in absolute net, braking and propulsive impulse ($r = 0.89$, 0.89 and 0.89, respectively; $p < 0.05$). While the pre-PHV EXP showed significant increases in absolute net and braking impulse ($r = 0.67$ and 0.57, respectively; $p < 0.05$), the pre-PHV CON only showed significant increases in absolute net impulse ($r = 0.82$; $p < 0.05$). Pre-PHV EXP and CON, as well as post-PHV EXP, exhibited significant increases in relative net impulse ($r = 0.64$, 0.82 and 0.89, respectively; $p < 0.05$). While pre- and post-PHV EXP exhibited significant increases in relative braking impulse ($g = 0.36$ and 0.53, respectively; $p < 0.05$), only post-PHV EXP exhibited significant increases in relative propulsive impulse ($g = 0.63$; $p < 0.05$). Pre- and post-PHV EXP groups exhibited trivial to moderate changes in relative braking (diff. $g = 0.23$ and 0.39, respectively) and relative propulsive impulse (diff. $g = 0.06$ and 0.90, respectively), relative to their CON counterparts. The post-PHV EXP exhibited significantly greater changes than pre-PHV EXP and CON for absolute net impulse ($p < 0.05$), and significantly greater changes in absolute and relative propulsive impulse compared post-PHV CON as well as pre-PHV EXP and CON ($p < 0.05$). The post-PHV EXP also exhibited significantly greater changes in relative braking impulse compared to pre-PHV CON ($p < 0.05$). The post-PHV CON showed no significant changes from baseline to post-intervention for any of the impulse variables ($p > 0.05$).

6.3.4 Work Rate Variables

Analysis revealed relative mean braking and propulsive power as the only normally distributed work rate variables. The post-PHV EXP group exhibited significant increases in absolute mean braking and propulsive power ($r = 0.89$ and 0.89, respectively; $p < 0.05$), absolute braking and propulsive work done ($r = 0.89$ and 0.89, respectively; $p < 0.05$), and relative mean braking and propulsive power ($g = 0.78$ and 0.63, respectively; $p < 0.05$). The pre-PHV EXP showed significant increases for braking work done ($r = 0.57$; $p = 0.05$), while pre-PHV CON showed significant increases for absolute mean propulsive power ($r = 0.66$; $p < 0.05$). The post-PHV EXP exhibited significantly greater changes for absolute mean braking and propulsive power, as well as propulsive work done compared to pre-PHV EXP and pre-PHV CON ($p < 0.05$). The post-PHV EXP also exhibited significantly greater changes than post-PHV CON for propulsive work done ($p < 0.05$), and significantly greater changes in relative mean braking and propulsive power compared to pre-PHV EXP ($p < 0.05$). The pre- and post-PHV EXP groups exhibited trivial to moderate changes relative to pre- and post-PHV CON for relative mean braking (diff. $g = 0.24$ and 0.73, respectively) and propulsive power (diff. $g = 0.18$ and 0.61, respectively). The post-PHV CON showed no significant changes from baseline to post-intervention for any work rate variables.

6.3.5 Landing Strategy Variables

Braking and propulsive phase durations were the only movement strategy variables that were deemed as normally distributed. Significant increases in peak COM displacement, as well as mean braking and propulsive COM velocity were observed in pre- ($r = 0.57$, 0.70 and 0.54, respectively; $p < 0.05$) and post-PHV EXP ($r = 0.89$, 0.89 and 0.89, respectively; $p < 0.05$). The pre- and post-PHV CON also showed significant increases in mean braking ($r = 0.78$ and 0.69, respectively; $p < 0.05$) and propulsive COM velocity ($r = 0.78$ and 0.84, respectively; $p < 0.05$). While no significant within or between group difference in change from baseline to post-intervention was observed for the braking and propulsive durations, pre- and post-PHV EXP exhibited trivial to small changes in braking phase (diff. $g = 0.30$ and 0.09, respectively) and propulsive phase durations (diff. $g = 0.08$ and 0.28, respectively) relative to their CON counterparts. While the post-PHV EXP exhibited a significantly greater change in propulsive

COM velocity compared to both pre-PHV EXP and CON ($p < 0.05$), they only showed a significantly greater change in braking COM velocity compared to pre-PHV EXP ($p < 0.05$)

6.4 DISCUSSION

The aim of the current study was to examine the development of DJ kinetics in pre- and post-PHV male youth in response to a 12-week, combined strength and plyometric resistance training programme. The hypothesis was partially accepted with only the post-PHV EXP group displaying improvements in most DJ kinetics in response to the 12-week training intervention, while the post-PHV CON as well as pre-PHV EXP and CON showed no significant changes from baseline to post-intervention for most variables. The main findings of the current study were that the post-PHV EXP group exhibited large significant improvements in mean braking and propulsive force, absolute and relative propulsive peak force, all absolute and relative impulse measures, absolute and relative power measures, absolute work done, as well as peak COM displacement and COM velocity, which resulted in small to moderate significant improvements in jump height and RSI. The pre-PHV EXP exhibited moderate significant increases in absolute and relative net and braking impulse, absolute braking work done, peak COM displacement and COM velocity, resulting in small increases in jump height, with no change in RSI. The post-PHV EXP showed significantly greater changes from baseline to post-intervention for absolute and relative propulsive impulse and absolute propulsive work done compared to the post-PHV CON. The post-PHV EXP also exhibited significantly greater changes compared to the pre-PHV EXP for jump height, absolute net impulse, absolute and relative propulsive impulse, absolute and relative mean braking and propulsive power, absolute propulsive work done, as well as braking and propulsive COM velocity.

The increases in jump height and RSI during a DJ observed in the post-PHV EXP following the training intervention are in agreement with previous research examining the effect of training on vertical and rebound jumping (Chelly et al., 2009; Lloyd et al., 2012c; Lloyd et al., 2016; Matavulj et al., 2001; McKinlay et al., 2018; Uzelac-Sciran et al., 2020). Jump height is underpinned by the preceding impulse (Kirby et al., 2011; Ruddock and Winter, 2015) and hence is strongly influenced by an individual's force producing capabilities (Bobbert et al., 1987b; van Ingen Schenau et al., 1997b). The improved performance in the post-PHV cohort could be attributed to the significant, large increases in absolute and relative net impulse, propulsive impulse and propulsive power following the intervention. Increases in impulse have a positive effect on take-off velocity, and jump height is principally dependent on this take-off velocity (Winter, 2005). Strength training elicits improvements in an individual's force producing capabilities (Cormie et al., 2011b) which would positively influence impulse. While these improvements tend to be in slow-speed strength and over longer time periods compared to DJs (Ball et al., 2010; Hedrick, 1993), the exposure to high-velocity movements such as plyometrics elicits adaptations allowing for the transfer of these augmented force producing capabilities to performance of high-velocity rebound based activities such DJs. (Cronin et al., 2002; McBride et al., 2002). The force producing capabilities of an individual are strongly influenced by muscle cross-sectional area (Cormie et al., 2011a; Radnor et al., 2021) and neural mechanisms such as muscle activation strategies and motor unit synchronisation (Cormie et al., 2011a). Although research examining training-related mechanistic changes in youth is scarce, strength training been evidenced to elicit increases in muscle cross-sectional area (Fukunaga and Funato, 1992), with plyometric training being suggested to elicit improvements in neural mechanisms such as motor unit recruitment and reflex excitability (Markovic and Mikulic, 2010; Ramsay et al., 1990). The findings from the current study would suggest that improvements exhibited by the post-PHV boys could be specific to the combined strength and plyometric training intervention, attributable to the process of synergistic adaptation.

Although muscle mass influences an individual's ability to produce force and power (Cormie et al., 2011a), the improved relative mean propulsive power observed in the post-PHV EXP suggests that power production might be underpinned by factors other than just muscle mass. Factors such as fascicle length have been suggested to allow muscles to remain close to optimal length for force production, implying greater force at longer lengths (Baroni et al., 2013). It has been suggested that natural changes in muscle thickness and fascicle length occur during and after puberty (Radnor et al., 2021), which could explain greater improvements being observed in post-PHV EXP. An increase in fascicle length allows the muscle to operate more effectively over a greater range of motion (Guex et al., 2016), thereby strongly influencing jump performance (Radnor et al., 2021). Additionally, improved muscle activation strategies have also been suggested to positively influence power production (Cormie et al., 2011a). Although there is limited evidence in youth, resistance training has been evidenced to elicit increases in fascicle length (Alegre et al., 2006; Blazevich et al., 2003; Vogt and Hoppeler, 2014) and improve motor unit recruitment strategies (Aagaard, 2003; Carroll et al., 2001) in adults. Another aspect to be considered is power being the product of force and velocity, the increased mean propulsive COM velocity would also underpin enhancements in absolute and relative mean propulsive power exhibited by the post-PHV EXP following the intervention.

The braking phase of the SSC action is suggested to strongly influence performance in the propulsive phase (Bosco et al., 1987; Komi, 2000). The current study observed increases in braking impulse, as well as absolute and relative mean braking power from baseline to post-intervention in the post-PHV EXP, attributable to the increase in braking forces and COM velocity. Prior research has associated increased braking forces during DJs with an increase in ground contact time (Ball et al., 2010) owing to the greater stretch loads elicited (Bobbert et al., 1987a; Komi and Gollhofer, 1997). However, no significant changes in ground contact time were observed for the post-PHV EXP. Interestingly, the post-PHV EXP appear to attenuate the increased braking forces with a greater braking COM displacement at an increased velocity, rather than increased ground contact times. The greater COM displacement positively influences the propulsive performance by allowing for the development of force over a greater distance (Hunter and Marshall, 2002). Additionally, the increased COM displacement could suggest a greater pre-stretch which has been linked to allowing the muscles to develop a higher active state and build a greater force output prior to the concentric contraction (van Ingen Schenau et al., 1997a). The increased mean braking COM velocity, typical of a faster pre-stretch, has been suggested to enhance the mechanical output (Edman et al., 1978). Additionally, an increase in greater negative work done, might suggest the storage of greater amounts of elastic energy at post-intervention (McCaulley et al., 2007).

Unlike previous studies which have reported increases in jump height and RSI in children following a training intervention (Lloyd et al., 2012c; Lloyd et al., 2016; Radnor et al., 2017; Uzelac-Sciran et al., 2020), the current study only observed a small significant increase in jump height for the pre-PHV EXP, with no change in RSI. This improved jump height exhibited by the pre-PHV EXP can be explained by the increased absolute and relative net impulse and mean propulsive COM velocity following the training intervention. It is suggested that the success of vertical jumping is underpinned by the velocity of vertical take-off, which is strongly influenced by the preceding net impulse (Ruddock and Winter, 2015). Although the lack of significant change in mean and peak force measures suggests that the training intervention failed to improve the force producing capabilities of the pre-PHV EXP, the improved impulse could potentially be explained by the non-significant increase in ground contact time, since impulse is the product of force and time. This lack of improvement in force producing capabilities could be attributed to children developmentally experiencing limited morphological changes that facilitate force generation (Tumkur Anil Kumar et al., 2021). While the lack of change in RSI is unlike the findings of prior research (Lloyd et al., 2012c;

Lloyd et al., 2016; Radnor et al., 2017; Uzelac-Sciran et al., 2020), it is important to note that these studies utilised self-regulated maximal hopping and repeated rebound jumps, rather than the DJ used in the current study. During maximal hopping the height is self-regulated, which might allow participants more room to manipulate ground contact time. In drop jumps however, the drop height being fixed might make it comparatively harder to elicit improvements in ground contact time from training. Although the pre-PHV EXP exhibited a small significant increase in jump height, they also exhibited an increase in ground contact time, albeit non-significant, which might have resulted in non-significant changes in RSI (given that RSI is the ratio of jump height and ground contact time).

While prior research has shown that children respond positively to plyometric training (Lloyd et al., 2016; Peitz et al., 2018), the large braking forces in the DJ and high speed braking action accompanied by a short delay between peak velocity of the braking phase and the start of propulsive phase (Bobbert et al., 1987b; Bobbert et al., 1986), makes the nature of DJ training unique. Both the pre-and post-PHV EXP were introduced to higher intensity plyometric training towards the latter part of the programme and only once a week, leaving participants with reduced exposure to that specific stimulus. It has been suggested that adaptations are specific to the nature of the stimulus (Vissing et al., 2008), and that longer exposure to training (> 23 sessions) with appropriate stimulus is required to elicit improvements in leg power, sprint abilities and sport-relevant tasks (Faude et al., 2017). Plyometric training has previously been evidenced to improve SSC function (Lloyd et al., 2012c) and spring-like behaviour (Otsuka et al., 2018), with improved SSC function being suggested to result in an enhanced force producing capability at the start of the propulsive phase (Turner and Jeffreys, 2010). While the training programme was designed to holistically develop athleticism as advocated by the LTAD guidelines, participants may have required greater and more concentrated dosage of DJ training to realise further gains in spring-like correlation. The post-PHV EXP's improvement in performance and DJ kinetics despite the suggested reduced exposure to DJs may be attributed to their increased force producing capabilities. Further research is required to examine the effect that greater and more concentrated exposure to DJ training might have on pre- and post-PHV boys.

6.5 LIMITATIONS

Although the current study was the first to examine the effect of resistance training on the DJ kinetics in male youth, certain limitations also need to be considered. While one of the methodological limitations of the current study includes the small sample size. While small sample sizes are suggested to make it difficult to determine if a certain outcome is a true finding, the use of effect sizes when reporting the results in the current study allows for better interpretation rather than solely relying on statistical significance. Although optimal drop height varies based on the individual's capabilities, prior research has suggested drop heights between 20 cm to 40 cm for drop jumps in youth (Birat et al., 2020). While Bassa et al. (2012) did not specify an optimal drop height, the authors did suggest low drop heights for children. Based on this, it could be speculated that the drop height of 30 cm utilised within the current study might have exceeded the capabilities of the pre-PHV boys, hence not allowing their training-related development to be reflected. Although some of the exercises prescribed to the pre- and post-PHV boys varied, this was based on the selection of maturity appropriate exercises with the same movement patterns being targeted for both groups across the programme. Additionally, although the first four weeks of the training intervention primarily addressed skill development, this was needed to ensure training competency was developed. Despite this, the current study provides novel information regarding the maturity status-related development of SSC function, assessed via DJ kinetics, following combined resistance training in youth.

6.6 CONCLUSIONS

The aim of the current study was to examine the development of DJ kinetics in pre- and post-PHV male youth in response to a 12-week combined strength and plyometric resistance training programme. The main finding of the current study was that the post-PHV EXP group exhibited larger training-related improvements compared to pre-PHV. The novel findings of the study highlight the large improvements in mean and peak forces, impulse measures, measures of power and work done, as well as COM velocity which underpin the small to moderate increases in jump height and RSI exhibited by the post-PHV EXP group following the training intervention. In accordance with prior research examining the effect of a combined strength and plyometric training programme on pre- and post-PHV youth, the post-PHV EXP exhibited greater improvements compared to the pre-PHV EXP (Lloyd et al., 2016; Peitz et al., 2018). The findings suggest that post-PHV boys respond better than pre-PHV boys to a combined strength and plyometric training programme, with this being attributable to the process of synergistic adaptation. Although the intervention resulted in small improvements in jump height for the pre-PHV EXP, it failed to elicit significant changes in most of the DJ kinetics, potentially due to insufficient exposure to an appropriate stimulus. Longer and more concentrated exposure to specific DJ training might be required to elicit adaptations in DJ kinetics in pre-PHV boys. Further research is needed to examine the effects of such longer duration interventions on DJ kinetics of pre- and post-PHV boys.

Chapter 7 Prelude

Chapter 6 highlighted that post-PHV boys respond better than pre-PHV boys to a short-term combined strength and plyometric programme. While the post-PHV boys exhibited large improvements in most of the drop jump kinetic variables underpinning small to moderate increases in jump height and RSI in response to training, the pre-PHV boys exhibited no significant changes in most of the kinetic variables resulting in small significant increases in jump height with no changes in RSI. However, it is currently unclear how boys would respond to a longer training intervention and how neuromuscular training vs a combination of neuromuscular and traditional resistance training would affect the development of drop jump kinetics. *Chapter 7* sought to examine the effect of resistance training dosage on the drop jump kinetics during a long-term combined strength and plyometric training intervention in youth.

Chapter 7 – Effects of Resistance Training Dosage During a 6-Month Combined Strength and Plyometric Training Programme on Drop Jump Kinetics in Young Male Athletes

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7.1 INTRODUCTION

Research has consistently reported that resistance training in youth improves performance of various sport-based movements such as running velocities (Chelly et al., 2015; Lloyd et al., 2016), sprint times (Meylan and Malatesta, 2009; Uzelac-Sciran et al., 2020) and vertical jump height (Chelly et al., 2009; Chelly et al., 2015; Lloyd et al., 2016; Matavulj et al., 2001; Uzelac-Sciran et al., 2020). Similarly, the findings of *Chapter 6* highlight the positive effects that resistance training has on drop jump (DJ) kinetics in male youth. The duration of the interventions in these studies were between six to 12 weeks, and although such short-term interventions have been shown to elicit significant changes in youth, a review by Lesinski et al. (2016) suggested that long-term (>23 weeks) interventions might allow youth across a spectrum of maturity status to make more meaningful changes. Longer interventions are more likely to provide sufficient exposure to the appropriate stimulus, thereby eliciting greater changes in leg power, sprint abilities and sport-relevant tasks (Faude et al., 2017). Research examining such long-term interventions in youth are scarce, with existing long-term studies primarily examining improvements in strength (Keiner et al., 2013; Sander et al., 2013), sprint times (Keiner et al., 2014b; Sander et al., 2013), change of direction speed (Keiner et al., 2014b), and countermovement jump height (Ferrete et al., 2014). While Keiner et al. (2018) highlighted the positive effects of long-term strength training in youth on measures of jump height and RSI during a DJ, the influence of a long-term training intervention on kinetic measures collected during the braking and propulsive phases of the DJ are unknown.

When considering the dose-response relationship of resistance training in youth, Lesinski et al. (2016) reported that in addition to implementing long-term training interventions, training twice a week, with multiple sets at intensitites of 80-89% of 1RM would be most beneficial for improving muscle strength. Training twice weekly has been suggested to elicit greater gains in muscle strength in young athletes compared with training only once per week (Behm et al., 2008; Lesinski et al., 2016; Stricker et al., 2020). However, it is important for researchers to acknowledge that gym-based facilities are not always accessible within some youth sport settings, making field-based neuromuscular training more achievable. Literature within paediatric strength and conditioning comparing the effects of what is most achievable (i.e., field-based neuromuscular training) vs what is desirable (i.e., gym-based traditional resistance training) is scarce. Therefore, the aim of the current study was to examine the effect of neuromuscular training vs neuromuscular and traditional resistance training on DJ kinetics in male youth, during a combined 6-month resistance training intervention. It was hypothesised that both training groups would exhibit greater improvements in the DJ kinetics than the CON. Additionally, the magnitude of improvement exhibited by the group performing neuromuscular and traditional resistance training for most kinetic variables was expected to be greater than the purely neuromuscular training group.

7.2 METHODS

7.2.1 Participants

Participants included 82 young male athletes aged 9-17 years, from a sports academy in the United Kingdom. Participants were assigned to either EXP (n = 60) or control (CON; n = 22) groups based on their location and ability to attend the sessions. The participants in the EXP group were randomly assigned to either a neuromuscular and traditional resistance training (EXPII; *n* = 28) or a neuromuscular training (EXPI; *n* = 32) group. Descriptive statistics for the EXPII, EXPI and CON groups can be found in *table 7.1*, with no significant differences between any of the groups. Participants reported no injuries at baseline testing, during the intervention or during post-intervention testing and were informed of the risks and benefits of taking part in the study. Prior to the intervention the EXP groups were provided with a 4-week long, general neuromuscular training programme but had no previous experience with strength and conditioning. Parents and participants were informed that participation in the study was completely voluntary, and that they could withdraw from the study at any point of time. Informed parental consent and participant assent were obtained, and physical readiness questionnaires completed after ethical approval was granted by the University Research Ethics Committee for the study.

Table 7.1 Mean (± SD) values for descriptive details of each maturity group's anthropometric data.

Group	N	Standing height(cm)	Mass(kg)	Age(years)	Maturity offset (years from phv)
EXPII	28	150.5 ± 8.9	42.6 ± 10.6	11.91 ± 1.28	-1.74 ± 1.09
EXPI	32	152.0 ± 11.6	46.2 ± 10.7	12.29 ± 1.39	-1.46 ± 1.20
CON	22	152.5 ± 13.8	45.6 ± 13.2	11.77 ± 1.63	-1.64 ± 1.47

PHV = peak height velocity; EXPII – twice weekly; EXPI – once weekly; CON – control.

7.2.2 Procedures

7.2.2.1 Anthropometrics

Anthropometrics and maturity status were assessed using the same method as Chapter 4 (refer to section 4.2.2.1).

7.2.2.2 Drop Jump Assessment

Drop Jump was assessed using the same procedures as Chapter 4 (refer to section 4.2.2.2).

7.2.2.3 Training Intervention

Following baseline testing, the EXPII and EXPI groups commenced their respective 6-month training interventions. The 6-month neuromuscular training programme was divided into 3 x 8-week training blocks for the EXPII and EXPI groups (*figure 7.1*). The EXPII group received twice weekly training which included a 60-minute field based neuromuscular training session and a 60-minute gym-based resistance training session. The EXPI group only received the field-based neuromuscular training sessions. Both field- and gym-based sessions utilised various forms of resistance including: body weight, resistance bands, medicine balls, kettlebells and dumbbells. All training sessions for the EXPII and EXPI groups were led and supervised by a National Strength and Conditioning Association Certified Strength and Conditioning Specialist. To be included in final analyses, all participants needed to attend ≥75% of the total training sessions.

Both field- and gym-based training sessions followed a similar structure, consisting of a 10-minute warmup followed by 50 minutes of a variety of neuromuscular training exercises. Exercises were similar across both sessions using a variety of fundamental and multi-joint dynamic movements such as squatting, hinging, pushing, pulling, jumping and landing which targeted lower and upper body strength and power development (Radnor et al., 2020a).

Participants were familiarized with each exercise within the programme and performed at least one warm up set for each given exercise. Technical proficiency was of high priority during the field- and gym-based sessions and additional load was never increased at the expense of technical execution. If technique was not displayed to a satisfactory standard during a set and relevant cueing failed to remedy the technical error, participants ceased the set and were instructed to decrease load. When participants displayed optimal technique consistently through the prescribed number of sets, they were instructed to increase load by ~5% the following week (Ratamess et al., 2009).

7.2.2.4 Periodised Programme

Each 8-week block was sub-divided into two mesocycles, and in bock one the first mesocycle primarily focused on developing technical competency and a range of motor skills. Sets and repetitions were increased during the second mesocycle, provided the participants exhibited satisfactory competence in the exercises. While sessions consisted primarily of multi-jointed dynamic exercises with relatively low load, participants were also given some exposure to higher-velocity movements with lower volumes. The second training block aimed to develop muscle strength and participants were instructed to appropriately increase loading, with technical competency still being prioritised (Ratamess et al., 2009). The focus of the plyometric exercises was on developing SSC capabilities through the prescription of bilateral multiple rebounding and multi-directional jumps. The goal of the final training block was to develop a high rate of force production, while continuing to maintain strength gains from the previous block. Training loads were increased appropriately and coupled with a gradual reduction in training volume. The focus of the plyometric exercises was to develop reactive strength qualities through a combination of unilateral and bilateral plyometric exercises.

<table>
<tr><th colspan="31">6 - MONTH TRAINING INTERVENTION OVERVIEW</th></tr>
<tr><td colspan="2">Week No</td><td>0</td><td>1</td><td>2</td><td>3</td><td>4</td><td>5</td><td>6</td><td>7</td><td>8</td><td>9</td><td>10</td><td>11</td><td>12</td><td>13</td><td>14</td><td>15</td><td>16</td><td>17</td><td>18</td><td>19</td><td>20</td><td>21</td><td>22</td><td>23</td><td>24</td><td>25</td><td>26</td><td>27</td><td>28</td></tr>
<tr><td colspan="2">School Holidays</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td colspan="2" rowspan="12">Christmas Break</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td rowspan="12">Easter</td><td></td><td></td><td></td></tr>
<tr><td colspan="2">Scheduled Testing</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td colspan="2">Training Blocks</td><td rowspan="10"></td><td colspan="8">Block 1</td><td colspan="8">Block 2</td><td colspan="6">Block 3 A</td><td colspan="2">Block 3 B</td><td rowspan="10"></td></tr>
<tr><td colspan="2">Mesocycle Focus</td><td colspan="8">Movement Development</td><td colspan="8">Strength</td><td colspan="6">Explosive Strength / Power</td><td colspan="2">continued</td></tr>
<tr><td colspan="2">Gym Based Resistance Training</td><td colspan="8">Introduction to fundamental athletic motor skill competencies. Teaching correct exercise technique and assessing movement deficits.</td><td colspan="8">Large focus on developing a strenth base; increasing volume for upper and lower body multi-joint exercises. Gradually increasing intensity by increasing load and decreasing rep-ranges throughout the training block to continuously challenge participants. Develop core-strength through exercises challenging antio-rotation, anti-extension and anti-flexion.</td><td colspan="6">Emphasis on increasding intensity through low-load and high-velocity movements to develop power while maintaining technique. Power based exercises included loaded squat jumps and drop jumps, while also maintaining strength gains from previous block.</td><td colspan="2">continued</td></tr>
<tr><td colspan="2">Set x Rep Ranges</td><td colspan="4">3 x 12-15</td><td colspan="4">4 x 12-15</td><td colspan="4">4 x 8-10</td><td colspan="4">4 x 5-8</td><td colspan="4">4 x 5</td><td colspan="2">4 x 3-5</td><td colspan="2">4 x 3-5</td></tr>
<tr><td colspan="2">Rest Periods</td><td colspan="8">< 90 seconds</td><td colspan="8">90 - 120 seconds</td><td colspan="6">2 minutes</td><td colspan="2">2 minutes</td></tr>
<tr><td colspan="2">Mesocycle Focus</td><td colspan="8">Movement Development</td><td colspan="8">Multi-directional Movements</td><td colspan="6">High Velocity Movement</td><td colspan="2">continued</td></tr>
<tr><td colspan="2">Field Based Training</td><td colspan="8">Introduce basic plyometric exercises and teach safe landing technique. Game-based activities for change of direction and agility. Observe and assess participants display of fundamental athletic motor skill competencies.</td><td colspan="8">Reinforce proper exercise technique from the previous training block while prescribing multidirectional drills to further develop stretch shortening cycle function. Perform similar upper, lower and core exercises as in the gym-based sessions but using resistance bands, kettlebells and medicine balls.</td><td colspan="6">Continue to address power development by introducing more advanced plyomertics such as unilateral and continuous jumps. Perform high-velocity loaded movements such as roational, vertical and overhead medicine ball throws. Ongoing mantenance of strength in multi-joint compoung exercises.</td><td colspan="2">continued</td></tr>
<tr><td rowspan="2">Set x Rep Ranges</td><td>Plyometric</td><td colspan="4">3 x 5</td><td colspan="4">4 x 5</td><td colspan="8">4 x 3-5</td><td colspan="6">4 x 3-5</td><td colspan="2">4 x 3-5</td></tr>
<tr><td>Resistance Training</td><td colspan="4">3 x 12-15</td><td colspan="4">4 x 12-15</td><td colspan="8">4 x 12-15</td><td colspan="6">4 x 12-15</td><td colspan="2">4 x 12-15</td></tr>
<tr><td colspan="2">Rest Periods</td><td colspan="8">< 90 seconds</td><td colspan="8">90 - 120 seconds</td><td colspan="6">2 minutes</td><td colspan="2">2 minutes</td></tr>
</table>

Figure 7.1 Overview of the 6-month training intervention for the gym-based and field-based training sessions.

7.2.2.4 Field-based Neuromuscular Training Sessions

The EXPII and EXPI group completed the same field-based neuromuscular training sessions once per week, which primarily consisted of plyometric and high-velocity, low-load exercises. Due to restricted equipment, the source of resistance for some exercises within the field-based sessions varied from the gym-based exercises (use of high velocity jumps, or utilising dumbbells and kettlebells instead of a barbell).

7.2.2.5 Gym-based Traditional Resistance Training Sessions

The gym-based traditional resistance training sessions were completed once per week by only the EXPII group. The foci of these sessions were to target movement competency and develop muscular strength using multi-joint exercises. Compared to the field-based training, the gym-based sessions consisted of higher-load and lower-velocity resistance training due to access to more equipment such as barbells and greater external loading. Each workout incorporated at least two lower body and two upper body strength development exercises in addition to a core bracing stabilization exercise.

7.2.3 Statistical Analyses

Normal distribution of data was assessed using the Shapiro-Wilk test. Descriptive statistics (means ± *SD*) were calculated for the normally distributed variables for each group at both baseline and post-intervention testing sessions. Paired sample t-tests were used to examine statistical differences within each group from baseline to post-intervention. Cohen's *d* effect sizes were calculated to determine the magnitude of within-group differences that were observed (Cohen, 2013) and were categorised as trivial: < 0.19; small: 0.20 - 0.59; moderate: 0.60 - 1.19; large: 1.20 - 1.99: very large: 2.00 – 3.99; and very large: > 4.00 (Hopkins et al., 2009). Separate one-way analysis of variance (ANOVA) tests were then employed to examine significant differences in the change from baseline to post-intervention between the groups

(EXPII vs EXPI, EXPII vs CON, and EXPI vs CON), and when significance was observed, post-hoc analyses was carried out using a Bonferroni test. Finally, the magnitude of change from baseline to post-intervention in the training groups relative to each other and the change in the control group was calculated (diff. *g*). Hedge's *g* was calculated to interpret this magnitude of relative difference in change using the following thresholds trivial: <0.20; small: 0.20 – 0.59; moderate: 0.60 – 1.19; large: 1.20- 1.69; and very large: > 1.70 (Sullivan and Feinn, 2012).

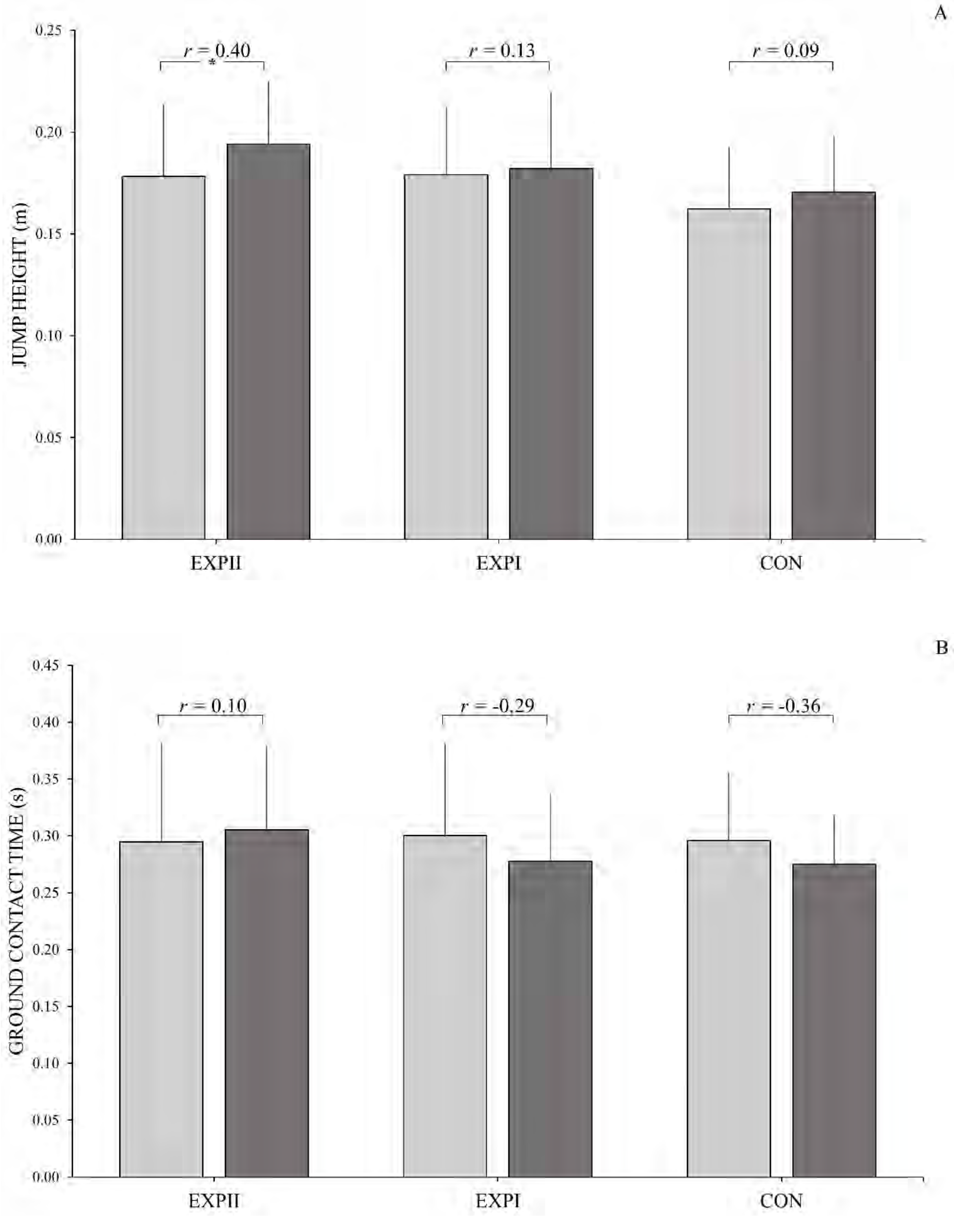
For the variables that were deemed as non-parametric, median scores were reported. To mirror the approach adopted for the normally distributed variables, Wilcoxon signed ranks tests were used to examine statistical differences within-group from baseline to post-intervention. Wilcoxon *r* effect sizes were subsequently reported and categorised as small: 0.10-0.29; moderate: 0.30-0.49; and large: > 0.50 (Fritz et al., 2012). Kruskal Wallis H-test was used to examine differences in the change from baseline to post-intervention between the three groups (EXPII vs EXPI, EXPII vs CON, and EXPI vs CON), and when significance was observed a post-hoc analyses was carried out using a Bonferroni test.

7.3 RESULTS

7.3.1 Within and Between Group Differences

7.3.1.1 Drop Jump Performance Variables

Analysis revealed all the DJ performance variables as non-parametric. Although EXPII was the only group to exhibit small significant increases in jump height from baseline to post-intervention ($r = 0.40$; $p < 0.05$; *figure 7.2*), no significant between group differences were observed for the changes from baseline to post-intervention ($p > 0.05$). No significant within or between group differences were observed for ground contact time and RSI in the EXPII, EXPI or CON groups ($p > 0.05$).


A
0.25
0.20
0.15
0.10
0.05
0.00
JUMP HEIGHT (m)
r = 0.40
*
r = 0.13
r = 0.09
EXPII
EXPI
CON
B
0.45
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
GROUND CONTACT TIME (s)
r = 0.10
r = -0.29
r = -0.36
EXPII
EXPI
CON

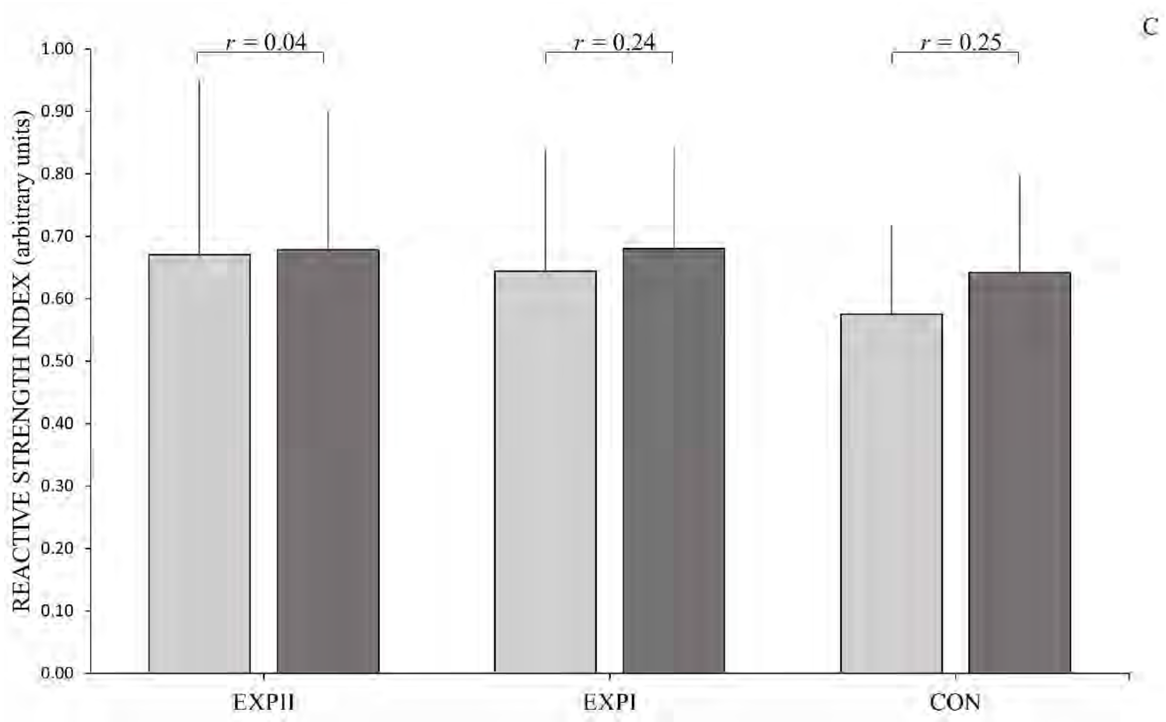


Figure 7.2 Effect of training intervention on (a) jump height, (b) ground contact time, and (c) reactive strength index.

r = Wilcoxon *r* within-group effect size for non-parametric data.

* significant difference from baseline to post-intervention ($p < 0.05$).

7.3.1.2 Force Variables

Relative braking peak force was the only force variable found to be normally distributed. Moderate to large significant increases in mean propulsive force, propulsive peak force and force at peak COM displacement were observed in EXPI ($r = 0.59$, 0.41 and 0.46, respectively; $p < 0.05$; *table 7.2*) and CON ($r = 0.54$, 0.42 and 0.51, respectively; $p < 0.05$; *table 7.2*). However, there were no significant differences between any groups for the change from baseline to post-intervention in mean propulsive force, propulsive peak force and force at peak COM displacement ($p > 0.05$). EXPI was the only group that exhibited a significant increase in mean braking force ($r = 0.41$; $p < 0.05$; *table 7.2*). The EXPII showed no significant changes from baseline to post-intervention in any of the absolute or relative peak force variables ($p >$

0.05; *table 7.2*). While no significant within or between group differences were observed from baseline to post-intervention for relative braking peak ($p > 0.05$), trivial relative changes were observed for EXPII vs EXPI, EXPII vs CON and EXPI vs CON (diff. $g = \leq 0.08$).

7.3.1.3 Impulse Variables

All the impulse variables being examined were deemed non-parametric. While the EXPII exhibited moderate to large significant increases in absolute net, braking and propulsive impulse ($r = 0.61$, 0.39 and 0.60, respectively; $p < 0.05$; *table 7.2*), EXPI exhibited a moderate significant decrease in relative propulsive impulse ($r = 0.39$; $p < 0.05$; *table 7.2*). While significantly greater changes for propulsive impulse were observed in EXPII compared to EXPI and CON ($p < 0.05$), EXPII exhibited significantly greater changes in relative propulsive impulse compared to EXPI ($p < 0.05$). The CON group showed no significant changes from baseline to post-intervention for any of the absolute or relative impulse variables ($p > 0.05$; *table 7.2*).

7.3.1.5 Work Rate Variables

Relative mean propulsive power was the only work rate variable found to be normally distributed. EXPII was the only group to show significant moderate to large increases from baseline to post-intervention for braking and propulsive work done ($r = 0.39$ and 0.60, respectively; $p < 0.05$; *table 7.2*). EXPII exhibited a significantly greater change from baseline to post-intervention for propulsive work done compared to EXPI ($p < 0.05$). While there no significant within or between group changes from baseline to post-intervention for relative mean propulsive power ($p > 0.05$; *table 7.2*), trivial to small relative changes were observed for EXPII vs EXPI, EXPII vs CON and EXPI vs CON (diff. $g \leq 0.21$). No significant changes were observed in EXPI or CON for any of the absolute or relative work rate variables ($p > 0.05$; *table 7.2*).

7.3.1.6 Landing Strategy Variables

Mean braking COM velocity was the only movement strategy variable found to be normally distributed. While EXPI exhibited a significant moderate decrease in the duration of the propulsive phase, they exhibited a significant moderate increase in spring-like correlation and absolute stiffness ($r = 0.35$, 0.45 and 0.47, respectively; $p < 0.05$; *table 7.2*). CON exhibited a significant moderate to large increase in absolute and relative stiffness ($r = 0.51$ and 0.42, respectively; $p < 0.05$; *table 7.2*). While there were no significant differences between groups in change from baseline to post-intervention for mean braking COM velocity ($p > 0.05$), trivial to small relative changes were observed for EXPII vs EXPI, EXPII vs CON and EXPI vs CON (diff. $g = 0.39$, 0.27 and 0.12, respectively). Although the EXPII showed no significant changes from baseline to post-intervention for any movement strategy variables ($p > 0.05$; *table 7.2*), no significant differences were observed between groups for changes from baseline to post-intervention ($p > 0.05$).

Table 7.2 Group means (± std dev) and medians for the kinetic variables with effect sizes for change from baseline to post-intervention.

Variables	EXPII			EXPI			CON		
	Baseline	Post	ES	Baseline	Post	ES	Baseline	Post	ES
Force Variables									
Mean Braking Force (N)	1109.1	1207.6	*r* = 0.18	1138.2	1288.0*	*r* = 0.41	1060.4	1177.6	*r* = 0.40
Braking Peak Force (N)	1796.6	1960.8	*r* = 0.03	2064.8	2060. 3	*r* = -0.05	2005.2	1915.1	*r* = -0.04
R Braking Peak Force (N/Kg$^{0.91}$)	64.8 ± 19.4	61.5 ± 10.8	*g* = -0.21	66.5 ± 14.3	63.0 ± 9.8	*g* = -0.26	63.1 ± 13.8	60.8 ± 7.5	*g* = -0.22
Mean Propulsive Force (N)	941.9	947.9	*r* = 0.13	957.7	999.2*	*r* = 0.59	889.8	930.1*	*r* = 0.54
Propulsive Peak Force (N)	1479.5	1490.7	*r* = 0.02	1479.7	1586.7*	*r* = 0.41	1294.9	1410.2*	*r* = 0.42
R Propulsive Peak Force (N/Kg$^{0.98}$)	38.1	34.4	*r* = -0.16	34.2	35.6	*r* = 0.14	33.7	35.8	*r* = 0.23
Force at Peak COMD (N)	1423.9	1454.5	*r* = 0.21	1411.8	1548.1*	*r* = 0.46	1287.9	1372.8*	*r* = 0.51
R Force at Peak COMD (N/Kg$^{0.98}$)	35.7	33.8	*r* = -0.04	32.2	34.4	*r* = 0.20	32.1	34.6	*r* = 0.40
Braking RFD (KN/s)	90.8	89.4	*r* = -0.08	91.3	93.8	*r* = 0.11	89.5	70.0	*r* = -0.02
Impulse Variables									
Net Impulse (N.s)	160.6	173.4*	*r* = 0.61	172.0	178.3	*r* = 0.26	151.3	153.6	*r* = 0.17
R Net Impulse (N.s/Kg$^{0.946}$)	4.89	4.92	*r* = 0.21	4.83	4.66	*r* = -0.22	4.60	4.61	*r* = 0.02

Braking Impulse (N.s)	131.7	141.7*	*r* = 0.39	156.1	150.6	*r* = -0.08	134.2	133.4	*r* = -0.01
R Braking Impulse (N.s/Kg$^{0.96}$)	3.58	3.74	*r* = 0.06	3.66	3.51	*r* = -0.28	3.56	3.54	*r* = -0.40
Propulsive Impulse (N.s)	147.2	162.3*	*r* = 0.60	171.3	170.4	*r* = -0.08	144.6	149.1	*r* = 0.04
R Propulsive Impulse (N.s/Kg$^{0.98}$)	3.62	3.84	*r* = 0.21	3.78	3.60*	*r* = -0.39	3.71	3.55	*r* = -0.20
Work Rate Variables									
Mean Braking Power (W)	1171.8	1281.5	*r* = 0.21	1205.3	1267.9	*r* = 0.19	1103.3	1160.4	*r* = 0.24
R Mean Braking Power (W/Kg$^{0.90}$)	41.8	39.7	*r* = -0.05	39.3	37.8	*r* = -0.01	37.9	38.1	*r* = 0.07
Mean Propulsive Power (W)	1143.8	1200.6	*r* = 0.27	1124.2	1158.6	*r* = 0.26	1044.6	1061.3	*r* = 0.28
R Mean Propulsive Power (W/Kg$^{0.93}$)	33.3 ± 7.7	33.3 ± 5.4	*g* = 0.00	33.1 ± 6.1	32.8 ± 4.4	*g* = -0.05	31.5 ± 5.7	32.6 ± 4.4	*g* = 0.19
Braking Work Done (KJ)	131.7	141.7*	*r* = 0.39	156.1	150.6	*r* = -0.08	134.2	133.4	*r* = -0.01
Propulsive Work Done (KJ)	147.2	162.3*	*r* = 0.60	171.3	170.4	*r* = -0.08	144.6	149.1	*r* = 0.04
Landing Strategy Variables									
Spring-like Correlation	0.87	0.87	*r* = 0.13	0.85	0.86*	*r* = 0.45	0.85	0.91	*r* = 0.39
Stiffness (KN/m)	9.63	9.36	*r* = -0.03	9.89	11.42*	*r* = 0.47	9.64	10.30*	*r* = 0.51
R Stiffness (KN/m/Kg$^{0.93}$)	0.31	0.28	*r* = -0.10	0.26	0.33	*r* = 0.30	0.26	0.31*	*r* = 0.42
Peak COMD (m)	0.14	0.15	*r* = 0.02	0.14	0.13	*r* = -0.21	0.14	0.15	*r* = 0.31

Mean Braking COM Velocity (m/s)	1.05 ± 0.09	1.06 ± 0.08	*g* = 0.19	1.05 ± 0.10	1.03 ± 0.09	*g* = -0.21	1.04 ± 0.10	1.03 ± 0.09	*g* = -0.09
Mean Propulsive COM Velocity (m/s)	1.19	1.20	*r* = 0.29	1.16	1.12	*r* = -0.26	1.13	1.15	*r* = 0.00
Braking Duration (s)	0.11	0.12	*r* = 0.01	0.12	0.11	*r* = -0.22	0.12	0.11	*r* = -0.32
Propulsive Duration (s)	0.16	0.17	*r* = 0.24	0.17	0.15*	*r* = -0.35	0.17	0.16	*r* = -0.23

COM = centre of mass; COMD = centre of mass displacement; ES = effect size; PHV = peak height velocity; R = relative; RFD = rate of force development.

r = Wilcoxon *r* within-group effect size for non-parametric data

g = within group effect size for parametric data

* Significant difference from baseline to post-intervention ($p < 0.05$)

7.4 DISCUSSION

The aim of the current study was to examine the effect of neuromuscular training vs neuromuscular and traditional resistance training on DJ kinetics in male youth, during a combined 6-month resistance training intervention. The hypothesis was only partially satisfied, with EXPII exhibiting significantly greater improvements than EXPI from baseline to post-intervention in absolute and relative propulsive impulse as well as absolute propulsive work done. EXPII showed moderate to large significant increases in all absolute impulse variables, as well as braking and propulsive work done, resulting in a moderate significant increase in jump height. EXPI exhibited moderate significant increases in mean braking and propulsive force, absolute propulsive peak force, absolute force at peak COM displacement, spring-like correlation and absolute stiffness. Moderate to large significant changes for mean propulsive force, absolute propulsive peak force, force at peak COM displacement, relative propulsive impulse as well as absolute and relative stiffness were observed in CON. Relative to EXPI and CON, EXPII exhibited trivial differences in improvement for relative braking peak force and relative mean propulsive power and small to moderate differences in improvement for mean braking COM velocity. EXPI exhibited trivial improvements in relative braking peak force and mean braking COM velocity, but small improvements in relative mean propulsive power, relative to CON.

The findings of the current study indicate that while only EXPII made significant increases in jump height from baseline to post-intervention, neither EXPII nor EXPI showed any significant changes in RSI following the 6-month intervention. The observations in the current study are not in accordance with prior research that have reported improvements in both jump height and RSI following short-term plyometric training in youth (Branet et al., 2021; Lloyd et al., 2012c; Lloyd et al., 2016; Radnor et al., 2017; Sankey et al., 2008). The lack of change in RSI observed in the EXPII despite their increased jump height can potentially be attributed to their increased ground contact time, although non-significant. Much like the EXPI group, most of these earlier studies utilised plyometric training interventions, suggesting that the lack of significant in change jump height and RSI exhibited by EXPI in the current study might stem from insufficient exposure to an appropriate plyometric stimulus. It is also important to note that these earlier studies all had the participants training twice weekly or more, while the EXPI in the current study trained only once a week. This would potentially suggest the need for higher training frequencies to elicit meaningful changes.

The improved jump height in EXPII with no significant change exhibited by EXPI can be attributed to the significant increases in absolute net and propulsive impulse, as well as the small non-significant increase in relative net impulse that only the EXPII exhibited. The findings of *chapter 4* and earlier research have shown that jump height is strongly underpinned by absolute and relative net impulse (Kirby et al., 2011; Ruddock and Winter, 2015). This impulse influences the take-off velocity which subsequently serves as a determinant of jump height (Ruddock and Winter, 2015). Although the EXPII did not exhibit an increase in mean or peak forces, they did exhibit a non-significant increase in ground contact time which would have facilitated an increased impulse, which is the product of force and time. However, this increased ground contact time, although non-significant, would result in RSI that was observed. Despite EXPII's improved jump height stemming from increases in impulse, from a performance perspective such an increase in ground contact time might not be desirable since the successful execution of most sport-based movements is underpinned by the individual's ability to apply force rapidly upon impact or release (Newton and Kraemer, 1994).

While both EXPII and EXPI groups performed the same resistance training movements during the field-based sessions, only the EXPII group had access to gym-based sessions which allowed for the use of heavier loads compared to what the EXPI used during the field-based sessions. Heavy training loads are suggested to innervate type 2 muscle fibres, which are recruited during exercise requiring near maximal force production, and are prescribed with the primary goal of improving maximal strength and eventually influencing maximal power production (Cormie et al., 2011b), suggesting that only the EXPII might have been exposed to the stimulus required to elicit significant improvements in strength. However, unlike EXPI and CON, the EXPII group displayed no significant changes in the propulsive mean and peak force variables. The DJ is a movement in which there is limited time available to develop force and involves large amounts of braking loading, along with a high-speed braking action, followed by a rapid transition from the braking action to the start of propulsive action (Bobbert et al., 1987b; Bobbert et al., 1986). While heavy resistance training elicits improvements in maximal strength (Cormie et al., 2011b), these improvements tend to be in slow-speed strength (Hedrick, 1993) that is high force application during slow contractions and may not have transferred to improvements in faster contractions required for the DJ (Wilkie, 1949). Additionally, during heavy resistance training force is developed over longer time periods compared to DJs (Ball et al., 2010). It has been suggested that greater exposure to high velocity movements is pivotal for enhancing high-velocity performance capabilities (Cronin et al., 2002; McBride et al., 2002). Although the EXPII did perform plyometric training as a part of their programme, the findings would suggest that they might not have received sufficient exposure to enhance their high-velocity performance capabilities.

Plyometric training has been suggested to elicit improvements in lower limb stiffness and spring-like behaviour (McMahon et al., 2012; Otsuka et al., 2018; Spurrs et al., 2003) potentially improving the efficiency of energy storage and recoil process and positively influencing SSC function (Fouré et al., 2011). The current study observed significant increases in absolute stiffness and spring-like behaviour in EXPI, with no significant changes exhibited by EXPII. Although EXPII and EXPI were exposed to the same plyometric training session, EXPI did exhibit a comparatively lower baseline score for spring-like correlation suggesting they had more greater scope for adaptation (Baker and Newton, 2006; Dotan et al., 2012). The lack of improvement in relative stiffness observed in EXPI, suggests that their increased absolute stiffness exhibited by was driven by muscle mass. Prior research has shown growth and maturity-related increases in muscle mass to positively influence stiffness (Meyers et al., 2019). Additionally, CON exhibited significant increases in absolute and relative stiffness, along with a non-significant improvement in spring-like behaviour. The CON group's significant improvements in absolute and relative stiffness could potentially be attributed to the maturation-related increases in mass and changes in neural mechanisms that occur in youth (Meyers et al., 2019; Tumkur Anil Kumar et al., 2021). Although the current study did not categorise participants based on SSC function, improvements in stiffness and spring-like behaviour have been suggested to positively influence SSC function (Lloyd et al., 2012b; Pedley et al., 2020; Tumkur Anil Kumar et al., 2021). Improvements in SSC function have been suggested to result in enhanced force production at the start of and through the propulsive phase (Bosco et al., 1982), which could explain the increased force at peak COM displacement and propulsive mean force exhibited by the EXPI and CON group.

Despite their improved force production during the propulsive phase, the EXPI and CON exhibited non-significant reductions ground contact time, stemming from shortened braking and propulsive phases. This reduced ground contact time might have contributed to the lack of any significant change in their impulse measures. With absolute and relative net impulse strongly influencing jump height (*see chapter 4*), the lack of significant change in absolute and relative net impulse exhibited by the CON and EXPI might explain their jump height remaining unaffected at post-intervention testing.

7.5 LIMITATIONS

While the current study was the first to examine the effect of resistance training dosage, in terms of purely neuromuscular training vs neuromuscular and traditional resistance training, on DJ kinetics in youth during a long-term resistance training intervention, the limitations need to be acknowledged. Although the training intervention was 6 months long, the initial 8 weeks were spent addressing movement development, which was needed to ensure training competency was developed. Additionally, although both EXPII and EXPI groups performed similar resistance training movements, only the EXPII group had access to gym-based sessions which allowed for the use of heavier loads compared to what the EXPI used during the field-based sessions. This would suggest that only the EXPII might have been exposed to the stimulus required to elicit significant improvements in strength. The programme design in the current study adopted a holistic intervention to reflect a true long-term athletic development (LTAD) approach (Lloyd and Oliver, 2012), rather than focusing solely on DJ training to improved the measures being examined. Prior research has suggested that the adaptations in response to training are specific to the nature of the stimulus (Vissing et al., 2008), and the transfer of improvements in maximal strength to athletic performance requiring sufficient exposure to high-velocity movements (Cronin et al., 2002; McBride et al., 2002). The findings in the current study would suggest that the participants did not receive sufficient exposure to plyometric training. It could also be speculated that the drop height of 30 cm utilised within the current study might have exceeded the capabilities of the participants, hence not allowing their training-related development to be reflected. Finally, the sample size in the current study did not allow for sub-group analysis examining maturity-related responses and the tempo of maturation across the longitudinal period was not considered. However, maturity status was assessed and no significant differences in maturity offset were observed between groups. Based on these limitations, future research should look to examine (i) the maturity-related response to long-term neuromuscular training vs neuromuscular and traditional resistance training on DJ kinetics during a 6-month resistance training intervention with consideration for the tempo of maturation across longitudinal period, and (ii) the maturity-related development of these DJ kinetics during a resistance training programme designed specifically to improve DJ performance and utilising a range of drop heights. Despite these limitations, the current study provides novel information regarding the influence of resistance training dosage on the development of DJ kinetics during a long-term combined resistance training intervention.

7.6 CONCLUSION

The aim of the current study was to examine the effect of neuromuscular training vs neuromuscular and traditional resistance training on DJ kinetics in male youth, during a combined 6-month resistance training intervention. The EXPII exhibited improvements in all absolute impulse variables, braking and propulsive work done and jump height. The EXPII exhibited large improvements in absolute net impulse and small non-significant increases in relative net impulse, which strongly influence jump height as per the findings of *Chapter 4*. The changes in absolute and relative propulsive impulse as well as absolute propulsive work done exhibited by EXPII were significantly greater than EXPI. While the hypothesis was only partially satisfied, the findings suggest that the addition of gym-based traditional resistance training might help to enhance adaptations that positively influence several DJ kinetics, and more importantly they highlight that the adaptations are specific to the nature of the stimulus. The results suggest that when assessing performance during rebound exercises like the DJ, which is primarily driven by the force producing capabilities of the individual, practitioners need to ensure that sufficiently high training loads are prescribed within the programme in order to ensure delivery of appropriate stimulus. The utilisation of heavy weight training alongside plyometric training will allow for optimal development and transfer of training adaptations to athletic activities.

Chapter 8 – General discussion and directions for future research

8.1 OVERALL SUMMARY

The purpose of the current thesis was to investigate the growth and maturation-related stretch shortening cycle (SSC) development through the examination of kinetic measures collected during the braking and propulsive phases of the drop jump (DJ). Subsequently, the thesis also sought to examine the development of these kinetic variables in response to the interaction of training and maturity status. Combined, the outcomes of the body of work furthers the understanding of the growth and maturation-related development and trainability of the kinetic qualities that underpin SSC function. Furthermore, studies from within the thesis provide practitioners and researchers with novel information regarding the kinetic qualities that are reflected by the field-based metrics that are most commonly utilised to assess SSC function. The studies also draw attention to the role that resistance training dosage plays in enhancing training-related development of these kinetic qualities and the specificity of the adaptations in response to the stimulus delivered.

Taking into account existing literature, the current thesis outlined several aims in *Chapter 1* that were researched in the subsequent empirical studies (*Chapters 4-7*).

Aim 1: *Determine the relative importance of jump height and ground contact time in the calculation of RSI, and understand the associations between performance measures and kinetic outcomes.*

Reactive strength index (RSI) is a measure that is commonly utilised to assess an individual's SSC function (Healy et al., 2018). Prior research has suggested this outcome measure fails to account for different jump strategies and does not reflect what is occurring during different phases of the jump (Healy et al., 2018), that could underpin the resultant jump performance. This RSI is derived as the ratio of jump height by ground contact time (Flanagan and Comyns, 2008) and it is currently unclear what kinetic qualities are represented by these outcome measures during a DJ. Therefore, *Chapter 4* sought to determine the relative importance of the variables utilised in the calculation of RSI and understand the associations between these performance variables and kinetic outcomes measured during the braking and propulsive phases of a DJ. The study revealed that jump height had a greater influence on RSI than ground contact time. Although RSI exhibited strong relationships with several kinetic variables, there were instances where stronger relationships were observed between the kinetic qualities and jump height or ground contact time such as for net impulse and relative peak forces respectively. The findings provide practitioners with novel information, suggesting that RSI might best represent absolute and relative power, while jump height and ground contact time might best reflect relative net impulse and relative propulsive force, respectively. However, with there being a degree of error when predicting these kinetic qualities from the outcome variables, it is important to directly examine kinetic measures when investigating SSC development.

Aim 2: *Determine the reliability of the kinetic variables measured during the braking and propulsive phases of a DJ, at different stages of maturation, and examine the influence of maturity status on these variables.*

Earlier research has evidenced the growth and maturation-related development of SSC function during various hopping and jumping tasks (Gillen et al., 2019; Laffaye et al., 2016; Lloyd et al., 2011b; Malina et al., 2004; Pedley et al., 2020). While a few of these studies have examined several kinetic measures during DJs in youth, they failed to consider the full range of important kinetic descriptors of DJ performance and SSC function (Gillen et al., 2019; Pedley et al., 2020). Additionally, although prior research has reported extremely good reliability for landing and take-off force in youth DJs (Quatman et al., 2006), the study included only 5 participants of mixed maturity status. This has left the reliability of these kinetic measures during the two phases of the DJ uncertain, and given the high jump variability that youth display (Gerodimos et al., 2008) it requires examination. Therefore, *Chapter 5* sought to (i) determine the reliability of the DJ kinetic outcomes in youth of different maturity status; and (ii) understand how these kinetic qualities develop amongst youth of different maturity status. The study established moderate to excellent relative reliability and acceptable absolute reliability for most drop jump kinetic variables across all maturity groups (ICC = 0.59 to 0.91; CV < 10%), with the acceptance threshold for random variation being exceeded in some cases, such as braking rate of force development and braking peak force (CV > 10%). The study observed that the post-PHV group exhibited comparatively better kinetic qualities than their less mature counterparts. The differences in kinetics observed from early-pre to late-pre-PHV, late-pre- to circa-PHV and circa- to post-PHV were similar in magnitude for most variables. Although, SSC function was observed to improve with maturity status, several mature individuals displayed POOR SSC function suggesting that development of SSC function is not exclusively related to maturation. The study also highlighted differences between maturity groups for several kinetic variables that were not reflected by the performance measures. This reinforces the importance for practitioners to refrain from relying solely on outcome measures when assessing performance or the efficiency of a training programme, as they might not reflect the underlying mechanisms.

Aim 3: *Examine the development of the DJ kinetic variables in pre- and post- PHV male athletes, in response to a 12-week combined strength and plyometric training programme.*

With the reliability for DJ kinetic qualities from the braking and propulsive phases established and an understanding of how these kinetic qualities developed with maturity status, it was important to understand how these qualities developed in response to training in youth of different maturity status. Resistance training in youth has been evidenced to elicit improvements in jump height (Chelly et al., 2009; Chelly et al., 2015; Lloyd et al., 2016; Matavulj et al., 2001; Uzelac-Sciran et al., 2020), change of direction speed (Meylan and Malatesta, 2009; Thomas et al., 2009), running velocities (Chelly et al., 2015; Lloyd et al., 2016) and sprint times (Keiner et al., 2014b; Sander et al., 2013). However, it is currently unclear how SSC function, which underpins the performance of these movements, develops in response to resistance training in youth. Therefore, *Chapter 6* sought to examine the interaction of maturation and short-term combined strength and plyometric training on the development of kinetic outcomes from a drop jump. The main findings of the study were that post-PHV EXP exhibited significantly greater training-related improvements in most kinetics compared to pre-PHV EXP. The post-PHV EXP exhibited large significant improvements in most kinetic qualities that resulted in small to moderate significant increases in jump height and RSI. The pre-PHV EXP only exhibited moderate significant improvements for absolute and relative net and braking impulse, absolute braking work done, peak COM displacement and COM velocity, resulting in small increases in jump height, with RSI remaining unchanged. The novel findings from the study provide insight into the training- and maturation status-related development of kinetic qualities collected during the braking and propulsive phases of the DJ. The observations suggest that post-PHV boys respond better than pre-PHV boys to a short-term combined strength and plyometric training programme, with this being attributable to the process of synergistic adaptation.

Aim 4: *Examine the effect of resistance training dosage during a 6-month combined strength and plyometric training intervention on the DJ kinetics in young male athletes.*

Chapter 6 highlighted the maturity-related responsiveness to a short-term combined strength and plyometric training programme in young male athletes. The chapter also provided an understanding of how DJ kinetic qualities develop as a result of the interaction of training and maturity status. *Chapter* 3 highlighted that most of the studies investigating the effect of resistance training in youth on DJ performance implemented short-term training interventions (≤ 12 Weeks). Although Keiner et al. (2018) reported the positive effects of long-term strength training in youth on measures of jump height and RSI during a DJ, the influence of a long-term training intervention on DJ kinetic outcomes remains unknown. Additionally, literature examining what is achievable in most youth settings (i.e., field-based neuromuscular training) vs what is desirable (field-neuromuscular and gym-based traditional resistance training) is scarce. Therefore, *Chapter 7* sought to examine the effect of neuromuscular training vs neuromuscular and traditional resistance training on DJ kinetics in male youth, during a combined 6-month resistance training intervention. The EXPII group exhibited a significant increase in jump height, which was attributed to their large significant improvements in absolute net impulse and small non-significant improvement in relative net impulse. However, they did not exhibit an increase in RSI and this was attributed to their non-significant increase in ground contact time. The EXPI and CON group exhibited significant increases in stiffness and spring-like behaviour, improvements in which have been linked to enhanced SSC function (Lloyd et al., 2012b; Pedley et al., 2020; Tumkur Anil Kumar et al., 2021). An improvement in the efficiency of SSC function has been linked to improved force production at the start of and through the propulsive phase of a jump (Bosco et al., 1982), which could explain the increased propulsive peak forces exhibited by once-weekly and CON. The findings suggest that when assessing performance during rebound-based exercises like the DJ, which is primarily driven by the force producing capabilities of the individual, practitioners need to ensure that sufficiently high training loads are prescribed within the programme in order to ensure delivery of appropriate stimulus. Furthermore, with the adaptations appearing to be specific to the stimulus delivered, the utilisation of heavy weight training alongside appropriate exposure to plyometric training will allow for optimal development and transfer of training adaptations to such athletic activities.

8.2 OVERALL CONCLUSIONS

The findings of the current thesis provide an understanding of the kinetic qualities that commonly utilised field-based metrics such as RSI, jump height and ground contact time might reflect. The thesis goes on to demonstrate that improvements in SSC function are exhibited with increasing maturity status, and highlights that these improvements are underpinned by changes in kinetic qualities such as mean and peak forces, impulse and power as well as changes in jump strategy such as centre of mass displacement and spring-like correlation. The findings also demonstrate that while resistance training can positively influence the development of SSC function in youth, the nature and magnitude of these training-related adaptations might be specific to the stimulus delivered.

The findings from the current thesis highlight the need for practitioners to refrain from relying solely on outcome measures when assessing the efficiency of a training programme or comparing performance between groups, as they might not reflect the mechanisms that underpin any differences observed. The examination of kinetic qualities is dependent on access to appropriate equipment such as force plates. Hence, for those practitioners lacking access to such equipment the findings from the current study provide an understanding of the kinetic qualities that the commonly reported field-based metrics might reflect. Additionally, the studies within the thesis highlight that the adaptations following training are specific to the nature of the stimulus delivered. The prescription of heavy weight training alongside plyometric training will allow for the optimal development and transfer of training adaptations to athletic activities.

There are certain limitations within the thesis that need to be acknowledged. It could be speculated that the drop height of 30 cm utilised within the current study might have exceeded the capabilities of the pre-PHV boys, thereby not allowing their training-related development to be reflected. The training programme design in the studies adopted a holistic intervention to reflect a true long-term athletic development, with the utilisation of maturity appropriate exercises. It is suggested that the adaptations in response to training are specific to the nature of the stimulus (Vissing et al., 2008), and the transfer of improvements in maximal strength to athletic performance requires sufficient exposure to high-velocity movements (Cronin et al., 2002; McBride et al., 2002). The sample in the final study did not allow for the comparison of maturity-related reponses to resistance training and did not take into account the tempo of maturation. Despite these limitations the novel findings from the current thesis furthers the understanding of the growth and maturation-related development and trainability of the kinetic qualities that underpin SSC function.

8.3 PRACTICAL IMPLICATIONS

Based on the findings from the current thesis, a few key takeaways for practitioners are listed below,

- Coaches should be aware that as youth mature they experience a large number of neuromuscular changes and implementing training programmes that are complementary to the natural adaptative process might elicit the most improvement.

- Coaches should be aware that the development of SSC function is not exclusively a function of maturation and that the prescription of plyometrics should take into account individual capabilities and be programmed purely based on maturity status.
- Coaches should refrain from using solely outcome measures when assessing performance, as the outcome measures may lack the sensitivity to detect changes in the underlying kinetic qualitites.
- Coaches should be aware that post-PHV boys respond better than pre-PHV boys to combined training interventions, and this can be explained by the adaptations in response to the training stimulus coinciding with the natural maturity-related adaptations of the post-pubertal boys.
- When prescribing training to improve athletic perforamnce, practitioners need to ensure that sufficiently high training loads are prescribed within the programme in order to ensure delivery of appropriate stimulus. The utilisation of heavy weight training alongside appropriate exposure to plyometric training will allow for optimal development of maximal strength and it's transfer to athletic activities.

8.4 DIRECTIONS FOR FUTURE RESEARCH

Literature within paediatric strength and conditioning has given the development of kinetics resulting from training and maturation little focus. While the current thesis has attempted to address this apparent gap in the research, there still exists a number of unanswered questions within this field of study. Listed below are some areas deemed worthy of future investigation in order to better understand the development of the kinetics underpinning performance in youth.

- *The effect of long-term training interventions specifically designed to improve SSC function on DJ kinetic qualities in young male athletes of different maturity status.* The current thesis provides an improved understanding of the changes in DJ kinetic qualities that underpin maturation- and training-related improvements in SSC function in young boys, following a short and long-term combined strength and plyometric programme. However, the training programme design in the current thesis adopted a holistic intervention to reflect a true long-term athletic development. It is important for future research to investigate the development of these kinetic qualities in youth in response to long-term training interventions designed specifically to elicit improvements in SSC function, while taking into consideration the tempo of maturation across the longitudinal period.

- *The effect of combined resistance training on DJ kinetics from optimal jump heights.* The current thesis provides novel information regarding the development of SSC function as assessed through kinetic qualities during a DJ from a 30 cm drop height. The authors acknowledge that the 30 cm drop could be a limiting factor if the drop height exceeded the capabilities of the less mature participants. It therefore becomes important for future research to examine how maturation and training interact to influence kinetic qualities collected during DJs from different drop heights.
- *Sex-specific development of DJ kinetics in response to resistance training. Chapters 2 and 3* from the thesis highlight the paucity of data in girls compared to boys. The studies within the current thesis focussed on the maturation- and training-related development of SSC function in boys. However, given the sex-related differences in the maturational process, it becomes necessary for future research to examine for potential differences in the development of DJ kinetics in girls compared to boys in response to resistance training. Such an understanding might then inform the design of alternative training programmes to males.

- *The effect of long-term training interventions specifically designed to improve SSC function on kinetic qualities in a range of tests in young male athletes of different maturity status.* The current thesis provides an improved understanding of the changes in DJ kinetic qualities that underpin maturation- and training-related improvements in SSC function in young boys, following a short and long-term combined strength and plyometric programme. However, in addition to examining the effect of a training programme designed to improve DJ performance, future research should use a larger testing battery to also examine for the transfer for the improved DJ performance to other athletic movements.
- *Mechanistic changes underpinning training-related improvements in DJ kinetics in youth.* Prior research has highlighted the various growth and maturation-related changes in muscle-tendon architecture and neural mechanisms that youth experience as they transition throught childhood towards adulthood (Radnor et al., 2020b; Tumkur Anil Kumar et al., 2021). These neuromuscular changes have been suggested to underpin maturity-related improvements in SSC function during hopping and jumping tasks (Laffaye et al., 2016; Lloyd et al., 2011b; Malina et al., 2004; Radnor et al., 2021). The neuromuscular changes that underpin improvements in SSC function following resistance training interventions remains unclear.

REFERENCES

Aagaard, P. (2003) Training-induced changes in neural function, *Exercise and Sport Sciences Reviews, 31*(2), pp. 61-67.

Aagaard, P., Andersen, J.L., Dyhre‐Poulsen, P., Leffers, A.M., Wagner, A., Magnusson, S.P., Halkjær‐Kristensen, J. and Simonsen, E.B. (2001) A mechanism for increased contractile strength of human pennate muscle in response to strength training: changes in muscle architecture, *The Journal of physiology, 534*(2), pp. 613-623.

Abe, T., Kumagai, K. and Brechue, W.F. (2000) Fascicle length of leg muscles is greater in sprinters than distance runners, *Medicine and Science in Sports and Exercise, 32*(6), pp. 1125-1129.

Alegre, L.M., Jiménez, F., Gonzalo-Orden, J.M., Martín-Acero, R. and Aguado, X. (2006) Effects of dynamic resistance training on fascicle lengthand isometric strength, *Journal of Sports Sciences, 24*(05), pp. 501-508.

Allen, G.M., McKenzie, D.K. and Gandevia, S.C. (1998) Twitch interpolation of the elbow flexor muscles at high forces, *Muscle & Nerve: Official Journal of the American Association of Electrodiagnostic Medicine, 21*(3), pp. 318-328.

Askew, G.N. and Marsh, R.L. (1998) Optimal shortening velocity (V/Vmax) of skeletal muscle during cyclical contractions: length-force effects and velocity-dependent activation and deactivation, *Journal of Experimental Biology, 201*(10), pp. 1527-1540.

Asmussen, E. (1953) Positive and negative muscular work, *Acta Physiologica Scandinavica, 28*(4), pp. 364-382.

Asmussen, E. and Heebøll-Nielsen, K. (1955) A dimensional analysis of physical performance and growth in boys, *Journal of Applied Physiology, 7*(6), pp. 593-603.

Assaiante, C. and Amblard, B. (1996) Visual factors in the child's gait: effects on locomotor skills, *Perceptual and Motor Skills, 83*(3), pp. 1019-1041.

Atkins, S.J. (2004) Normalizing expressions of strength in elite rugby league players, *Journal of Strength and Conditioning Research, 18*(1), pp. 53-58.

Augustsson, J., Thomee, R., Linden, C., Folkesson, M., Tranberg, R. and Karlsson, J. (2006) Single‐leg hop testing following fatiguing exercise: reliability and biomechanical analysis, *Scandinavian Journal of Medicine and Science in Sports, 16*(2), pp. 111-120.

Babault, N., Pousson, M., Ballay, Y. and Van Hoecke, J. (2001) Activation of human quadriceps femoris during isometric, concentric, and eccentric contractions, *Journal of Applied Physiology, 91*(6), pp. 2628-2634.

Bailey, A.J., Paul, R.G. and Knott, L. (1998) Mechanisms of maturation and ageing of collagen, *Mechanisms of Ageing and Development, 106*(1-2), pp. 1-56.

Baker, D.G. and Newton, R.U. (2006) Adaptations in upper-body maximal strength and power output resulting from long-term resistance training in experienced strength-power athletes, *The Journal of Strength & Conditioning Research, 20*(3), pp. 541-546.

Baker, J., Cote, J. and Abernethy, B. (2003) Sport-specific practice and the development of expert decision-making in team ball sports, *Journal of Applied Sport Psychology, 15*(1), pp. 12-25.

Ball, N.B., Stock, C.G. and Scurr, J.C. (2010) Bilateral contact ground reaction forces and contact times during plyometric drop jumping, *The Journal of Strength & Conditioning Research, 24*(10), pp. 2762-2769.

Ball, N.B. and Zanetti, S. (2012) Relationship between reactive strength variables in horizontal and vertical drop jumps, *The Journal of Strength & Conditioning Research, 26*(5), pp. 1407-1412.

Baroni, B.M., Geremia, J.M., Rodrigues, R., De Azevedo Franke, R., Karamanidis, K. and Vaz, M.A. (2013) Muscle architecture adaptations to knee extensor eccentric training: rectus femoris vs. vastus lateralis, *Muscle and Nerve, 48*(4), pp. 498-506.

Barr, M.J. and Nolte, V.W. (2011) Which measure of drop jump performance best predicts sprinting speed?, *The Journal of Strength & Conditioning Research, 25*(7), pp. 1976-1982.

Bassa, E.I., Patikas, D.A., Panagiotidou, A.I., Papadopoulou, S.D., Pylianidis, T.C. and Kotzamanidis, C.M. (2012) The effect of dropping height on jumping performance in trained and untrained prepubertal boys and girls, *The Journal of Strength & Conditioning Research, 26*(8), pp. 2258-2264.

Baxter, J.R. and Piazza, S.J. (2014) Plantar flexor moment arm and muscle volume predict torque-generating capacity in young men, *Journal of Applied Physiology, 116*(5), pp. 538-544.

Beasley, T.M. and Schumacker, R.E. (1995) Multiple regression approach to analyzing contingency tables: Post hoc and planned comparison procedures, *The Journal of Experimental Education, 64*(1), pp. 79-93.

Beattie, K., Carson, B.P., Lyons, M. and Kenny, I.C. (2017) The relationship between maximal strength and reactive strength, *International Journal of Sports Physiology and Performance, 12*(4), pp. 548-553.

Beckham, G.K., Suchomel, T.J., Sole, C.J., Bailey, C.A., Grazer, J.L., Kim, S.B., Talbot, K.B. and Stone, M.H. (2019) Influence of sex and maximum strength on reactive strength index-modified, *Journal of Sports Science & Medicine, 18*(1), p 65.

Behm, D.G., Faigenbaum, A.D., Falk, B. and Klentrou, P. (2008) Canadian Society for Exercise Physiology position paper: resistance training in children and adolescents, *Applied physiology, nutrition, and metabolism, 33*(3), pp. 547-561.

Behm, D.G., Young, J.D., Whitten, J.H., Reid, J.C., Quigley, P.J., Low, J., Li, Y., Lima, C.D., Hodgson, D.D. and Chaouachi, A. (2017) Effectiveness of traditional strength vs. power training on muscle strength, power and speed with youth: a systematic review and meta-analysis, *Frontiers in Physiology, 8*, p 423.

Behringer, M., Heede, A.v., Matthews, M. and Mester, J. (2011) Effects of strength training on motor performance skills in children and adolescents: a meta-analysis, *Pediatric Exercise Science, 23*(2), pp. 186-206.

Behringer, M., vom Heede, A., Yue, Z. and Mester, J. (2010) Effects of resistance training in children and adolescents: a meta-analysis, *Pediatrics, 126*(5), pp. e1199-e1210.

Benjamin, H.J. and Glow, K.M. (2003) Strength training for children and adolescents: What can physicians recommend?, *The Physician and Sportsmedicine, 31*(9), pp. 19-26.

Benjamin, M., Kaiser, E. and Milz, S. (2008) Structure ‐ function relationships in tendons: a review, *Journal of Anatomy, 212*(3), pp. 211-228.

Bergeron, M.F., Mountjoy, M., Armstrong, N., Chia, M., Côté, J., Emery, C.A., Faigenbaum, A., Hall, G., Kriemler, S. and Léglise, M. (2015) International Olympic Committee consensus statement on youth athletic development, *British Journal of Sports Medicine, 49*(13), pp. 843-851.

Beunen, G. and Malina, R.M. (2008) Growth and biologic maturation: relevance to athletic performance, *The young athlete, 1*, pp. 3-17.

Biewener, A.A. and Roberts, T.J. (2000) Muscle and tendon contributions to force, work, and elastic energy savings: a comparative perspective, *Exercise and Sport Sciences Reviews, 28*(3), pp. 99-107.

Binzoni, T., Bianchi, S., Hanquinet, S., Kaelin, A., Sayegh, Y., Dumont, M. and Jéquier, S. (2001) Human gastrocnemius medialis pennation angle as a function of age: from newborn to the elderly, *Journal of Physiological Anthropology and Applied Human Science, 20*(5), pp. 293-298.

Birat, A., Sebillaud, D., Bourdier, P., Doré, E., Duché, P., Blazevich, A.J., Patikas, D. and Ratel, S. (2020) Effect of drop height on vertical jumping performance in pre-, circa-, and post-pubertal boys and girls, *Pediatric Exercise Science, 32*(1), pp. 23-29.

Blazevich, A.J. (2006) Effects of physical training and detraining, immobilisation, growth and aging on human fascicle geometry, *Sports Medicine, 36*(12), pp. 1003-1017.

Blazevich, A.J., Cannavan, D., Coleman, D.R. and Horne, S. (2007) Influence of concentric and eccentric resistance training on architectural adaptation in human quadriceps muscles, *Journal of Applied Physiology*

Blazevich, A.J., Gill, N.D., Bronks, R. and Newton, R.U. (2003) Training-specific muscle architecture adaptation after 5-wk training in athletes, *Medicine and Science in Sports and Exercise, 35*(12), pp. 2013-2022.

Blazevich, A.J., Wilson, C.J., Alcaraz, P.E. and Rubio-Arias, J.A. (2020) Effects of Resistance Training Movement Pattern and Velocity on Isometric Muscular Rate of Force Development: A Systematic Review with Meta-analysis and Meta-regression, *Sports Medicine*, pp. 1-21.

Blickhan, R. (1989) The spring-mass model for running and hopping, *Journal of Biomechanics, 22*(11-12), pp. 1217-1227.

Blimkie, C.J. (1993) Resistance training during preadolescence, *Sports Medicine, 15*(6), pp. 389-407.

Bobbert, M.F., Gerritsen, K.G., Litjens, M.C. and Van Soest, A.J. (1996) Why is countermovement jump height greater than squat jump height?, *Medicine and Science in Sports and Exercise, 28*, pp. 1402-1412.

Bobbert, M.F., Huijing, P.A. and van Ingen Schenau, G. (1987a) Drop jumping. I. The influence of jumping technique on the biomechanics of jumping, *Medicine and Science in Sports and Exercise, 19*(4), pp. 332-338.

Bobbert, M.F., Huijing, P.A. and Van Ingen Schenau, G.J. (1987b) Drop jumping. II. The influence of dropping height on the biomechanics of drop jumping, *Medicine and Science in Sports and Exercise, 19*(4), pp. 339-346.

Bobbert, M.F., Mackay, M., Schinkelshoek, D., Huijing, P. and van Ingen Schenau, G. (1986) Biomechanical analysis of drop and countermovement jumps, *European Journal of Applied Physiology and Occupational Physiology, 54*(6), pp. 566-573.

Bogdanis, G.C., Donti, O., Papia, A., Donti, A., Apostolidis, N. and Sands, W.A. (2019) Effect of plyometric training on jumping, sprinting and change of direction speed in child female athletes, *Sports, 7*(5), p 116.

Bojsen-Møller, J., Magnusson, S.P., Rasmussen, L.R., Kjaer, M. and Aagaard, P. (2005) Muscle performance during maximal isometric and dynamic contractions is influenced by the stiffness of the tendinous structures, *Journal of Applied Physiology, 99*(3), pp. 986-994.

Borenstein, M., Hedges, L.V., Higgins, J.P. and Rothstein, H.R. (2010) A basic introduction to fixed‐effect and random‐effects models for meta‐analysis, *Research synthesis methods, 1*(2), pp. 97-111.

Bosco, C., Montanari, G., Tarkkai, I., Latteri, F., Cozzi, M., Iachelli, G., Faina, M., Colli, R., MONTE, A.D. and La Rosa, M. (1987) The effect of pre‐stretch on mechanical efficiency of human skeletal muscle, *Acta Physiologica Scandinavica, 131*(3), pp. 323-329.

Bosco, C., Tihanyi, J., Komi, P., Fekete, G. and Apor, P. (1982) Store and recoil of elastic energy in slow and fast types of human skeletal muscles, *Acta Physiologica Scandinavica, 116*(4), pp. 343-349.

Bottinelli, R., Pellegrino, M., Canepari, M., Rossi, R. and Reggiani, C. (1999) Specific contributions of various muscle fibre types to human muscle performance: an in vitro study, *Journal of Electromyography and Kinesiology, 9*(2), pp. 87-95.

Branet, C., Grigoroiu, C., Netolitzchi, M. and Wesselly, T. (2021) The Effect of Plyometric Training on Lower Body Strength in Preadolescent Athletes, *BRAIN. Broad Research in Artificial Intelligence and Neuroscience, 11*(4Sup1), pp. 13-29.

Brooks, G.A., Fahey, T.D. and White, T.P. (1996) *Exercise physiology: Human bioenergetics and its applications*: Mayfield publishing company.

Brownlee, T.E., Murtagh, C.F., Naughton, R.J., Whitworth-Turner, C.M., O'Boyle, A., Morgans, R., Morton, J.P., Erskine, R.M. and Drust, B. (2018) Isometric maximal voluntary force evaluated using an isometric mid-thigh pull differentiates English Premier League youth soccer players from a maturity-matched control group, *Science and Medicine in Football, 2*(3), pp. 209-215.

Buchheit, M. and Simpson, B.M. (2017) Player-tracking technology: half-full or half-empty glass?, *International Journal of Sports Physiology and Performance, 12*(s2), pp. S2-35-S32-41.

Buscemi, N., Hartling, L., Vandermeer, B., Tjosvold, L. and Klassen, T.P. (2006) Single data extraction generated more errors than double data extraction in systematic reviews, *Journal of Clinical Epidemiology, 59*(7), pp. 697-703.

Campos, G.E., Luecke, T.J., Wendeln, H.K., Toma, K., Hagerman, F.C., Murray, T.F., Ragg, K.E., Ratamess, N.A., Kraemer, W.J. and Staron, R.S. (2002) Muscular adaptations in response to three different resistance-training regimens: specificity of repetition maximum training zones, *European Journal of Applied Physiology, 88*(1), pp. 50-60.

Carroll, T.J., Riek, S. and Carson, R.G. (2001) Neural adaptations to resistance training, *Sports Medicine, 31*(12), pp. 829-840.

Carvalho, H.M., Coelho-e-Silva, M.J., Gonçalves, C.E., Philippaerts, R.M., Castagna, C. and Malina, R.M. (2011) Age-related variation of anaerobic power after controlling for size and maturation in adolescent basketball players, *Annals of Human Biology, 38*(6), pp. 721-727.

Cavagna, G.A., Dusman, B. and Margaria, R. (1968) Positive work done by a previously stretched muscle, *Journal of Applied Physiology, 24*(1), pp. 21-32.

Cavanagh, P.R. and Komi, P.V. (1979) Electromechanical delay in human skeletal muscle under concentric and eccentric contractions, *European Journal of Applied Physiology and Occupational Physiology, 42*(3), pp. 159-163.

Channell, B.T. and Barfield, J. (2008) Effect of Olympic and traditional resistance training on vertical jump improvement in high school boys, *The Journal of Strength & Conditioning Research, 22*(5), pp. 1522-1527.

Chelly, M.S., Fathloun, M., Cherif, N., Amar, M.B., Tabka, Z. and Van Praagh, E. (2009) Effects of a back squat training program on leg power, jump, and sprint performances in junior soccer players, *The Journal of Strength & Conditioning Research, 23*(8), pp. 2241-2249.

Chelly, M.S., Hermassi, S. and Shephard, R.J. (2015) Effects of in-season short-term plyometric training program on sprint and jump performance of young male track athletes, *The Journal of Strength & Conditioning Research, 29*(8), pp. 2128-2136.

Chestnut, J.L. and Docherty, D. (1999) The effects of 4 and 10 repetition maximum weight-training protocols on neuromuscular adaptations in untrained men, *The Journal of Strength & Conditioning Research, 13*(4), pp. 353-359.

Cohen, J. (2013) *Statistical power analysis for the behavioral sciences*: Academic press.

Cohen, R., Mitchell, C., Dotan, R., Gabriel, D., Klentrou, P. and Falk, B. (2010) Do neuromuscular adaptations occur in endurance-trained boys and men?, *Applied physiology, nutrition, and metabolism, 35*(4), pp. 471-479.

Comfort, P. and Pearson, S.J. (2014) Scaling—Which methods best predict performance?, *The Journal of Strength & Conditioning Research, 28*(6), pp. 1565-1572.

Comyns, T.M., Flanagan, E.P., Fleming, S., Fitzgerald, E. and Harper, D.J. (2019) Interday Reliability and Usefulness of a Reactive Strength Index Derived From 2 Maximal Rebound Jump Tests, *International Journal of Sports Physiology and Performance, 14*(9), pp. 1200-1204.

Cormack, S.J., Newton, R.U., McGuigan, M.R. and Doyle, T.L. (2008) Reliability of measures obtained during single and repeated countermovement jumps, *International Journal of Sports Physiology and Performance, 3*(2), pp. 131-144.

Cormie, P., McBride, J.M. and McCaulley, G.O. (2009) Power-time, force-time, and velocity-time curve analysis of the countermovement jump: impact of training, *The Journal of Strength & Conditioning Research, 23*(1), pp. 177-186.

Cormie, P., McCaulley, G.O., Triplett, N.T. and McBride, J.M. (2007) Optimal loading for maximal power output during lower-body resistance exercises, *Medicine and Science in Sports and Exercise, 39*(2), pp. 340-349.

Cormie, P., McGuigan, M.R. and Newton, R.U. (2011a) Developing maximal neuromuscular power: Part 1 - Biological basis of maximal power production, *Sports Medicine, 41*(1), pp. 17-38.

Cormie, P., McGuigan, M.R. and Newton, R.U. (2011b) Developing maximal neuromuscular power: Part 2 - Training Considerations for Improving Maximal Power Production, *Sports Medicine, 41*(2), p 125.

Couppe, C., Kongsgaard, M., Aagaard, P., Hansen, P., Bojsen-Moller, J., Kjaer, M. and Magnusson, S.P. (2008) Habitual loading results in tendon hypertrophy and increased stiffness of the human patellar tendon, *Journal of Applied Physiology, 105*(3), pp. 805-810.

Crewther, B.T., Gill, N., Weatherby, R.P. and Lowe, T. (2009) A comparison of ratio and allometric scaling methods for normalizing power and strength in elite rugby union players, *Journal of Sports Sciences, 27*(14), pp. 1575-1580.

Cronin, J., McNair, P. and Marshall, R. (2002) Is velocity-specific strength training important in improving functional performance?, *Journal of sports medicine and physical fitness, 42*(3), pp. 267-273.

Cronin, J.B., Hing, R.D. and McNair, P.J. (2004) Reliability and validity of a linear position transducer for measuring jump performance, *The Journal of Strength & Conditioning Research, 18*(3), pp. 590-593.

Cunha, G.d.S., Vaz, M.A., Herzog, W., Geremia, J.M., Leites, G.T. and Reischak-Oliveira, Á. (2020) Maturity status effects on torque and muscle architecture of young soccer players, *Journal of Sports Sciences, 38*(11-12), pp. 1286-1295.

Daly, R.M., Saxon, L., Turner, C.H., Robling, A.G. and Bass, S.L. (2004) The relationship between muscle size and bone geometry during growth and in response to exercise, *Bone, 34*(2), pp. 281-287.

Darby, J., Li, B., Costen, N., Loram, I. and Hodson-Tole, E. (2013) Estimating skeletal muscle fascicle curvature from B-mode ultrasound image sequences, *IEEE Transactions on Biomedical Engineering, 60*(7), pp. 1935-1945.

de Salles, B.F., Simao, R., Miranda, F., da Silva Novaes, J., Lemos, A. and Willardson, J.M. (2009) Rest interval between sets in strength training, *Sports Medicine, 39*(9), pp. 765-777.

de Villarreal, E.S.S., Izquierdo, M. and Gonzalez-Badillo, J.J. (2011) Enhancing jump performance after combined vs. maximal power, heavy-resistance, and plyometric training alone, *The Journal of Strength & Conditioning Research, 25*(12), pp. 3274-3281.

DerSimonian, R. and Laird, N. (1986) Meta-analysis in clinical trials, *Controlled Clinical Trials, 7*(3), pp. 177-188.

Desmedt, J.E. and Godaux, E. (1977a) Ballistic contractions in man: characteristic recruitment pattern of single motor units of the tibialis anterior muscle, *The Journal of physiology, 264*(3), pp. 673-693.

Desmedt, J.E. and Godaux, E. (1977b) Fast motor units are not preferentially activated in rapid voluntary contractions in man, *Nature, 267*(5613), pp. 717-719.

Dietz, V., Noth, J. and Schmidtbleicher, D. (1981) Interaction between pre‐activity and stretch reflex in human triceps brachii during landing from forward falls, *The Journal of physiology, 311*(1), pp. 113-125.

Dotan, R., Mitchell, C., Cohen, R., Klentrou, P., Gabriel, D. and Falk, B. (2012) Child—adult differences in muscle activation—a review, *Pediatric Exercise Science, 24*(1), pp. 2-21.

Dotan, R., Mitchell, C.J., Cohen, R., Gabriel, D., Klentrou, P. and Falk, B. (2013) Explosive sport training and torque kinetics in children, *Applied physiology, nutrition, and metabolism, 38*(7), pp. 740-745.

Duclay, J., Martin, A., Duclay, A., Cometti, G. and Pousson, M. (2009) Behavior of fascicles and the myotendinous junction of human medial gastrocnemius following eccentric strength training, *Muscle & Nerve: Official Journal of the American Association of Electrodiagnostic Medicine, 39*(6), pp. 819-827.

Earp, J.E., Kraemer, W.J., Cormie, P., Volek, J.S., Maresh, C.M., Joseph, M. and Newton, R.U. (2011) Influence of muscle–tendon unit structure on rate of force development during the squat, countermovement, and drop jumps, *The Journal of Strength & Conditioning Research, 25*(2), pp. 340-347.

Earp, J.E., Kraemer, W.J., Newton, R.U., Comstock, B.A., Fragala, M.S., Dunn-Lewis, C., Solomon-Hill, G., Penwell, Z.R., Powell, M.D. and Volek, J.S. (2010) Lower-body muscle structure and its role in jump performance during squat, countermovement, and depth drop jumps, *The Journal of Strength & Conditioning Research, 24*(3), pp. 722-729.

Edman, K., Elzinga, G. and Noble, M. (1978) Enhancement of mechanical performance by stretch during tetanic contractions of vertebrate skeletal muscle fibres, *The Journal of physiology, 281*(1), pp. 139-155.

Edwen, C., Thorlund, J.B., Magnusson, S.P., Slinde, F., Svantesson, U., Hulthen, L. and Aagaard, P. (2014) Stretch‐shortening cycle muscle power in women and men aged 18–81 years: Influence of age and gender, *Scandinavian Journal of Medicine and Science in Sports, 24*(4), pp. 717-726.

Elliott, B.C., Wilson, G.J. and Kerr, G.K. (1989) A biomechanical analysis of the sticking region in the bench press, *Medicine and Science in Sports and Exercise, 21*(4), pp. 450-462.

Ettema, G. (1996) Mechanical efficiency and efficiency of storage and release of series elastic energy in skeletal muscle during stretch-shorten cycles, *Journal of Experimental Biology, 199*(9), pp. 1983-1997.

Faigenbaum, A.D. (2000) Strength training for children and adolescents, *Clinics in Sports Medicine, 19*(4), pp. 593-619.

Faigenbaum, A.D. (2007) State of the Art Reviews: Resistance Training for Children and Adolescents: Are There Health Outcomes?, *American Journal of Lifestyle Medicine, 1*(3), pp. 190-200.

Faigenbaum, A.D., Lloyd, R.S., MacDonald, J. and Myer, G.D. (2016) Citius, Altius, Fortius: beneficial effects of resistance training for young athletes: narrative review, *British Journal of Sports Medicine, 50*(1), pp. 3-7.

Faigenbaum, A.D. and Myer, G.D. (2010) Resistance training among young athletes: safety, efficacy and injury prevention effects, *British Journal of Sports Medicine, 44*(1), pp. 56-63.

Faigenbaum, A.D. and Myer, G.D. (2012) Exercise deficit disorder in youth: play now or pay later, *Current Sports Medicine Reports, 11*(4), pp. 196-200.

Faigenbaum, A.D., Westcott, W.L., Loud, R.L. and Long, C. (1999) The effects of different resistance training protocols on muscular strength and endurance development in children, *Pediatrics, 104*(1), pp. e5-e5.

Falk, B., Brunton, L., Dotan, R., Usselman, C., Klentrou, P. and Gabriel, D. (2009a) Muscle strength and contractile kinetics of isometric elbow flexion in girls and women, *Pediatric exercise science, 21*(3), pp. 354-364.

Falk, B. and Eliakim, A. (2003) Resistance training, skeletal muscle and growth, *Pediatric endocrinology reviews: PER, 1*(2), pp. 120-127.

Falk, B. and Tenenbaum, G. (1996) The effectiveness of resistance training in children, *Sports Medicine, 22*(3), pp. 176-186.

Falk, B., Usselman, C., Dotan, R., Brunton, L., Klentrou, P., Shaw, J. and Gabriel, D. (2009b) Child–adult differences in muscle strength and activation pattern during isometric elbow flexion and extension, *Applied physiology, nutrition, and metabolism, 34*(4), pp. 609-615.

Faude, O., Rössler, R., Petushek, E.J., Roth, R., Zahner, L. and Donath, L. (2017) Neuromuscular adaptations to multimodal injury prevention programs in youth sports: a systematic review with meta-analysis of randomized controlled trials, *Frontiers in Physiology, 8*, p 791.

Ferrete, C., Requena, B., Suarez-Arrones, L. and de Villarreal, E.S. (2014) Effect of strength and high-intensity training on jumping, sprinting, and intermittent endurance performance in prepubertal soccer players, *The Journal of Strength & Conditioning Research, 28*(2), pp. 413-422.

Ferretti, G., Narici, M., Binzoni, T., Gariod, L., Le Bas, J., Reutenauer, H. and Cerretelli, P. (1994) Determinants of peak muscle power: effects of age and physical conditioning, *European Journal of Applied Physiology and Occupational Physiology, 68*(2), pp. 111-115.

Field, A. (2009) Discovering statistics using spss third edition,

Flanagan, E.P. and Comyns, T.M. (2008) The use of contact time and the reactive strength index to optimize fast stretch-shortening cycle training, *Strength & Conditioning Journal, 30*(5), pp. 32-38.

Fouré, A., Nordez, A., McNair, P. and Cornu, C. (2011) Effects of plyometric training on both active and passive parts of the plantarflexors series elastic component stiffness of muscle–tendon complex, *European Journal of Applied Physiology, 111*(3), pp. 539-548.

Franchi, M., Trirè, A., Quaranta, M., Orsini, E. and Ottani, V. (2007) Collagen structure of tendon relates to function, *TheScientificWorldJOURNAL, 7*, pp. 404-420.

Fritz, C.O., Morris, P.E. and Richler, J.J. (2012) Effect size estimates: current use, calculations, and interpretation, *Journal of Experimental Psychology: General, 141*(1), p 2.

Frost, G., Bar-Or, O., Dowling, J. and Dyson, K. (2002) Explaining differences in the metabolic cost and efficiency of treadmill locomotion in children, *Journal of Sports Sciences, 20*(6), pp. 451-461.

Frost, G., Dowling, J., Dyson, K. and Bar-Or, O. (1997) Cocontraction in three age groups of children during treadmill locomotion, *Journal of Electromyography and Kinesiology, 7*(3), pp. 179-186.

Fukashiro, S., Besier, T.F., Barrett, R., Cochrane, J., Nagano, A. and Lloyd, D.G. (2005) Direction control in standing horizontal and vertical jumps, *International Journal of Sport and Health Science, 3*(Special_Issue_2005), pp. 272-279.

Fukunaga, T. and Funato, K. (1992) The effects of resistance training on muscle area and strength in prepubescent age, *The Annals of physiological anthropology, 11*(3), pp. 357-364.

Fukunaga, T., Miyatani, M., Tachi, M., Kouzaki, M., Kawakami, Y. and Kanehisa, H. (2001) Muscle volume is a major determinant of joint torque in humans, *Acta Physiologica Scandinavica, 172*(4), pp. 249-255.

Fukutani, A. and Kurihara, T. (2015) Comparison of the muscle fascicle length between resistance-trained and untrained individuals: cross-sectional observation, *Springerplus, 4*(1), pp. 1-6.

Fukutani, A., Kurihara, T. and Isaka, T. (2015) Factors of force potentiation induced by stretch-shortening cycle in plantarflexors, *PloS One, 10*(6), p e0120579.

Fukutani, A., Misaki, J. and Isaka, T. (2016) Effect of preactivation on torque enhancement by the stretch-shortening cycle in knee extensors, *PloS One, 11*(7), p e0159058.

Gans, C. (1982) Fiber architecture and muscle function, *Exercise and Sport Sciences Reviews, 10*(1), pp. 160-207.

Gartlehner, G., Affengruber, L., Titscher, V., Noel-Storr, A., Dooley, G., Ballarini, N. and König, F. (2020) Single-reviewer abstract screening missed 13 percent of relevant studies: a crowd-based, randomized controlled trial, *Journal of Clinical Epidemiology, 121*, pp. 20-28.

Gavaghan, D.J., Moore, R.A. and McQuay, H.J. (2000) An evaluation of homogeneity tests in meta-analyses in pain using simulations of individual patient data, *Pain, 85*(3), pp. 415-424.

Gerodimos, V., Zafeiridis, A., Perkos, S., Dipla, K., Manou, V. and Kellis, S. (2008) The contribution of stretch-shortening cycle and arm-swing to vertical jumping performance in children, adolescents, and adult basketball players, *Pediatric Exercise Science, 20*(4), pp. 379-389.

Gillen, Z.M., Jahn, L.E., Shoemaker, M.E., McKay, B.D., Mendez, A.I., Bohannon, N.A. and Cramer, J.T. (2019) Effects of eccentric preloading on concentric vertical jump performance in youth athletes, *Journal of Applied Biomechanics, 35*(5), pp. 327-335.

Granacher, U., Goesele, A., Roggo, K., Wischer, T., Fischer, S., Zuerny, C., Gollhofer, A. and Kriemler, S. (2011) Effects and mechanisms of strength training in children, *International Journal of Sports Medicine, 32*(05), pp. 357-364.

Granacher, U., Lesinski, M., Büsch, D., Muehlbauer, T., Prieske, O., Puta, C., Gollhofer, A. and Behm, D.G. (2016) Effects of resistance training in youth athletes on muscular fitness and athletic performance: a conceptual model for long-term athlete development, *Frontiers in Physiology, 7*, p 164.

Greulich, W. and Pyle, S. (1959) *Radiographic atlas of skeletal development of the hand and wrist* Californa, USA: Stanford University Press.

Grimby, L. and Hannerz, J. (1968) Recruitment order of motor units on voluntary contraction: changes induced by proprioceptive afferent activity, *Journal of neurology, neurosurgery, and psychiatry, 31*(6), p 565.

Grosset, J.-F., Mora, I., Lambertz, D. and Pérot, C. (2007) Changes in stretch reflexes and muscle stiffness with age in prepubescent children, *Journal of Applied Physiology, 102*(6), pp. 2352-2360.

Grosset, J.-F., Piscione, J., Lambertz, D. and Pérot, C. (2009) Paired changes in electromechanical delay and musculo-tendinous stiffness after endurance or plyometric training, *European Journal of Applied Physiology, 105*(1), p 131.

Grosset, J.F., Mora, I., Lambertz, D. and Pérot, C. (2008) Voluntary activation of the triceps surae in prepubertal children, *Journal of Electromyography and Kinesiology, 18*(3), pp. 455-465.

Guex, K., Degache, F., Morisod, C., Sailly, M. and Millet, G.P. (2016) Hamstring architectural and functional adaptations following long vs. short muscle length eccentric training, *Frontiers in Physiology, 7*, p 340.

Halin, R., Germain, P., Bercier, S., Kapitaniak, B. and Buttelli, O. (2003) Neuromuscular response of young boys versus men during sustained maximal contraction, *Medicine and Science in Sports and Exercise, 35*(6), pp. 1042-1048.

Hamill, B. (1994) Relative safety of weightlifting and weight training, *Journal of Strength and Conditioning Research, 8*(1), pp. 53-57.

Hannerz, J. (1974) Discharge properties of motor units in relation to recruitment order in voluntary contraction, *Acta Physiologica Scandinavica, 91*(3), pp. 374-384.

Harridge, S., Bottinelli, R., Canepari, M., Pellegrino, M., Reggiani, C., Esbjörnsson, M. and Saltin, B. (1996) Whole-muscle and single-fibre contractile properties and myosin heavy chain isoforms in humans, *Pflügers Archiv, 432*(5), pp. 913-920.

Harrison, A.J. and Gaffney, S. (2001) Motor development and gender effects on stretch-shortening cycle performance, *Journal of Science and Medicine in Sport, 4*(4), pp. 406-415.

Healy, R., Kenny, I.C. and Harrison, A.J. (2018) Reactive strength index: a poor indicator of reactive strength?, *International Journal of Sports Physiology and Performance, 13*(6), pp. 802-809.

Hedges, L.V. and Olkin, I. (2014) *Statistical methods for meta-analysis*: Academic press.

Hedrick, A. (1993) Strength Training: Literature Review High Speed Resistance Training, *Strength & Conditioning Journal, 15*(6), pp. 22-30.

Henchoz, Y., Malatesta, D., Gremion, G. and Belli, A. (2006) Effects of the transition time between muscle-tendon stretch and shortening on mechanical efficiency, *European Journal of Applied Physiology, 96*(6), pp. 665-671.

Henneman, E. (1957) Relation between size of neurons and their susceptibility to discharge, *Science, 126*(3287), pp. 1345-1347.

Hernández, S., Ramirez-Campillo, R., Álvarez, C., Sanchez-Sanchez, J., Moran, J., Pereira, L.A. and Loturco, I. (2018) Effects of plyometric training on neuromuscular performance in youth basketball players: a pilot study on the influence of drill randomization, *Journal of Sports Science & Medicine, 17*(3), p 372.

Hewett, T.E., Myer, G.D., Ford, K.R. and Slauterbeck, J.R. (2006) Preparticipation physical examination using a box drop vertical jump test in young athletes: the effects of puberty and sex, *Clinical Journal of Sport Medicine, 16*(4), pp. 298-304.

Higgins, J.P., Thompson, S.G., Deeks, J.J. and Altman, D.G. (2003) Measuring inconsistency in meta-analyses, *BMJ, 327*(7414), pp. 557-560.

Hiort, O. (2002) Androgens and puberty, *Best Practice & Research Clinical Endocrinology & Metabolism, 16*(1), pp. 31-41.

Hobara, H., Kanosue, K. and Suzuki, S. (2007) Changes in muscle activity with increase in leg stiffness during hopping, *Neuroscience Letters, 418*(1), pp. 55-59.

Hobara, H., Kimura, K., Omuro, K., Gomi, K., Muraoka, T., Iso, S. and Kanosue, K. (2008) Determinants of difference in leg stiffness between endurance-and power-trained athletes, *Journal of Biomechanics, 41*(3), pp. 506-514.

Hodson-Tole, E.F. and Wakeling, J.M. (2009) Motor unit recruitment for dynamic tasks: current understanding and future directions, *Journal of Comparative Physiology B, 179*(1), pp. 57-66.

Hoffren, M., Ishikawa, M. and Komi, P.V. (2007) Age-related neuromuscular function during drop jumps, *Journal of Applied Physiology, 103*(4), pp. 1276-1283.

Hopkins, W., Marshall, S., Batterham, A. and Hanin, J. (2009) Progressive statistics for studies in sports medicine and exercise science, *Medicine+ Science in Sports+ Exercise, 41*(1), p 3.

Hopkins, W.G. (2017) Spreadsheets for analysis of validity and reliability, *Sportscience, 21*

Hopper, A.J., Haff, E.E., Joyce, C., Lloyd, R.S. and Haff, G.G. (2017) Neuromuscular training improves lower extremity biomechanics associated with knee injury during landing in 11–13 year old female netball athletes: A randomized control study, *Frontiers in Physiology, 8*, p 883.

Horita, T., Komi, P., Nicol, C. and Kyröläinen, H. (2002) Interaction between pre-landing activities and stiffness regulation of the knee joint musculoskeletal system in the drop jump: implications to performance, *European Journal of Applied Physiology, 88*(1-2), pp. 76-84.

Housh, T.J., Johnson, G.O., Housh, D.J., Stout, J.R., Weir, J.P., Weir, L.L. and Eckerson, J.M. (1996) Isokinetic peak torque in young wrestlers, *Pediatric Exercise Science, 8*(2), pp. 143-155.

Hreljac, A. (2004) Impact and overuse injuries in runners, *Medicine and Science in Sports and Exercise, 36*(5), pp. 845-849.

Hudelmaier, M., Wirth, W., Himmer, M., Ring ‐ Dimitriou, S., Sänger, A. and Eckstein, F. (2010) Effect of exercise intervention on thigh muscle volume and anatomical cross ‐ sectional areas—Quantitative assessment using MRI, *Magnetic Resonance in Medicine, 64*(6), pp. 1713-1720.

Hughes, D., Babbs, C.F., Geddes, L. and Bourland, J. (1979) Measurements of Young's modulus of elasticity of the canine aorta with ultrasound, *Ultrasonic Imaging, 1*(4), pp. 356-367.

Hume, P. and Russell, K. (2014) Overuse injuries and injury prevention strategies for youths, *Strength and conditioning for young athletes: science and application/ed. by RS Lloyd, JL Oliver.–London*, pp. 200-212.

Hunter, J.P. and Marshall, R.N. (2002) Effects of power and flexibility training on vertical jump technique, *Medicine and Science in Sports and Exercise, 34*(3), pp. 478-486.

Ikai, M. and Fukunaga, T. (1970) A study on training effect on strength per unit cross-sectional area of muscle by means of ultrasonic measurement, *Internationale Zeitschrift für Angewandte Physiologie Einschliesslich Arbeitsphysiologie, 28*(3), pp. 173-180.

Jaric, S., Mirkov, D. and Markovic, G. (2005) Normalizing physical performance tests for body size: aproposal for standardization, *The Journal of Strength & Conditioning Research, 19*(2), pp. 467-474.

Jeffreys, I. (2006) Warm up revisited–the 'ramp'method of optimising performance preparation, *UKSCA Journal, 6*, pp. 15-19.

Jidovtseff, B., Quievre, J., Nigel, H. and Cronin, J. (2014) Influence of jumping strategy on kinetic and kinematic variables, *Journal of sports medicine and physical fitness, 54*, pp. 129-138.

Jones, E.J., Bishop, P.A., Woods, A.K. and Green, J.M. (2008) Cross-sectional area and muscular strength, *Sports Medicine, 38*(12), pp. 987-994.

Jones, G.M. and Watt, D.G.D. (1971) Observations on the control of stepping and hopping movements in man, *The Journal of physiology, 219*(3), pp. 709-727.

Jones, S.L. and Caldwell, G.E. (2003) Mono-and biarticular muscle activity during jumping in different directions, *Journal of Applied Biomechanics, 19*(3), pp. 205-222.

Kanehisa, H., Ikegawa, S., Tsunoda, N. and Fukunaga, T. (1995) Strength and cross-sectional areas of reciprocal muscle groups in the upper arm and thigh during adolescence, *International Journal of Sports Medicine, 16*(01), pp. 54-60.

Karagianni, K., Donti, O., Katsikas, C. and Bogdanis, G.C. (2020) Effects of Supplementary Strength–Power Training on Neuromuscular Performance in Young Female Athletes, *Sports, 8*(8), p 104.

Kastelic, J., Palley, I. and Baer, E. (1980) A structural mechanical model for tendon crimping, *Journal of Biomechanics, 13*(10), pp. 887-893.

Katsikari, K., Bassa, E., Skoufas, D., Lazaridis, S., Kotzamanidis, C. and Patikas, D.A. (2020) Kinetic and kinematic changes in vertical jump in prepubescent girls after 10 weeks of plyometric training, *Pediatric Exercise Science, 32*(2), pp. 81-88.

Kawakami, Y., Abe, T. and Fukunaga, T. (1993) Muscle-fiber pennation angles are greater in hypertrophied than in normal muscles, *Journal of Applied Physiology, 74*(6), pp. 2740-2744.

Kawakami, Y., Abe, T., Kuno, S.-Y. and Fukunaga, T. (1995) Training-induced changes in muscle architecture and specific tension, *European Journal of Applied Physiology and Occupational Physiology, 72*(1-2), pp. 37-43.

Kawakami, Y., Ichinose, Y., Kubo, K., Ito, M., Imai, M. and Fukunaga, T. (2000) Architecture of contracting human muscles and its functional significance, *Journal of Applied Biomechanics, 16*(1), pp. 88-97.

Keiner, M., Sander, A., Hartmann, H., Mickel, C. and Wirth, K. (2018) Do long-term strength training and age affect the performance of drop jumps in adolescents? Separating the effects of training and age, *Journal of Australian Strength & Conditioning, 26*(4), pp. 24-38.

Keiner, M., Sander, A., Wirth, K., Caruso, O., Immesberger, P. and Zawieja, M. (2013) Strength performance in youth: trainability of adolescents and children in the back and front squats, *The Journal of Strength & Conditioning Research, 27*(2), pp. 357-362.

Keiner, M., Sander, A., Wirth, K. and Schmidtbleicher, D. (2014a) The impact of 2 years of additional athletic training on the jump performance of young athletes, *Science & Sports, 29*(4), pp. e39-e46.

Keiner, M., Sander, A., Wirth, K. and Schmidtbleicher, D. (2014b) Long-term strength training effects on change-of-direction sprint performance, *The Journal of Strength & Conditioning Research, 28*(1), pp. 223-231.

Khamis, H.J. and Roche, A.F. (1994) Predicting adult stature without using skeletal age: the Khamis-Roche method, *Pediatrics, 94*(4), pp. 504-507.

Kijowksi, K.N., Capps, C.R., Goodman, C.L., Erickson, T.M., Knorr, D.P., Triplett, N.T., Awelewa, O.O. and McBride, J.M. (2015) Short-term resistance and plyometric training improves eccentric phase kinetics in jumping, *The Journal of Strength & Conditioning Research, 29*(8), pp. 2186-2196.

Kirby, T.J., McBride, J.M., Haines, T.L. and Dayne, A.M. (2011) Relative net vertical impulse determines jumping performance, *Journal of Applied Biomechanics, 27*(3), pp. 207-214.

Knight, C. and Kamen, G. (2001) Adaptations in muscular activation of the knee extensor muscles with strength training in young and older adults, *Journal of Electromyography and Kinesiology, 11*(6), pp. 405-412.

Koh, T.H. and Eyre, J.A. (1988) Maturation of corticospinal tracts assessed by electromagnetic stimulation of the motor cortex, *Archives of Disease in Childhood, 63*(11), pp. 1347-1352.

Komi, P.V. (2000) Stretch-shortening cycle: a powerful model to study normal and fatigued muscle, *Journal of Biomechanics, 33*(10), pp. 1197-1206.

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

Komi, P.V. and Gollhofer, A. (1997) Stretch reflexes can have an important role in force enhancement during SSC exercise, *Journal of Applied Biomechanics, 13*(4), pp. 451-460.

Koo, T.K. and Li, M.Y. (2016) A guideline of selecting and reporting intraclass correlation coefficients for reliability research, *Journal of Chiropractic Medicine, 15*(2), pp. 155-163.

Korff, T., Horne, S.L., Cullen, S.J. and Blazevich, A.J. (2009) Development of lower limb stiffness and its contribution to maximum vertical jumping power during adolescence, *Journal of Experimental Biology, 212*(22), pp. 3737-3742.

Kraemer, W.J. and Ratamess, N.A. (2004) Fundamentals of resistance training: progression and exercise prescription, *Medicine and Science in Sports and Exercise, 36*(4), pp. 674-688.

Krzysztofik, M., Wilk, M., Wojdała, G. and Gołaś, A. (2019) Maximizing muscle hypertrophy: a systematic review of advanced resistance training techniques and methods, *International Journal of Environmental Research and Public Health, 16*(24), p 4897.

Kubo, K., Kanehisa, H., Kawakami, Y. and Fukanaga, T. (2001) Growth changes in the elastic properties of human tendon structures, *International Journal of Sports Medicine, 22*(02), pp. 138-143.

Kubo, K., Teshima, T., Hirose, N. and Tsunoda, N. (2014a) A cross-sectional study of the plantar flexor muscle and tendon during growth, *International Journal of Sports Medicine, 35*(10), pp. 828-834.

Kubo, K., Teshima, T., Hirose, N. and Tsunoda, N. (2014b) Growth changes in morphological and mechanical properties of human patellar tendon in vivo, *Journal of Applied Biomechanics, 30*(3), pp. 415-422.

Kubo, K., Teshima, T., Ikebukuro, T., Hirose, N. and Tsunoda, N. (2014c) Tendon properties and muscle architecture for knee extensors and plantar flexors in boys and men, *Clinical Biomechanics, 29*(5), pp. 506-511.

Kupa, E.J., Roy, S.H., Kandarian, S.C. and De Luca, C.J. (1995) Effects of muscle fiber type and size on EMG median frequency and conduction velocity, *Journal of Applied Physiology, 79*(1), pp. 23-32.

Kurokawa, S., Fukunaga, T. and Fukashiro, S. (2001) Behavior of fascicles and tendinous structures of human gastrocnemius during vertical jumping, *Journal of Applied Physiology*

Kurokawa, S., Fukunaga, T., Nagano, A. and Fukashiro, S. (2003) Interaction between fascicles and tendinous structures during counter movement jumping investigated in vivo, *Journal of Applied Physiology, 95*(6), pp. 2306-2314.

Laffaye, G., Choukou, M., Benguigui, N. and Padulo, J. (2016) Age-and gender-related development of stretch shortening cycle during a sub-maximal hopping task, *Biology of Sport, 33*(1), p 29.

Lagas, I.F., Meuffels, D.E., Visser, E., Groot, F.P., Reijman, M., Verhaar, J.A. and de Vos, R.-J. (2019) High knee loading in male adolescent pre-professional football players: Effects of a targeted training programme, *Journal of Science and Medicine in Sport, 22*(2), pp. 164-168.

Lambertz, D., Mora, I., Grosset, J.-F. and Pérot, C. (2003) An evaluation of musculo-tendinous stiffness in prepubertal children and adults, taking into account muscle activity, *Journal of Applied Physiology*

LaStayo, P.C., Woolf, J.M., Lewek, M.D., Snyder-Mackler, L., Reich, T. and Lindstedt, S.L. (2003) Eccentric muscle contractions: their contribution to injury, prevention, rehabilitation, and sport, *Journal of Orthopaedic and Sports Physical Therapy, 33*(10), pp. 557-571.

Latorre Román, P.Á., Villar Macias, F.J. and García Pinillos, F. (2018) Effects of a contrast training programme on jumping, sprinting and agility performance of prepubertal basketball players, *Journal of Sports Sciences, 36*(7), pp. 802-808.

Lazaridis, S., Bassa, E., Patikas, D., Giakas, G., Gollhofer, A. and Kotzamanidis, C. (2010) Neuromuscular differences between prepubescents boys and adult men during drop jump, *European Journal of Applied Physiology, 110*(1), pp. 67-74.

Leard, J.S., Cirillo, M.A., Katsnelson, E., Kimiatek, D.A., Miller, T.W., Trebincevic, K. and Garbalosa, J.C. (2007) Validity of two alternative systems for measuring vertical jump height, *The Journal of Strength & Conditioning Research, 21*(4), pp. 1296-1299.

Lees, A., Vanrenterghem, J. and De Clercq, D. (2004) Understanding how an arm swing enhances performance in the vertical jump, *Journal of Biomechanics, 37*(12), pp. 1929-1940.

Legerlotz, K., Marzilger, R., Bohm, S. and Arampatzis, A. (2016) Physiological adaptations following resistance training in youth athletes—a narrative review, *Pediatric Exercise Science, 28*(4), pp. 501-520.

Lesinski, M., Prieske, O. and Granacher, U. (2016) Effects and dose–response relationships of resistance training on physical performance in youth athletes: a systematic review and meta-analysis, *British Journal of Sports Medicine, 50*(13), pp. 781-795.

Lillegard, W.A., Brown, E.W., Wilson, D.J., Henderson, R. and Lewis, E. (1997) Efficacy of strength training in prepubescent to early postpubescent males and females: effects of gender and maturity, *Pediatric Rehabilitation, 1*(3), pp. 147-157.

Lindblom, H., Waldén, M., Carlfjord, S. and Hägglund, M. (2020) Limited positive effects on jump-landing technique in girls but not in boys after 8 weeks of injury prevention exercise training in youth football, *Knee Surgery, Sports Traumatology, Arthroscopy, 28*(2), pp. 528-537.

Lloyd, R. and Oliver, J. (2013a). The impact of growth and maturation on physical performance *Strength and Conditioning for Young Athletes* (pp. 25-40): Routledge.

Lloyd, R.S., Faigenbaum, A.D., Myer, G., Stone, M., Oliver, J., Jeffreys, I. and Pierce, K. (2012a) UKSCA position statement: Youth resistance training, *Prof Strength Cond, 26*, pp. 26-39.

Lloyd, R.S., Faigenbaum, A.D., Stone, M.H., Oliver, J.L., Jeffreys, I., Moody, J.A., Brewer, C., Pierce, K.C., McCambridge, T.M. and Howard, R. (2014) Position statement on youth resistance training: the 2014 International Consensus, *British Journal of Sports Medicine, 48*(7), pp. 498-505.

Lloyd, R.S., Oliver, J., Hughes, M.G. and Williams, C.A. (2011a) Specificity of test selection for the appropriate assessment of different measures of stretch-shortening cycle function in children, *The Journal of sports medicine and physical fitness, 51*(4), p 595.

Lloyd, R.S. and Oliver, J.L. (2012) The youth physical development model: A new approach to long-term athletic development, *Strength & Conditioning Journal, 34*(3), pp. 61-72.

Lloyd, R.S. and Oliver, J.L. (2013b) *Strength and conditioning for young athletes: Science and application*: Routledge.

Lloyd, R.S. and Oliver, J.L. (2019) *Strength and conditioning for young athletes: science and application*: Routledge.

Lloyd, R.S., Oliver, J.L., Hughes, M.G. and Williams, C.A. (2011b) The influence of chronological age on periods of accelerated adaptation of stretch-shortening cycle performance in pre and postpubescent boys, *The Journal of Strength & Conditioning Research, 25*(7), pp. 1889-1897.

Lloyd, R.S., Oliver, J.L., Hughes, M.G. and Williams, C.A. (2012b) Age-related differences in the neural regulation of stretch–shortening cycle activities in male youths during maximal and sub-maximal hopping, *Journal of Electromyography and Kinesiology, 22*(1), pp. 37-43.

Lloyd, R.S., Oliver, J.L., Hughes, M.G. and Williams, C.A. (2012c) The effects of 4-weeks of plyometric training on reactive strength index and leg stiffness in male youths, *The Journal of Strength & Conditioning Research, 26*(10), pp. 2812-2819.

Lloyd, R.S., Radnor, J.M., Croix, M.B.D.S., Cronin, J.B. and Oliver, J.L. (2016) Changes in sprint and jump performances after traditional, plyometric, and combined resistance training in male youth pre-and post-peak height velocity, *The Journal of Strength & Conditioning Research, 30*(5), pp. 1239-1247.

Malina, R.M., Bouchard, C. and Bar-Or, O. (2004) *Growth, maturation, and physical activity*: Human kinetics.

Markovic, G. and Mikulic, P. (2010) Neuro-musculoskeletal and performance adaptations to lower-extremity plyometric training, *Sports Medicine, 40*(10), pp. 859-895.

Markwick, W.J., Bird, S.P., Tufano, J.J., Seitz, L.B. and Haff, G.G. (2015) The intraday reliability of the Reactive Strength Index calculated from a drop jump in professional men's basketball, *International Journal of Sports Physiology and Performance, 10*(4), pp. 482-488.

Marshall, B.M. and Moran, K.A. (2013) Which drop jump technique is most effective at enhancing countermovement jump ability,"countermovement" drop jump or "bounce" drop jump?, *Journal of Sports Sciences, 31*(12), pp. 1368-1374.

Marshall, P.W., McEwen, M. and Robbins, D.W. (2011) Strength and neuromuscular adaptation following one, four, and eight sets of high intensity resistance exercise in trained males, *European Journal of Applied Physiology, 111*(12), pp. 3007-3016.

Matavulj, D., Kukolj, M., Ugarkovic, D., Tihanyi, J. and Jaric, S. (2001) Effects of pylometric training on jumping performance in junior basketball players, *Journal of sports medicine and physical fitness, 41*(2), pp. 159-164.

Maughan, R.J., Watson, J.S. and Weir, J. (1983) Relationships between muscle strength and muscle cross-sectional area in male sprinters and endurance runners, *European Journal of Applied Physiology and Occupational Physiology, 50*(3), pp. 309-318.

McBride, J.M., Kirby, T.J., Haines, T.L. and Skinner, J. (2010) Relationship between relative net vertical impulse and jump height in jump squats performed to various squat depths and with various loads, *International Journal of Sports Physiology and Performance, 5*(4), pp. 484-496.

McBride, J.M., Triplett-McBride, T., Davie, A. and Newton, R.U. (2002) The effect of heavy-vs. light-load jump squats on the development of strength, power, and speed, *The Journal of Strength & Conditioning Research, 16*(1), pp. 75-82.

McCaulley, G.O., Cormie, P., Cavill, M.J., Nuzzo, J.L., Urbiztondo, Z.G. and McBride, J.M. (2007) Mechanical efficiency during repetitive vertical jumping, *European Journal of Applied Physiology, 101*(1), pp. 115-123.

McClymont, D. (2003). *Use of the reactive strength index (RSI) as an indicator of plyometric training conditions.* Science and Football V: The proceedings of the fifth World Congress on Sports Science and Football, Lisbon, Portugal.

McDonagh, M. and Raina, P. (2013) Avoiding bias in selecting studies methods guide for effectiveness and comparative effectiveness reviews, *Rockville (MD): Agency for Healthcare Research and Quality (US)*

McEvoy, K.P. and Newton, R.U. (1998) Baseball throwing speed and base running speed: The effects of ballistic resistance training, *The Journal of Strength & Conditioning Research, 12*(4), pp. 216-221.

McKay, H., Tsang, G., Heinonen, A., MacKelvie, K., Sanderson, D. and Khan, K. (2005) Ground reaction forces associated with an effective elementary school based jumping intervention, *British Journal of Sports Medicine, 39*(1), pp. 10-14.

McKinlay, B.J., Wallace, P., Dotan, R., Long, D., Tokuno, C., Gabriel, D.A. and Falk, B. (2018) Effects of plyometric and resistance training on muscle strength, explosiveness, and neuromuscular function in young adolescent soccer players, *The Journal of Strength & Conditioning Research, 32*(11), pp. 3039-3050.

McMahon, J.J., Comfort, P. and Pearson, S. (2012) Lower limb stiffness: Effect on performance and training considerations, *Strength & Conditioning Journal, 34*(6), pp. 94-101.

McMahon, T.A. and Cheng, G.C. (1990) The mechanics of running: how does stiffness couple with speed?, *Journal of Biomechanics, 23*, pp. 65-78.

McNitt-Gray, J.L. (1993) Kinetics of the lower extremities during drop landings from three heights, *Journal of Biomechanics, 26*(9), pp. 1037-1046.

Metaxas, T.I., Mandroukas, A., Vamvakoudis, E., Kotoglou, K., Ekblom, B. and Mandroukas, K. (2014) Muscle fiber characteristics, satellite cells and soccer performance in young athletes, *Journal of Sports Science & Medicine, 13*(3), p 493.

Meyers, R.W., Moeskops, S., Oliver, J.L., Hughes, M.G., Cronin, J.B. and Lloyd, R.S. (2019) Lower-limb stiffness and maximal sprint speed in 11–16-year-old boys, *The Journal of Strength & Conditioning Research, 33*(7), pp. 1987-1995.

Meyers, R.W., Oliver, J.L., Hughes, M.G., Cronin, J.B. and Lloyd, R.S. (2015) Maximal sprint speed in boys of increasing maturity, *Pediatric Exercise Science, 27*(1), pp. 85-94.

Meyers, R.W., Oliver, J.L., Hughes, M.G., Lloyd, R.S. and Cronin, J.B. (2017) Influence of age, maturity, and body size on the spatiotemporal determinants of maximal sprint speed in boys, *Journal of Strength and Conditioning Research, 31*(4), pp. 1009-1016.

Meylan, C. and Malatesta, D. (2009) Effects of in-season plyometric training within soccer practice on explosive actions of young players, *The Journal of Strength & Conditioning Research, 23*(9), pp. 2605-2613.

Meylan, C.M., Cronin, J.B., Oliver, J.L., Hughes, M.G. and McMaster, D. (2012) The reliability of jump kinematics and kinetics in children of different maturity status, *The Journal of Strength & Conditioning Research, 26*(4), pp. 1015-1026.

Meylan, C.M., Nosaka, K., Green, J.P. and Cronin, J.B. (2010) Variability and influence of eccentric kinematics on unilateral vertical, horizontal, and lateral countermovement jump performance, *The Journal of Strength & Conditioning Research, 24*(3), pp. 840-845.

Michailidis, Y., Fatouros, I.G., Primpa, E., Michailidis, C., Avloniti, A., Chatzinikolaou, A., Barbero-Álvarez, J.C., Tsoukas, D., Douroudos, I.I. and Draganidis, D. (2013) Plyometrics' trainability in preadolescent soccer athletes, *The Journal of Strength & Conditioning Research, 27*(1), pp. 38-49.

Milner-Brown, H., Stein, R. and Yemm, R. (1973) The orderly recruitment of human motor units during voluntary isometric contractions, *The Journal of physiology, 230*(2), p 359.

Milner, T. and Cloutier, C. (1995). *The effect of antagonist muscle co-contraction on damping of the wrist joint during voluntary movement.* Proceedings of 17th International Conference of the Engineering in Medicine and Biology Society.

Mirwald, R.L., Baxter-Jones, A.D., Bailey, D.A. and BEUNEN, G.P. (2002) An assessment of maturity from anthropometric measurements, *Medicine and Science in Sports and Exercise, 34*(4), pp. 689-694.

Mitchell, C., Cohen, R., Dotan, R., Gabriel, D., Klentrou, P. and Falk, B. (2011) Rate of muscle activation in power-and endurance-trained boys, *International Journal of Sports Physiology and Performance, 6*(1), pp. 94-105.

Moeskops, S., Oliver, J.L., Read, P.J., Cronin, J.B., Myer, G.D., Haff, G.G. and Lloyd, R.S. (2020) The influence of biological maturity and competitive level on isometric force-time curve variables and vaulting performance in young female gymnasts, *The Journal of Strength & Conditioning Research, 34*(8), pp. 2136-2145.

Moeskops, S., Oliver, J.L., Read, P.J., Myer, G.D. and Lloyd, R.S. (2021) The Influence of Biological Maturity on Sprint Speed, Standing Long Jump, and Vaulting Performance in Young Female Gymnasts, *International Journal of Sports Physiology and Performance, 1*(aop), pp. 1-8.

Moeskops, S., Read, P.J., Oliver, J.L. and Lloyd, R.S. (2018) Individual responses to an 8-week neuromuscular training intervention in trained pre-pubescent female artistic gymnasts, *Sports, 6*(4), p 128.

Mont, M.A., Cohen, D.B., Campbell, K.R., Gravare, K. and Mathur, S.K. (1994) Isokinetic concentric versus eccentric training of shoulder rotators with functional evaluation of performance enhancement in elite tennis players, *The American journal of sports medicine, 22*(4), pp. 513-517.

Morris, J. (2008) Oxford Dictionary of Sports Science and Medicine, Michael Kent, *Book reviews, 94*, pp. 260-264.

Myer, G.D., Ford, K.R., PALUMBO, O.P. and Hewett, T.E. (2005) Neuromuscular training improves performance and lower-extremity biomechanics in female athletes, *The Journal of Strength & Conditioning Research, 19*(1), pp. 51-60.

Nakazawa, K., Kawakami, Y., Fukunaga, T., Yano, H. and Miyashita, M. (1993) Differences in activation patterns in elbow flexor muscles during isometric, concentric and eccentric contractions, *European Journal of Applied Physiology and Occupational Physiology, 66*(3), pp. 214-220.

Nasirzade, A., Ehsanbakhsh, A., Ilbeygi, S., Sobhkhiz, A., Argavani, H. and Aliakbari, M. (2014) Relationship between sprint performance of front crawl swimming and muscle fascicle length in young swimmers, *Journal of Sports Science & Medicine, 13*(3), p 550.

Negra, Y., Chaabene, H., Fernandez-Fernandez, J., Sammoud, S., Bouguezzi, R., Prieske, O. and Granacher, U. (2020) Short-term plyometric jump training improves repeated-sprint ability in prepuberal male soccer players, *The Journal of Strength & Conditioning Research, 34*(11), pp. 3241-3249.

Newton, R.U. and Kraemer, W.J. (1994) Developing explosive muscular power: Implications for a mixed methods training strategy, *Strength & Conditioning Journal, 16*(5), pp. 20-31.

Newton, R.U., Kraemer, W.J., Häkkinen, K., Humphries, B.J. and Murphy, A.J. (1996) Kinematics, kinetics, and muscle activation during explosive upper body movements, *Journal of Applied Biomechanics, 12*(1), pp. 31-43.

Nicol, C., Komi, P. and Marconnet, P. (1991) Fatigue effects of marathon running on neuromuscular performance: I. Changes in muscle force and stiffness characteristics, *Scandinavian Journal of Medicine and Science in Sports, 1*(1), pp. 10-17.

Nunes, J.P., Grgic, J., Cunha, P.M., Ribeiro, A.S., Schoenfeld, B.J., de Salles, B.F. and Cyrino, E.S. (2021) What influence does resistance exercise order have on muscular strength gains and muscle hypertrophy? A systematic review and meta-analysis, *European journal of sport science, 21*(2), pp. 149-157.

O'Donoghue, P. (2013) *Statistics for sport and exercise studies: An introduction* London: Routledge.

O'Brien, T.D., Reeves, N.D., Baltzopoulos, V., Jones, D.A. and Maganaris, C.N. (2010a) In vivo measurements of muscle specific tension in adults and children, *Experimental Physiology, 95*(1), pp. 202-210.

O'Brien, T.D., Reeves, N.D., Baltzopoulos, V., Jones, D.A. and Maganaris, C.N. (2010b) Mechanical properties of the patellar tendon in adults and children, *Journal of Biomechanics, 43*(6), pp. 1190-1195.

O'Brien, T.D., Reeves, N.D., Baltzopoulos, V., Jones, D.A. and Maganaris, C.N. (2010c) Muscle–tendon structure and dimensions in adults and children, *Journal of Anatomy, 216*(5), pp. 631-642.

Oliver, J. and Smith, P.M. (2010) Neural control of leg stiffness during hopping in boys and men, *Journal of Electromyography and Kinesiology, 20*(5), pp. 973-979.

Oliver, J.L., Croix, M.B.D.S., Lloyd, R.S. and Williams, C.A. (2014) Altered neuromuscular control of leg stiffness following soccer-specific exercise, *European Journal of Applied Physiology, 114*(11), pp. 2241-2249.

Otsuka, M., Kurihara, T. and Isaka, T. (2018) Bilateral deficit of spring-like behaviour during hopping in sprinters, *European Journal of Applied Physiology, 118*(2), pp. 475-481.

Ovalie, W.K. (1987) The human muscle-tendon junction, *Anatomy and Embryology, 176*(3), pp. 281-294.

Pääsuke, M., Ereline, J. and Gapeyeva, H. (2001) Knee extensor muscle strength and vertical jumping performance characteristics in pre-and post-pubertal boys, *Pediatric Exercise Science, 13*(1), pp. 60-69.

Padua, D.A., Carcia, C.R., Arnold, B.L. and Granata, K.P. (2005) Gender differences in leg stiffness and stiffness recruitment strategy during two-legged hopping, *Journal of motor behavior, 37*(2), pp. 111-126.

Page, M.J., McKenzie, J.E., Bossuyt, P.M., Boutron, I., Hoffmann, T.C., Mulrow, C.D., Shamseer, L., Tetzlaff, J.M. and Moher, D. (2021) Updating guidance for reporting systematic reviews: development of the PRISMA 2020 statement, *Journal of Clinical Epidemiology, 134*, pp. 103-112.

Palma-Muñoz, I., Ramírez-Campillo, R., Azocar-Gallardo, J., Álvarez, C., Asadi, A., Moran, J. and Chaabene, H. (2021) Effects of progressed and nonprogressed volume-based overload plyometric training on components of physical fitness and body composition variables in youth male basketball players, *The Journal of Strength & Conditioning Research, 35*(6), pp. 1642-1649.

Palmer-Green, D.S., Stokes, K.A., Fuller, C.W., England, M., Kemp, S.P. and Trewartha, G. (2015) Training activities and injuries in English youth academy and schools rugby union, *The American journal of sports medicine, 43*(2), pp. 475-481.

Panagoulis, C., Chatzinikolaou, A., Avloniti, A., Leontsini, D., Deli, C.K., Draganidis, D., Stampoulis, T., Oikonomou, T., Papanikolaou, K. and Rafailakis, L. (2020) In-season integrative neuromuscular strength training improves performance of early-adolescent soccer athletes, *The Journal of Strength & Conditioning Research, 34*(2), pp. 516-526.

Papaiakovou, G., Giannakos, A., Michailidis, C., Patikas, D., Bassa, E., Kalopisis, V., Anthrakidis, N. and Kotzamanidis, C. (2009) The effect of chronological age and gender on the development of sprint performance during childhood and puberty, *The Journal of Strength & Conditioning Research, 23*(9), pp. 2568-2573.

Parry, D., Barnes, G. and Craig, A. (1978) A comparison of the size distribution of collagen fibrils in connective tissues as a function of age and a possible relation between fibril size distribution and mechanical properties, *Proceedings of the Royal Society of London. Series B. Biological Sciences, 203*(1152), pp. 305-321.

Pedley, J., Lloyd, R.S., Read, P., Moore, I., Myer, G. and Oliver, J. (2020) A novel method to categorise stretch-shortening cycle performance across maturity in youth soccer players, Pedley, J.S., Lloyd, R.S., Read, P., Moore, I.S. and Oliver, J.L. (2017) Drop jump: a technical model for scientific application, *Strength & Conditioning Journal, 39*(5), pp. 36-44.

Peitz, M., Behringer, M. and Granacher, U. (2018) A systematic review on the effects of resistance and plyometric training on physical fitness in youth-What do comparative studies tell us?, *PloS One, 13*(10), p e0205525.

Pham, M.T., Waddell, L., Rajić, A., Sargeant, J.M., Papadopoulos, A. and McEwen, S.A. (2016) Implications of applying methodological shortcuts to expedite systematic reviews: three case studies using systematic reviews from agri‐food public health, *Research synthesis methods, 7*(4), pp. 433-446.

Pierce, K., Brewer, C., Ramsey, M., Byrd, R., Sands, W.A., Stone, M.E. and Stone, M.H. (2008) Youth resistance training, *Profess Strength Cond, 10*, pp. 9-23.

Proske, U. and Morgan, D.L. (2001) Muscle damage from eccentric exercise: mechanism, mechanical signs, adaptation and clinical applications, *The Journal of physiology, 537*(2), pp. 333-345.

Quatman, C.E., Ford, K.R., Myer, G.D. and Hewett, T.E. (2006) Maturation leads to gender differences in landing force and vertical jump performance: a longitudinal study, *The American journal of sports medicine, 34*(5), pp. 806-813.

Radnor, J.M., Lloyd, R.S. and Oliver, J.L. (2017) Individual response to different forms of resistance training in school-aged boys, *Journal of Strength and Conditioning Research, 31*(3), pp. 787-797.

Radnor, J.M., Moeskops, S., Morris, S.J., Mathews, T.A., Kumar, N.T., Pullen, B.J., Meyers, R.W., Pedley, J.S., Gould, Z.I. and Oliver, J.L. (2020a) Developing athletic motor skill competencies in youth, *Strength & Conditioning Journal, 42*(6), pp. 54-70.

Radnor, J.M., Oliver, J.L., Waugh, C., Myer, G.D. and Lloyd, R.S. (2021) Muscle Architecture and Maturation Influences Sprint and Jump Ability in Young Boys: A Multi-Study Approach, *The Journal of Strength & Conditioning Research*

Radnor, J.M., Oliver, J.L., Waugh, C.M., Myer, G.D. and Lloyd, R.S. (2020b) The Influence of Maturity Status on Muscle Architecture in School-Aged Boys, *Pediatric Exercise Science, 1*(aop), pp. 1-8.

Radnor, J.M., Oliver, J.L., Waugh, C.M., Myer, G.D., Moore, I.S. and Lloyd, R.S. (2018) The influence of growth and maturation on stretch-shortening cycle function in youth, *Sports Medicine, 48*(1), pp. 57-71.

Ramirez-Campillo, R., Alvarez, C., García-Pinillos, F., Gentil, P., Moran, J., Pereira, L.A. and Loturco, I. (2019) Effects of plyometric training on physical performance of young male soccer players: potential effects of different drop jump heights, *Pediatric Exercise Science, 31*(3), pp. 306-313.

Ramirez-Campillo, R., Alvarez, C., Gentil, P., Loturco, I., Sanchez-Sanchez, J., Izquierdo, M., Moran, J., Nakamura, F.Y., Chaabene, H. and Granacher, U. (2020) Sequencing effects of plyometric training applied before or after regular soccer training on measures of physical fitness in young players, *The Journal of Strength & Conditioning Research, 34*(7), pp. 1959-1966.

Ramirez-Campillo, R., Alvarez, C., Gentil, P., Moran, J., García-Pinillos, F., Alonso-Martínez, A.M. and Izquierdo, M. (2018) Inter-individual variability in responses to 7 weeks of plyometric jump training in male youth soccer players, *Frontiers in Physiology, 9*, p 1156.

Ramirez-Campillo, R., Andrade, D.C., Álvarez, C., Henríquez-Olguín, C., Martínez, C., Báez-SanMartín, E., Silva-Urra, J., Burgos, C. and Izquierdo, M. (2014a) The effects of interset rest on adaptation to 7 weeks of explosive training in young soccer players, *Journal of Sports Science & Medicine, 13*(2), p 287.

Ramírez-Campillo, R., Burgos, C.H., Henríquez-Olguín, C., Andrade, D.C., Martínez, C., Álvarez, C., Castro-Sepúlveda, M., Marques, M.C. and Izquierdo, M. (2015a) Effect of unilateral, bilateral, and combined plyometric training on explosive and endurance performance of young soccer players, *The Journal of Strength & Conditioning Research, 29*(5), pp. 1317-1328.

Ramírez-Campillo, R., Gallardo, F., Henriquez-Olguín, C., Meylan, C.M., Martínez, C., Álvarez, C., Caniuqueo, A., Cadore, E.L. and Izquierdo, M. (2015b) Effect of vertical, horizontal, and combined plyometric training on explosive, balance, and endurance performance of young soccer players, *The Journal of Strength & Conditioning Research, 29*(7), pp. 1784-1795.

Ramírez-Campillo, R., Henríquez-Olguín, C., Burgos, C., Andrade, D.C., Zapata, D., Martínez, C., Álvarez, C., Baez, E.I., Castro-Sepúlveda, M. and Peñailillo, L. (2015c) Effect of progressive volume-based overload during plyometric training on explosive and endurance performance in young soccer players, *The Journal of Strength & Conditioning Research, 29*(7), pp. 1884-1893.

Ramírez-Campillo, R., Meylan, C., Álvarez, C., Henríquez-Olguín, C., Martínez, C., Cañas-Jamett, R., Andrade, D.C. and Izquierdo, M. (2014) Effects of in-season low-volume high-intensity plyometric training on explosive actions and endurance of young soccer players, *The Journal of Strength & Conditioning Research, 28*(5), pp. 1335-1342.

Ramírez-Campillo, R., Meylan, C.M., Álvarez-Lepín, C., Henriquez-Olguín, C., Martinez, C., Andrade, D.C., Castro-Sepúlveda, M., Burgos, C., Baez, E.I. and Izquierdo, M. (2015d) The effects of interday rest on adaptation to 6 weeks of plyometric training in young soccer players, *The Journal of Strength & Conditioning Research, 29*(4), pp. 972-979.

Ramsay, J.A., Blimkie, C.J., Smith, K., Garner, S., Macdougall, J.D. and Sale, D.G. (1990) Strength training effects in prepubescent boys, *Medicine and science in sports and exercise, 22*(5), pp. 605-614.

Ratamess, N.A., Alvar, B.A., Evetoch, T.E., Housh, T.J., Ben Kibler, W., Kraemer, W.J. and Triplett, N.T. (2009) Progression models in resistance training for healthy adults, *Medicine and Science in Sports and Exercise, 41*(3), pp. 687-708.

Reina, M., García-Rubio, J., Esteves, P.T. and Ibáñez, S.J. (2020) How external load of youth basketball players varies according to playing position, game period and playing time, *International Journal of Performance Analysis in Sport, 20*(6), pp. 917-930.

Roberts, T.J. (2002) The integrated function of muscles and tendons during locomotion, *Comparative Biochemistry and Physiology Part A: Molecular & Integrative Physiology, 133*(4), pp. 1087-1099.

Roche, A., Chumlea, W. and Thissen, D. (1988) *Assessing the Skeletal Maturity of the Hand-Wrist: Fels method* Springfield, IL: Charles C Thomas.

Rogol, A.D., Clark, P.A. and Roemmich, J.N. (2000) Growth and pubertal development in children and adolescents: effects of diet and physical activity, *The American journal of clinical nutrition, 72*(2), pp. 521S-528S.

Romero, C., Ramirez-Campillo, R., Alvarez, C., Moran, J., Slimani, M., Gonzalez, J. and Banzer, W.E. (2021) Effects of maturation on physical fitness adaptations to plyometric jump training in youth females, *Journal of Strength and Conditioning Research, 35*(10), pp. 2870-2877.

Rosas, F., Ramirez-Campillo, R., Diaz, D., Abad-Colil, F., Martinez-Salazar, C., Caniuqueo, A., Canas-Jamet, R., Loturco, I., Nakamura, F. and McKenzie, C. (2016) Jump training in youth soccer players: effects of haltere type handheld loading, *International Journal of Sports Medicine, 37*(13), pp. 1060-1065.

Rosengrant, D. (2011) Impulse-momentum diagrams, *The Physics Teacher, 49*(1), pp. 36-39.

Rowland, T. (2005) Children's Exercise Physiology. Champaign IL, *IL: Human Kinetics*

Ruddock, A. and Winter, E. (2015) Jumping depends on impulse not power, *Journal of Sports Sciences, 34*(6), pp. 584-585.

Sacks, R.D. and Roy, R.R. (1982) Architecture of the hind limb muscles of cats: functional significance, *Journal of Morphology, 173*(2), pp. 185-195.

Sahrom, S.B., Cronin, J.B. and Harris, N.K. (2013) Understanding stretch shortening cycle ability in youth, *Strength & Conditioning Journal, 35*(3), pp. 77-88.

Sander, A., Keiner, M., Wirth, K. and Schmidtbleicher, D. (2013) Influence of a 2-year strength training programme on power performance in elite youth soccer players, *European journal of sport science, 13*(5), pp. 445-451.

Sankey, S.P., Jones, P.A. and Bampouras, T. (2008) Effects of two plyometric training programmes of different intensity on vertical jump performance in high school athletes, *Serbian journal of sports sciences, 2*(4), pp. 123-130.

Santos, E.J. and Janeira, M.A. (2012) The effects of resistance training on explosive strength indicators in adolescent basketball players, *The Journal of Strength & Conditioning Research, 26*(10), pp. 2641-2647.

Schmidtbleicher, D. (1992). Training for power events. In P. Komi (Ed.), *Strength and power in sport* (Vol. 3, pp. 169–179.): Oxford: Blackwell.

Secomb, J.L., Lundgren, L.E., Farley, O.R., Tran, T.T., Nimphius, S. and Sheppard, J.M. (2015) Relationships between lower-body muscle structure and lower-body strength, power, and muscle-tendon complex stiffness, *The Journal of Strength & Conditioning Research, 29*(8), pp. 2221-2228.

Seger, J.Y. and Thorstensson, A. (2000) Muscle strength and electromyogram in boys and girls followed through puberty, *European Journal of Applied Physiology, 81*(1-2), pp. 54-61.

Seynnes, O.R., de Boer, M. and Narici, M.V. (2007) Early skeletal muscle hypertrophy and architectural changes in response to high-intensity resistance training, *Journal of Applied Physiology, 102*(1), pp. 368-373.

Smart, N.A., Waldron, M., Ismail, H., Giallauria, F., Vigorito, C., Cornelissen, V. and Dieberg, G. (2015) Validation of a new tool for the assessment of study quality and reporting in exercise training studies: TESTEX, *JBI Evidence Implementation, 13*(1), pp. 9-18.

Spector, S.A., Gardiner, P.F., Zernicke, R.F., Roy, R.R. and Edgerton, V.R. (1980) Muscle architecture and force-velocity characteristics of cat soleus and medial gastrocnemius: implications for motor control, *Journal of Neurophysiology, 44*(5), pp. 951-960.

Spurrs, R.W., Murphy, A.J. and Watsford, M.L. (2003) The effect of plyometric training on distance running performance, *European Journal of Applied Physiology, 89*(1), pp. 1-7.

Stock, M.S., Mota, J.A., Hernandez, J.M. and Thompson, B.J. (2017) Echo intensity and muscle thickness as predictors Of athleticism and isometric strength in middle ‐ school boys, *Muscle and Nerve, 55*(5), pp. 685-692.

Stokes, M. and Young, A. (1984) The contribution of reflex inhibition to arthrogenous muscle weakness, *Clinical Science, 67*(1), pp. 7-14.

Stone, M. and Mizuguchi, S. (2013) Dispelling the myths of resistance training for youths, *Strength and Conditioning for Young Athletes: Science and Application. London: Routledge*, pp. 169-184.

Stratton, G. and Oliver, J. (2013). The impact of growth and maturation on physical performance. In R. S. Lloyd & J. L. Oliver (Eds.), *Strength and conditioning for young athletes: Science and application* (pp. 3-18). Oxford: Routledge Publishing.

Streckis, V., Skurvydas, A. and Ratkevicius, A. (2007) Children are more susceptible to central fatigue than adults, *Muscle & Nerve: Official Journal of the American Association of Electrodiagnostic Medicine, 36*(3), pp. 357-363.

Stricker, P.R., Faigenbaum, A.D. and McCambridge, T.M. (2020) Resistance training for children and adolescents, *Pediatrics, 145*(6)

Struzik, A., Juras, G., Pietraszewski, B. and Rokita, A. (2016) Effect of drop jump technique on the reactive strength index, *Journal of human kinetics, 52*, p 157.

Suchomel, T.J., Nimphius, S. and Stone, M.H. (2018) Scaling isometric mid-thigh pull maximum strength in division I Athletes: are we meeting the assumptions?, *Sports Biomechanics*

Suchomel, T.J., Sands, W.A. and McNeal, J.R. (2016) Comparison of static, countermovment, and drop jumps of the upper and lower extremities in US junior national team male gymnasts, *Science of Gymnastics Journal, 8*(1)

Sullivan, G.M. and Feinn, R. (2012) Using effect size—or why the P value is not enough, *Journal of Graduate Medical Education, 4*(3), pp. 279-282.

Tanner, J., Goldstein, H. and Whitehouse, R. (1970) Standards for children's height at ages 2-9 years allowing for height of parents, *Archives of Disease in Childhood, 45*(244), pp. 755-762.

Tanner, J., MJR, H., Goldstein, H. and Cameron, N. (2001) *Assessment of skeletal maturity and prediction of adult height (TW3 method)* London: Saunders.

Tanner, J.M. (1962) *Growth at adolescence*: Blackwell Science.

Taylor, M.J., Cohen, D., Voss, C. and Sandercock, G.R. (2010) Vertical jumping and leg power normative data for English school children aged 10–15 years, *Journal of Sports Sciences, 28*(8), pp. 867-872.

Thomas, K., French, D. and Hayes, P.R. (2009) The effect of two plyometric training techniques on muscular power and agility in youth soccer players, *The Journal of Strength & Conditioning Research, 23*(1), pp. 332-335.

Tillin, N.A. and Folland, J.P. (2014) Maximal and explosive strength training elicit distinct neuromuscular adaptations, specific to the training stimulus, *European Journal of Applied Physiology, 114*(2), pp. 365-374.

Tonson, A., Ratel, S., Le Fur, Y., Cozzone, P. and Bendahan, D. (2008) Effect of maturation on the relationship between muscle size and force production, *Medicine and Science in Sports and Exercise, 40*(5), pp. 918-925.

Tsimahidis, K., Galazoulas, C., Skoufas, D., Papaiakovou, G., Bassa, E., Patikas, D. and Kotzamanidis, C. (2010) The effect of sprinting after each set of heavy resistance training on the running speed and jumping performance of young basketball players, *The Journal of Strength & Conditioning Research, 24*(8), pp. 2102-2108.

Tumkur Anil Kumar, N., Oliver, J.L., Lloyd, R.S., Pedley, J.S. and Radnor, J.M. (2021) The influence of growth, maturation and resistance training on muscle-tendon and neuromuscular adaptations: A narrative review, *Sports, 9*(5), p 59.

Turner, A.N. and Jeffreys, I. (2010) The stretch-shortening cycle: Proposed mechanisms and methods for enhancement, *Strength & Conditioning Journal, 32*(4), pp. 87-99.

Uzelac-Sciran, T., Sarabon, N. and Mikulic, P. (2020) Effects of 8-Week Jump Training Program on Sprint and Jump Performance and Leg Strength in Pre-and Post-Peak Height Velocity Aged Boys, *Journal of Sports Science and Medicine, 19*(3), pp. 547-555.

van Ingen Schenau, G.J., Bobbert, M.F. and de Haan, A. (1997a) Does elastic energy enhance work and efficiency in the stretch-shortening cycle?, *Journal of Applied Biomechanics, 13*(4), pp. 389-415.

van Ingen Schenau, G.J., Bobbert, M.F. and de Haan, A. (1997b) Mechanics and energetics of the stretch-shortening cycle: a stimulating discussion, *Journal of Applied Biomechanics, 13*(4), pp. 484-496.

Vera-Assaoka, T., Ramirez-Campillo, R., Alvarez, C., Garcia-Pinillos, F., Moran, J., Gentil, P. and Behm, D. (2020) Effects of maturation on physical fitness adaptations to plyometric drop jump training in male youth soccer players, *The Journal of Strength & Conditioning Research, 34*(10), pp. 2760-2768.

Viitasalo, J.T., Salo, A. and Lahtinen, J. (1998) Neuromuscular functioning of athletes and non-athletes in the drop jump, *European Journal of Applied Physiology and Occupational Physiology, 78*(5), pp. 432-440.

Vissing, K., Brink, M., Lønbro, S., Sørensen, H., Overgaard, K., Danborg, K., Mortensen, J., Elstrøm, O., Rosenhøj, N. and Ringgaard, S. (2008) Muscle adaptations to plyometric vs. resistance training in untrained young men, *The Journal of Strength & Conditioning Research, 22*(6), pp. 1799-1810.

Vitale, J.A., La Torre, A., Banfi, G. and Bonato, M. (2018) Effects of an 8-week body-weight neuromuscular training on dynamic balance and vertical jump performances in elite junior skiing athletes: A randomized controlled trial, *The Journal of Strength & Conditioning Research, 32*(4), pp. 911-920.

Vogt, M. and Hoppeler, H.H. (2014) Eccentric exercise: mechanisms and effects when used as training regime or training adjunct, *Journal of Applied Physiology, 116*(11), pp. 1446-1454.

Wagle, J.P., Carroll, K.M., Cunanan, A.J., Taber, C.B., Wetmore, A., Bingham, G.E., DeWeese, B.H., Sato, K., Stuart, C.A. and Stone, M.H. (2017) Comparison of the relationship between lying and standing ultrasonography measures of muscle morphology with isometric and dynamic force production capabilities, *Sports, 5*(4), p 88.

Wakeling, J.M., Blake, O.M., Wong, I., Rana, M. and Lee, S.S. (2011) Movement mechanics as a determinate of muscle structure, recruitment and coordination, *Philosophical Transactions of the Royal Society B: Biological Sciences, 366*(1570), pp. 1554-1564.

Walker, S., Trezise, J., Haff, G.G., Newton, R.U., Häkkinen, K. and Blazevich, A.J. (2020) Increased fascicle length but not patellar tendon stiffness after accentuated eccentric-load strength training in already-trained men, *European Journal of Applied Physiology, 120*(11), pp. 2371-2382.

Waugh, C., Blazevich, A., Fath, F. and Korff, T. (2012) Age‐related changes in mechanical properties of the Achilles tendon, *Journal of Anatomy, 220*(2), pp. 144-155.

Waugh, C.M., Korff, T. and Blazevich, A.J. (2017) Developmental differences in dynamic muscle–tendon behaviour: implications for movement efficiency, *Journal of Experimental Biology, 220*(7), pp. 1287-1294.

Waugh, C.M., Korff, T., Fath, F. and Blazevich, A.J. (2014) Effects of resistance training on tendon mechanical properties and rapid force production in prepubertal children, *American Journal of Physiology-Heart and Circulatory Physiology*

Wilkie, D. (1949) The relation between force and velocity in human muscle, *The Journal of physiology, 110*(3-4), pp. 249-280.

Williams, T.D., Tolusso, D.V., Fedewa, M.V. and Esco, M.R. (2017) Comparison of periodized and non-periodized resistance training on maximal strength: a meta-analysis, *Sports Medicine, 47*(10), pp. 2083-2100.

Winter, E.M. (2005) Jumping: Power or impulse, *Medicine and Science in Sports and Exercise, 37*(3), pp. 523-524.

Witvrouw, E., Mahieu, N., Roosen, P. and McNair, P. (2007) The role of stretching in tendon injuries, *British Journal of Sports Medicine, 41*(4), pp. 224-226.

Xu, Y., Zhang, S., Bao, X., Zheng, D. and Dong, F. (2020) Amplitude modulation method for acoustic radiation force impulse excitation, *IEEE Transactions on Instrumentation and Measurement, 69*(5), pp. 2429-2438.

Young, W. (1995) Laboratory strength assessment of athletes, *New studies in athletics, 10*, pp. 89-89.

Young, W.B., Pryor, J.F. and Wilson, G.J. (1995) Effect of instructions on characteristics of countermovement and drop jump performance, *Journal of Strength and Conditioning Research, 9*(4), pp. 232-236.

Zghal, F., Colson, S.S., Blain, G., Behm, D.G., Granacher, U. and Chaouachi, A. (2019) Combined resistance and plyometric training is more effective than plyometric training alone for improving physical fitness of pubertal soccer players, *Frontiers in Physiology, 10*, p 1026.

APPENDICES

APPENDIX 1 - TOOL FOR THE ASSESSMENT OF STUDY QUALITY AND REPORTING IN EXERCISE (TESTEX) SCALE

Item	Question	Additional Information	Scoring
		Study Quality	
1	Eligibility criteria specified	Eligibility criteria should be specified and fulfilled, and specific diagnostic test values should be provided for all participants.	Yes (1) /No (0)
2	Allocation concealment	It should be stated if group allocation was concealed; meaning if a patient was eligible for inclusion in the trial was unaware (when this decision was made) of which group the patient would be allocated to. Yes, if group allocation was concealed from patients eligible for inclusion in the trial (e.g., consent should be given before randomization).	Yes (1) /No (0)
3	Randomization specified	A description of the method used to allocate patients into treatment groups should be provided. Yes, if methods are described and they are truly random e.g., coin-tossing, sequence of randomly generated numbers.	Yes (1) /No (0)
4	Groups similar at baseline	Baseline data of all participants who were randomized should be presented. There should be no significant difference in the measure of the severity of the treated condition between treatment groups. 1 Point – if baseline	Yes (1) /No (0)

		data are separated by group allocation, presented and no differences are apparent.	
5	Blinding of assessor for at least one key outcome	It is not always possible to blind patients and/or therapists; however, blinding of assessors is reasonable. If assessors of primary outcome measures are blinded to the intervention allocation of the patients, this should be stated clearly.	Yes (1) /No (0)
		Study Reporting	
6	Assessment of outcome measures	The percentage of patients completing the study in both groups should be reported. 1 Point if adherence>85%, 1 point if adverse events are reported and 1 point if exercise attendance is reported.	Yes (3) /No (0)
7	Intention-to-treat analysis	When a patient withdraws, this analysis is conducted by using either the last value obtained for each of the outcome measures as a post-intervention value, or by using the baseline value as a post value. This analysis should be added to the data of those that did complete the study and an analysis conducted. 1 point for no withdrawal.	Yes (2) /No (0)
8	Between-group statistical comparisons reported	Comparison of exercise vs. comparator (control) group for the primary and at least one secondary outcome should be performed. 1 Point if between-group statistical comparisons are reported for the primary outcome measure of interest, 1-point if f between-group statistical comparisons are reported for at least one secondary outcome measure.	Yes (1) /No (0)
9	Point measures and measures of variability for all reported outcome measures	Point estimates should be provided for all outcomes, otherwise this could be deemed selective outcome reporting.	Yes (1) /No (0)

10	Activity monitoring in control groups	Between-group differences may be diluted if control patients crossover to intervention. As many as one third of patients do this, so some measure e.g. exercise diary or activity monitoring should be supplied so this effect can be measured and quantified. 1 point if control patients are asked to report their levels of physical activity and data are presented.	Yes (1) /No (0)
11	Relative exercise intensity remained constant	Exercise intensity is considered by many to be the best stimulus for adaptation. Once patients begin an exercise programme at a set intensity they will begin to adapt. Throughout the study duration the relative intensity will fall in those that do adapt. Therefore, periodic assessment of exercise capacity should be conducted and the intensity titrated up (or in those that lose fitness, titrated down) so that exercise intensity remains constant. 1 point where attempt is made to keep relative intensity constant/ absolute intensity progressive.	Yes (1) /No (0)
12	Exercise volume and energy expenditure reported	Exercise parameters; session and programme duration, session frequency, exercise training intensity and modality should be clearly reported.	Yes (1) /No (0)

APPENDIX 2 – YOUTH PHYSICAL DEVELOPMENT CENTRE ETHICS APPROVAL

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 application and letter(s) of approval in order that your School has a record of the project.

The document ***Guidelines for obtaining ethics approval*** 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.

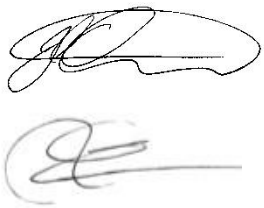
PLEASE NOTE:
Participant recruitment or data collection MUST NOT commence until ethics approval has been obtained.

PART ONE	
Name of applicant:	Prof Jon Oliver and Dr Rhodri Lloyd
Supervisor (if student project):	Click here to enter text.
School / Unit:	Sport and Health Sciences
Student number (if applicable):	Click here to enter text.
Programme enrolled on (if applicable):	Click here to enter text.
Project Title:	Long-term athletic development of children who do and do not participate in strength and conditioning
Expected start date of data collection:	01/07/2020
Approximate duration of data collection:	5 years
Funding Body (if applicable):	Click here to enter text.
Other researcher(s) working on the project:	Dr Rob Meyers, Dr John Radnor, Dr Jason Pedley, Tom Matthews, Sylvia Moeskops, Steph Morris, Saldiam Barillas, Ben Pullen, Nakul Kumar, and James Shaw. Given that other researchers will become involved in various research activites, we will be using a Delegation of Duties log to outline roles and responsibilities within the group. The log is presented at the end of this application.
Will the study involve NHS patients or staff?	No

Will the study involve taking samples of human origin from participants?	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 tissue 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 is required (e.g., NHS)	No
If you have answered YES to any of these questions, make this clear 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 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. However, very few studies have examined the long-term benefits of being involved in systematic strength and conditioning during childhood and adolescence. Similarly few studies have directly examined the influence of maturation on long-term training gains. Therefore, this study proposes to examine the wellbeing, injury risk and performance benefits of being involved in a long-term strength and conditioning programming during childhood and adolescence. **Note that this application is being submitted to replace the existing approved ethics application (16/9/01S).**

DECLARATION: **I confirm that this project conforms with the Cardiff Met Research Governance Framework**	
Signature of the applicant: 	Date: 3rd June 2019
FOR STUDENT PROJECTS ONLY	
Name of supervisor:	Date:

Signature of supervisor:

Research Ethics Committee use only	
Decision reached:	Project approved ☑ Project approved in principle ☐ Decision deferred ☐ Project not approved ☐ Project rejected ☐
Project reference number: Sta-1346	
Name: Click here to enter text.	
Date: Signature:	
Details of any conditions upon which approval is dependant: All individuals involved in data collection to have an up-to-date DBS stored on file	

PART TWO

A RESEARCH DESIGN	
A1 Will you be using an approved protocol in your project?	No
A2 If yes, please state the name and code of the approved protocol to be used[1]	
• 40 m sprint test (16/10/02L) • Two-legged countermovement jump (16/10/04L) • Single-leg countermovement jump (16/10/04L) • Drop jump from 30 cm (16/10/04L) • Yo-yo intermittent recovery test (16/10/06L) • 1 rep max bench press/back squat (16/10/07L) • Agility sprint (16/10/08L) • Isometric-mid thigh pull (16/10/09L) • Motion analysis and kinetic measurement of sports and exercise related movements and techiques (13/5/01L – re-approval 16/10/01L)	
A3 Describe the research design to be used in your project	
The Youth Physical Development (YPD) Centre at the Cardiff School of Sport has been set-up to offer local boys and girls the opportunity to receive afterschool strength and conditioning provision from within the strength and conditioning facility within NIAC. The purpose of the YPD Centre is to expose youth members to personalised strength and conditioning provision that will facilitate their athletic	

[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

development; this includes improving their athletic performance, reducing their risk of injury when engaging in sport, and improving their overall health and wellbeing.

Members will be recruited into the YPD Centre through contacts with local schools, clubs, academies and national governing bodies. Currently, cohorts trained through the YPD Centre include boys and girls from the CMU Soccer academy, tennis academy, local gymnastics clubs, Welsh kayaking, trampolining, and others. The YPD Centre will be open to children from 5 to 18 years old. Children (and their parents) will be offered the opportunity to purchase termly memberships to attend either one or two sessions per week. It is likely that some children will remain in the YPD Centre for many years, while others will be more transient. In the recruitment of volunteer participants from the YPD Centre membership it will be made clear (to both participants and their parents/guardians) that volunteering to take part in the research does not influence the training they receive when attending the Centre; all sessions will be designed to maximise individual development and fitness testing will be used to evaluate progression and inform prescription of all members (whether research participants or not). Participants can still attend the YPD Centre and participate in training even if they choose not to be included in any associated research projects.

The YPD Centre will regularly monitor and fitness test members to help evaluate programme effectiveness and inform future programme design. In this regard, all members of the YPD Centre will be exposed to a range of monitoring processes and fitness assessments. Monitoring will be an ongoing process to track training loads and wellbeing. Fitness assessment will occur between three to six times per year depending on the training phase/programme. This application is requesting access to use that information to allow data from the YPD Centre to be used for research purposes. To supplement the research, control groups will be recruited from a local school and/or sports club, where children who are not part of the YPD Centre will be longitudinally tested.

Monitoring

Members of the YPD Centre will be asked to complete a training diary each time they train at our facility. Members will need to record the exercises completed, the number of sets, reps and loads lifted. Participants will also be asked to highlight the number of other training and competition sessions completed since they last attended the YPD Centre (i.e. sessions completed outside of the academy). This will enable us to monitor training loads and volumes. In the same system, members will also be asked to rate their wellbeing using a system similar to that developed by McLean et al (2010) and previously used in youth rugby players (Oliver et al., 2015). Members will provide a score from 0-5 on factors such as their mood, quality of sleep, soreness and fatigue. Athletes will also be asked to rate their enjoyment of each training session at the academy. This information will be collected manually at first, with data then inputted into a password protected master spreadsheet by the YPD coach that is reponsible for each training group. This spreadsheet will not include any personal information. The Chair (RSL), Head of Research (JLO) and the YPD Centre coaches that deliver training to the participants will all have access to the spreadsheet. The anonymised codes used in the master spreadsheet will be stored in a separate password protected spreadsheet with personal identifiable information – this will only be accessible by The Chair (RSL), Head of Research (JLO).

Anthropometric & Maturity Assessment
Members of the YPD Centre and the control group will be assessed for their standing height, sitting height and body mass following the International Standards for Anthropometric Assessment (ISAK). Maturity will be non-invasively estimated using two methods. Firstly, anthropometric measures will be entered into a predictive equation to determine how close a participant is to their peak height velocity (middle of the growth spurt) (Mirwald et al., 2002). Secondly, parental height will be captured and used to predict the participants adult height and their current %adult height (Khamis and Roche, 1994). Parents will have the option to have their height directly measured at the Centre or to recall their height and enter this onto a consent form.

Physical Fitness Measures
Members of the YPD Centre and the control group will be regularly assessed on a range of variables chosen to reflect athletic development; this will include measures associated with both sports performance and injury risk. The control group will be tested a minimum of once per academic year and a maximum of three times per year. The YPD Centre members will be tested no more than six times per year. However, the yo-yo intermittent endurance test will only be used once per year in both groups. The pattern used will mirror the testing schedule of the YPD Centre and will allow analyses to determine the effects of training over and above growth and maturation.

Testing will include the following approved protocols:
- 40 m sprint test (16/10/02L)
- Two-legged countermovement jump (16/10/04L)
- Drop jump from 30 cm (16/10/04L)
- Sub Maximal & Maximal Hopping Contact Mat Protocol (16/10/05L)
- Yo-yo intermittent recovery test (16/10/06L)
- 1 rep max bench press/back squat (16/10/07L)
- Agility sprint (16/10/08L)
- Isometric-mid thigh pull (16/10/09L)
- Motion analysis and kinetic measurement of sports and exercise related movements and techiques (13/5/01L – re-approval 16/10/01L)

Testing will also include very minor modifications of an approved protocol:
- Single-leg countermovement jump – modification of approved protocol 16/10/04L
- Two-legged horizontal jump – modification of approved protocol 16/10/04L
- Single-leg horizontal jump (left and right) – modification of approved protocol 16/10/04L

Testing will also include the following protocols, which are yet to be approved:
- Medicine ball throw*
- Rotational medicine ball throw*
- Y-balance test*
- Plank hold test*

*All of these tests have previously been included in paediatric PhD research projects that have been approved by the Cardiff School of Sport Research Ethics Committee. All of these tests currently have applications that are due to be submitted to the research ethics committee. If successful, future data collection will adhere to instructions in the approved protocols. General principles of protocols for two-legged vertical jumps will be applied to single-legged and horizontal jumps. Risk Assessments are included within the approved protocol applications.

For the motion analysis, non-invasive full-body kinematic (technique) measures will be obtained from superficially located skin and shoe markers using an automatic motion analysis system (Vicon) and a video camera placed in the sagittal plane.

The isometric mid-thigh pull and 1 rep max bench press are measures of maximal strength. The bench press will only be used with academy participants (and not the control group). It has long been accepted that healthy children can safely engage in maximal strength testing providing appropriate procedures are followed (Faigenbaum et al., 2003), and national position statements (Faigenbaum et al., 2009 NSCA position statement, Lloyd et al., 2012 UKSCA position statement) and international consensus statements (Lloyd et al., 2014) have supported the use of maximal strength testing in children. Appropriate procedures include making sure participants are familiarised and able to maintain correct technical form while applying maximal effort; this is made easier by the use of low skill tasks such as the isometric mid-thigh pull and bench press. The isometric mid-thigh pull involves pulling maximally on an immovable bar while standing on a force platform, meaning there is no external load moved. During the bench press, loads start at a known submaximal level and are gradually increased. An adult spotter is used to assist the participant should they fail to fully move a given load on their own.

Training Programme

Members of the YPD Centre will receive personalised training programmes and coaching. Training programmes will be based on the participants technical abilities, training history, maturation, fitness and training goals, but with an overall aim of improving the physical fitness and reducing the risk of injury when engaging in sport. Training programmes will follow contemporary guidelines (e.g. Lesinski et al., 2016) and models of youth physical development (Lloyd et al., 2012). Training will focus on neuromuscular development, using various training modes including the use of body weight resistance, moving external loads (e.g. dumbbells and barbells) and developing weightlifting abilities. Training will also include the use of movement skill, plyometric, speed and agility exercises.

Sample Size

The total sample size for athletes in the YPD Centre is somewhat unknown. Currently n = ~80-100 youth athletes are trained per week. However, with a more proactive recruitment drive it is expected that upto 150+ may be training in the YPD Centre each week. A control sample of n = ~200 will be recruited across an age range of 11-18 years old; the control will be recruited either from a local school and/or a local sports clubs where children are not engaging in strength and conditioning. Each year older participants will leave the study once they reach 18 years of age and new participants will be recruited at the entry age (11 years old).

Statistical Analyses

Long-term, multi-level modelling will be used to compare the progress of children in the academy compared to controls. Confounding factors, including the effects of maturation, body size, baseline fitness and sex will be considered when examining development. A range of statistical approaches will be used for various studies, including magnitude-based inferences, which will be used to examine the

magnitude and meaningfulness of changes over time, as well as providing a method to examine individual responsiveness across the cohort.	
A4 Will the project involve deceptive or covert research?	No
A5 If yes, give a rationale for the use of deceptive or covert research	
Click here to enter text.	
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	
Click here to enter text.	

B PREVIOUS EXPERIENCE
B1 What previous experience of research involving human participants relevant to this project do you have?
As a Professor in Paediatric Exercise Science I have extensive experience of research with youth populations. This includes publishing approximately 90 international peer review publications and supervising eight PhD students to completion. Dr Rhodri Lloyd is a Reader in Paediatric Strength and Conditioning and has published 3 books and in excess of 85 peer-reviewed manuscripts on the topics of athletic development and reducing injury risk in youth populations. Dr Rob Meyers, Dr John Radnor and Dr Jason Pedley have extensive experience of research with athletic paediatric populations, including research that involves training interventions. Tom Mathews, Sylvia Moeskops and Steph Morris are all research active members of staff working towards PG and PhD qualifications and have experience of research with human participants from their UG and PG studies. Ian Dobbs, Megan Wong, Saldiam Barillas, Ben Pullen, Nakul Kumar, James Shaw and Josh Dragone are some of the PhD/MSc students that will be involved in strength and conditioning delivery to the YPD Centre members and will use some of the collected data for research masnuscripts/PG Studies. Prof Avery Faigenbaum, Prof John Cronin and Dr Greg Myer are international leaders in the field of paediatric strength and conditioning, with arguably the longest and most well established global reputations for paediatric focused research. They have worked closely with other members of the research team in collaborative/supervisory roles in numerous youth athlete research projects over the last decade.
B2 **Student project only** What previous experience of research involving human participants relevant to this project does your supervisor have?
Click here to enter text.

C POTENTIAL RISKS
C1 What potential risks do you foresee?
1) Safeguarding and welfare issues when working with minors

2) There is the possibility of underlying medical conditions or existing injuries leading to an increased risk of injury during the testing period.
3) Potential injury from training and physical fitness testing
4) Feeling dizzy or faint during maximal strength testing
5) Environmental risks.
6) The identification of participants from within the study.

C2 How will you deal with the potential risks?

1) All researchers directly involved in data collection and coaching of children to have an up-to-date DBS. Similarly, all such persons shall be made familiar with the Cardiff Metropolitan University Child Protection Policy and Procedure prior to any contact with children.
2) An approved physical activity readiness questionnaire (PAR-Q) 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 members of the YPD Centre taking part in the training sessions, the head coach will perform a verbal PAR-Q at the beginning of each training session to ensure all individuals are fit to participate. Reasons for not participating (e.g. injury or illness) will also be documented.
3) The risk of injury will be no more than that if children were engaging in normal physical activity, and likely less than during competitive sport and unsupervised play. A thorough warm-up will precede all training and testing to help avoid muscle strain. All participants will be familiarised with all test-procedures with sub-maximal efforts before progressing to maximal efforts. Progression to a maximal test effort will only be allowed where participants can execute a technically sound movement.
4) In line with the risk assessment for maximal strength testing, participants will be instructed to stop any effort if they experience a feeling of dizziness or light-headiness. Where this does occur participants will be withdrawn from testing, sat or lay down and monitored until they have recovered.
5) 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.
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 approved laboratory procedures (laboratory procedures manual). As the project involves participants under the age of 18 years old, both assent from the child and consent from a parent or guardian will be obtained prior to the child engaging within the study. The university will keep stored data securely for a period of up to 10 years.

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.

YOUTH PHYSICAL DEVELOPMENT CENTRE
PARENT INFORMATION SHEET (MEMBER)

Ethical Approval Code: Sta-1346

Lead Researchers: Prof. Jon Oliver (joliver@cardiffmet.ac.uk)
Dr. Rhodri Lloyd (rlloyd@cardiffmet.ac.uk)

Dear Parent/Guardian,

Background
We are delighted that your child has decided to join the Youth Physical Development (YPD) Centre. Your child will now start to use strength and conditioning to help improve their athletic abilities and reduce their risks of sports-related injuries.

This information sheet is to let you know about our planned research project in the YPD Centre, which your child can choose to participate in. The following information should help you decide on whether or not you want your child to be part of our research. 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. Research has shown that participating in neuromuscular training programmes (inclusive of resistance training), leads to greater gains in athleticism than sports training alone. We are hoping to examine the long-term effects of training on the strength and power of children and adolescents. These results will be compared against other chidlren who are not participating in the strength and conditioning programmes at the YPD Centre, to evalute the effects of the additional neuromuscular training.

As a member of the YPD Centre your child will:

- Regularly take part in fitness testing (including height, sitting height, weight, sprints, jumps, agility, throws, balance, strength and endurance)
- We might also record them performing some movements using 2D or 3D cameras
- Be given feedback on their fitness test results
- Receive training that has been designed to maximise their individual physical development
- Keep a record of their training and how they are feeling – this will be collected each time they come attend a session at the YPD Centre

When each member starts in the YPD Centre, we will also ask you as parents/guardians to tell us your standing heights; this allows us to estimate how tall each child will be as an adult and how much more growing they have left to do. The information above will be collected on every member of the YPD Centre. We would also like to use this information for research, to allow us to evaluate how successful the YPD Centre has been and to share our findings with others. **We are asking that you consent to us using the data that we collect on your child as part of their involvement with the YPD Centre for research purposes, but stress that you are in no way required to do so.** Allowing us to use your child's data for research in no way affects the training they will receive; all members will be given the training we believe is most appropriate to benefit their physical development.

Aims of the research
This research aims to compare the long-term development of athletic abilities in children who do and do not participate in structured strength and conditioning programmes.

Why is my child being asked to volunteer
Your child is being asked to volunteer as they are a member of the YPD Centre and are in receipt of individualised neuromuscular training.

What will happen if you decide to consent?
Nothing different will happen whether you do or do not consent to us using your child's test data for research. Your child can still attend the YPD Centre and participate in training even if you choose for them not to be included in any associated research projects.

What are the risks of participating in the study?
The risks are the same as those associated with being a member of the YPD Centre and generally taking part in strength and conditioning activities and fitness testing, rather than any related to volunteering for the research. The risks of getting injured should be no higher than the risks of getting injured during your normal sports practice or during physical education lessons. All coaching and fitness testing staff at the YPD Centre will hold a current DBS and all coaches will hold formal strength and conditioning qualifications (e.g. Accredited Strength and Conditioning Coach (ASCC), Certified Strength and Conditioning Specialist (CSCS)) and valid first aid qualifications.

What are the benefits of my child participating in the study?
Your child will help us to understand how effective the YPD Centre is at promoting physical development and levels of athleticism in children.

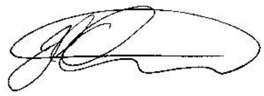
What will happen to the information collected?
In terms of research, all data will be made anonymous and stored securely at the University for 10 years, after which it will be destroyed. Data will only be accessible to University researchers working on the associated projects. Results of this project may be published but any data included will in no way be linked to any specific participant.

Any information linked to your child will be treated in accordance with data protection principles for the purposes specified within the Participant Information Sheet. Cardiff Metropolitan University will process your child's personal data in line with Article 6(1)(a) and Article 9(2)(a) of the General Data Protection Regulation 2018 which specifies that your child's personal data can only be processed with your explicit consent and their own assent. By signing this form and ticking the boxes above you are confirming that you have understood the reasons for obtaining your data and you are happy for your child's data to be used for research purposes. Please note that you have the right to withdraw consent at any point. Should you wish to invoke that right please contact the Independent University Research & Innovation department: ccr-i@cardiffmet.ac.uk

What next?
If you have any questions about the research then please do not hesitate to contact us. If you would like to participate in the study, then the consent form needs to be signed by the parent/guardian and the assent form signed by the participant and returned to us. Please note you have the right to withdraw consent at any point; should you wish to invoke that right (or

speak with someone outside of the project team) please contact the Independent University Research & Innovation department: ccr-i@cardiffmet.ac.uk

Many thanks,



Prof. Jon Oliver,
Professor of Applied Paediatric Exercise Science
Cardiff Metropolitan University
Tel: 029 2041 7276 **e-mail:** joliver@cardiffmet.ac.uk

Dr. Rhodri Lloyd
Reader in Paediatric Strength and Conditioning
Cardiff Metropolitan University
Tel: 029 2041 7062 **e-mail:** rlloyd@cardiffmet.ac.uk

YOUTH PHYSICAL DEVELOPMENT CENTRE
PARENT INFORMATION SHEET (NON-MEMBER)

Ethical Approval Code: Sta-1346

Lead Researchers: Prof. Jon Oliver (joliver@cardiffmet.ac.uk)
Dr. Rhodri Lloyd (rlloyd@cardiffmet.ac.uk)

Dear Parent/Guardian,

Background

This information sheet is to let you know about our planned research project in the Youth Physical Development (YPD) Centre, based at 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. The aims of the study are to assess how a long-term strength and power training programme effects measurses of athleticism in children and adolescents.

We are asking for your consent for your child to be involved in our research study.

What will happen once you agree to your child participating in the study?

Your child will need to attend fitness testing sessions approximately every 4-6 months. The testing sessions will be performed in groups, which will take approximately 2 hours including a break. All testing will take place at the National Indoor Athletic Centre (NIAC) which is situated at Cardiff Metropolitan University Cyncoed Campus.

Your child will be asked to complete some (but not necessarily all) of the following tests. These tests are all ethically approved protocols that hundreds of chidlren have safely performed at our research facility;

- Anthropometric data (i.e. age, body mass, height and sitting height)
- 40 m sprint test
- Various jump and hopping tests (either on one leg or two legs)
- Agility sprint
- Isometric-mid thigh pull (standing on a platform that collects force data through pulling on a bar)
- Medicine ball throws
- Balance tests
- Running endurance
- We might also record your child performing some movements using 2D or 3D cameras

Why is my child being asked to volunteer

We are looking for children 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:

What are the risks of participating in the study?
The risks associated with the study are minimal. The vast majority of tests last no longer than 15 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 your child was taking part in sports. The researchers involved in the YPD Centre have successfully used all tests to collect data on a large number of children and adolescents in previous studies, without any reports of injury.

Benefits to the participant
Participants will be given reports on their performances in the tests. This will provide them with information about their athletic abilities (e.g. how strong, fast or powerful they are), 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 period, your child will be given a training programme based on their results collected over the study period (e.g. 12 months). Your child will also be invited to the YPD Centre for two taster training sessions at the end of study period and be given a copy of their training programme (of body-weight exercises) to take home and complete under the supervision of a parent/guardian.

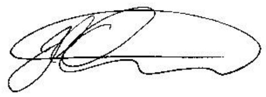
Benefits to us, the research team
Participants will provide the research team with relevant, novel and impactful data which will be used to address important research questions. Importantly the findings of the study will provide the research team with important, new information which teachers, sports 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?
In terms of research, all data will be made anonymous and stored securely at the University for 10 years, after which it will be destroyed. Data will only be accessible to University researchers working on the associated projects. Results of this project may be published but any data included will in no way be linked to any specific participant.

Any information linked to your child will be treated in accordance with data protection principles for the purposes specified within the Participant Information Sheet. Cardiff Metropolitan University will process your child's personal data in line with Article 6(1)(a) and Article 9(2)(a) of the General Data Protection Regulation 2018 which specifies that your child's personal data can only be processed with your explicit consent and their own assent. By signing this form and ticking the boxes above you are confirming that you have understood the reasons for obtaining your data and you are happy for your child's data to be used for research purposes. Please note that you have the right to withdraw consent at any point. Should you wish to invoke that right please contact the Independent University Research & Innovation department: ccr-i@cardiffmet.ac.uk

What next?
If you have any questions about the research then please do not hesitate to contact us. If you would like to participate in the study, then the consent form needs to be signed by the parent/guardian and the assent form signed by the participant and returned to us. Please note you have the right to withdraw consent at any point; should you wish to invoke that right (or speak with someone outside of the project team) please contact

Many thanks,



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CARDIFF METROPOLITAN UNIVERSITY

YOUTH PHYSICAL DEVELOPMENT CENTRE
RESEARCH PARTICIPANT INFORMATION SHEET (MEMBER)

Ethical Approval Code: Sta-1346

Lead Researchers: Prof. Jon Oliver (joliver@cardiffmet.ac.uk)
Dr. Rhodri Lloyd (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 the strength and conditioning training you do with us in the YPD Centre effects how fast, strong and powerful you are. We also want to know if this training changes depending on how old you are.

We are wondering if you would like to take part in our study? You do not need to do any strength and conditioning (fitness training), but you will need to take part in some fitness testing on a few occasions throughout the year.

What will happen if you decide to volunteer?
You will need to attend fitness testing sessions roughly every 4-6 months. The testing sessions will be performed in groups, and will last roughly 2 hours. Don't worry - this includes breaks! All testing will take place at the National Indoor Athletic Centre (NIAC) which is situated at Cardiff Metropolitan University Cyncoed Campus.

You will be asked to complete some (but not necessarily all) of the following tests, which are all safe for children like you to perform;

- 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 how strong you are when you pull on a bar.
- After this we will see how powerful you are by asking you to perform some jumping and hopping tests.
- Then we'll see how fast you can run in a straight line and when changing direction.
- We might also ask you to see how far you can throw a ball, stand on one leg, hold a plank position, and see how fit you are running.
- A clever machine will also be put on your skin to look at the shape of the muscle below your knee and we might video you doing some movements (like jumping) using special cameras that they use in the movies!

What type of participants do we want?
We want to recruit children and adolescents aged between 5 and 18.

What are the risks of participating in the study?
The risks are not any different to those of being a member of the YPD Centre – and they are pretty small risks! Taking part in strength and conditioning activities and fitness testing offers

less risk than playing sports or playing in the background. All of the coaches and researchers working in the YPD Centre are all super qualified.

Benefits to the participant

You will be given a record of your performance during the tests, which will help you understand more about your athletic abilities. You will also get to learn some new movement skills and exercises to make your stronger and more powerful that you might not have done before.

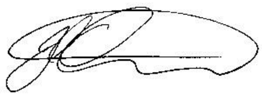
What will happen to the information collected?

All members of the YPD Centre 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 certain members of staff. Results of this project may be published in magazines or books, but the results will not have your name within them, so nobody will know that it was you or what your test results were.

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 agree to participate in the study then you will need to complete the research participant assent form as well as the Physical Activity Readiness Questionnaire. Your parents/guardians need to complete the parental consent form too. If there is anything you do nott understand on the form, please just ask. You will need to retur the signed forms either to myself or the main coach that looks after you in the YPD Centre.

Thank you!



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CARDIFF METROPOLITAN UNIVERSITY

YOUTH PHYSICAL DEVELOPMENT CENTRE
RESEARCH PARTICIPANT INFORMATION SHEET (NON-MEMBER)

Project Title: Long-term athletic development of children who do and do not participate in strength and conditioning

Ethical Approval Code: Sta-1346

Lead Researchers: Prof Jon Oliver (joliver@cardiffmet.ac.uk)
Dr Rhodri Lloyd (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 the strength and conditioning training (e.g. lifting weights, sprinting, jumping) effects how fast, strong and powerful children are. We also want to know if this training changes depending on how old you are.

What will happen if you decide to volunteer?
Nothing changes! As a member of the YPD Centre you will regularly take part in fitness testing (including height, sitting height, weight, sprints, jumps, agility, throws, balance, strength and endurance and we might also record you performing some movements using special video cameras. This information is fed back to you in a report and we then use the results to help plan the best programme for you possible. We'll also ask you to keep a record of your training and how you are feeling – this will be collected each time they come attend a session at the YPD Centre. If you agree to take part in the research project, it just means that you agree to us using the data that we collect from you to answer some importantresearch questions.

What type of participants do we want?
We want to recruit children and adolescents aged between 5 and 18.

What are the risks of participating in the study?
The risks are not any different to those of being a member of the YPD Centre – and they are pretty small risks! Taking part in strength and conditioning activities and fitness testing offers less risk than playing sports or playing in the background. All of the coaches and researchers working in the YPD Centre are all super qualified.

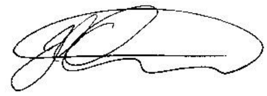
Benefits to the participant
You will be given a record of your performance during the tests, which will help you understand more about your athletic abilities. You will also get to learn some new movement skills and exercises to make your stronger and more powerful that you might not have done before.

What will happen to the information collected?
All members of the YPD Centre 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 certain members of staff. Results of this project may be published in magazines or books, but the results will not have your name within them, so nobody will know that it was you or what your test results were.

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 agree to participate in the study then you will need to complete the research participant assent form as well as the Physical Activity Readiness Questionnaire. Your parents/guardians need to complete the parental consent form too. If there is anything you do nott understand on the form, please just ask. You will need to retur the signed forms either to myself or the main coach that looks after you in the YPD Centre.

Thank you!

Many thanks,



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CARDIFF METROPOLITAN UNIVERSITY

APPLICATION FOR ETHICS APPROVAL

RESEARCH PARENTAL CONSENT FORM (MEMBER)

Ethical Approval Code: Sta-1346

Lead Researchers: Dr Jon Oliver (joliver@cardiffmet.ac.uk)
Dr Rhodri Lloyd (rlloyd@cardiffmet.ac.uk)

I have fully read and understood the information sheet that has been provided to me. I have had the opportunity to ask any questions I may have and all the answers I have been provided with are satisfactory.

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

I understand that:

ü As a member of the Youth Physical Development Centre my child will regularly undergo fitness testing and keep a record of their training and how they are feeling

ü I am being asked to provide consent to allow data that is collected as part of the academy to be used for research

ü Providing consent does not affect the training or services my child will receive as part of the academy.

ü 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.

ü My child may be filmed performing certain exercises to determine how competently they move

ü Data collected may be used in published research but it no way will my child be identified in any publications

Parent/guardian Name (print):

Signed (parent/guardian): Date:

Principle investigator's name: : Dr Jon Oliver / Dr Rhodri Lloyd

Signed (principle investigator): Date:

To help with the research please also provide, if known, the height of both the biological mother and father of the child (either in meters of feet and inches). If you know your height simply enter below, otherwise parental height can be measured by one of the research team. Also, if known, please provide the birth weight of your child

Mothers Height____________________ Fathers Height________________________

Child Birth Weight__________________

CARDIFF METROPOLITAN UNIVERSITY

APPLICATION FOR ETHICS APPROVAL

RESEARCH PARENTAL CONSENT FORM (NON-MEMBER)

Project Title: Long-term athletic development of children who do and do not participate in strength and conditioning

Ethical Approval Code: Sta-1346

Lead Researchers: Prof Jon Oliver (joliver@cardiffmet.ac.uk)
Dr Rhodri Lloyd (rlloyd@cardiffmet.ac.uk)

I have fully read and understood the information sheet that has been provided to me. I have had the opportunity to ask any questions I may have and all the answers I have been provided with are satisfactory.

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

I understand that:

- ü 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.
- ü To be eligible my child will have to confirm that they are not regularly taking part in strength and conditioning outside of their normal PE or sports club activities.
- ü My child will be required to take part in regular fitness testing sessions, up to three times per year for up to seven years.
- ü My child may be filmed performing certain exercises to determine how competently they move
- ü Data collected may be used in published research but it no way will my child be identified in any publications

Parent/guardian Name (print):	
Signed (parent/guardian):	Date:
Principle investigator's name: Dr Jon Oliver / Dr Rhodri Lloyd	
Signed (principle investigator):	Date:

To help with the research please also provide, if known, the height of both the biological mother and father of the child (either in meters of feet and inches). If you know your height simply enter below, otherwise parental height can be measured by one of the research team. Also, if known, please provide the birth weight of your child

Mothers Height____________________ Fathers Height________________________

Child Birth Weight__________________

CARDIFF METROPOLITAN UNIVERSITY

APPLICATION FOR ETHICS APPROVAL

RESEARCH PARTICIPANT ASSENT FORM (MEMBER)

Ethical Approval Code: Sta-1346

Lead Researchers: Prof Jon Oliver (JOliver@cardiffmet.ac.uk)
Dr Rhodri Lloyd (RLloyd@cardiffmet.ac.uk)

I have fully read and understood the information sheet that has been provided to me.

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

I understand that:

- ü I have decided to take part in the study because I want to and nobody has made me
- ü As a member of the Youth Physical Development (YPD) Centre I will regularly undergo fitness testing and I will keep a record of my training and how I am feeling
- ü I have agreed to let data that is collected as part of the academy be used for research
- ü Agreeing to this does not affect the training or services I will receive as part of the YPD Centre
- ü I can change my mind at any time, I just need to tell one of the research team or YPD Centre coaches. If I do change my mind I can still be a member of the academy
- ü I may be filmed performing certain exercises to determine how well I can move
- ü All my information and results collected will be kept in a secret location at the university for 10 years. 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
- ü Data collected may be used in published research but it no way will I be identified in any publications

Participant's name (print):

Signed (participant): Date:

Principle investigator's name: Dr Jon Oliver / Dr Rhodri Lloyd

Signed (principle investigator): Date:

CARDIFF METROPOLITAN UNIVERSITY

APPLICATION FOR ETHICS APPROVAL

RSEARCH PARTICIPANT ASSENT FORM (NON-MEMBER)

Project Title: Long-term athletic development of children who do and do not participate in strength and conditioning

Ethical Approval Code: Sta-1346

Lead Researchers: Prof Jon Oliver (JOliver@cardiffmet.ac.uk)
Dr Rhodri Lloyd (RLloyd@cardiffmet.ac.uk)

I have fully read and understood the information sheet that has been provided to me. I have had the opportunity to ask any questions I may have and all the answers I have been provided with are satisfactory.

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

I understand that:

- ü I have agreed to join in the study and nobody has made me
- ü I can leave the study at any time. I just have to tell a member of the research team of YPD Centre coaches
- ü I will need to take part in fitness testing sessions up to three times per year
- ü I may be filmed performing certain exercises to determine how well I can move
- ü All information about me will be kept safely at the university for 10 years. 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
- ü Data collected may be used in published research but it no way will I be identified in any publications

Participants name (print):

Signed (participant): Date:

Principle investigator's name: Dr Jon Oliver / Dr Rhodri Lloyd

Signed (principle investigator): Date:

CARDIFF METROPOLITAN UNIVERSITY

APPLICATION FOR ETHICS APPROVAL

PARTICIPANT ASSENT FORM (MEMBER)

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 J If
you aren't sure, circle this face K If
you disagree, circle this face L

I understand that:

I have decided to take part in the study because I want to and nobody has made me	J	K	L
As a member of the Youth Physical Development (YPD) Centre I will regularly undergo fitness testing and I will keep a record of my training and how I am feeling	J	K	L
I have agreed to let data that is collected as part of the academy be used for research	J	K	L
Agreeing to this does not affect the training or services I will receive as part of the YPD Centre	J	K	L
I can change my mind at any time, I just need to tell one of the research team or YPD Centre coaches. If I do change my mind I can still be a member of the academy	J	K	L
I may be filmed performing certain exercises to determine how well I can move	J	K	L
All my information and results collected will be kept in a secret location at the university for 10 years. 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	J	K	L
Data collected may be used in published research but it no way will I be identified in any publications	J	K	L

Participant's name (print):

Signed (participant): Date:

Principle investigator's name: Dr Jon Oliver / Dr Rhodri Lloyd

Signed (principle investigator): Date:

CARDIFF METROPOLITAN UNIVERSITY

APPLICATION FOR ETHICS APPROVAL

PARTICIPANT ASSENT FORM (NON-MEMBER)

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 J If
you aren't sure, circle this face K If
you disagree, circle this face L

I understand that:

I have agreed to join in the study and nobody has made m	J	K	L
I can leave the study at any time. I just have to tell a member of the research team of YPD Centre coaches	J	K	L
I will need to take part in fitness testing sessions up to three times per year	J	K	L
I may be filmed performing certain exercises to determine how well I can move	J	K	L
I can change my mind at any time, I just need to tell one of the research team or YPD Centre coaches. If I do change my mind I can still be a member of the academy	J	K	L
I may be filmed performing certain exercises to determine how well I can move	J	K	L
All my information and results collected will be kept in a secret location at the university for 10 years. 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	J	K	L
Data collected may be used in published research but it no way will I be identified in any publications	J	K	L

Participant's name (print):

Signed (participant): Date:

Principle investigator's name: Dr Jon Oliver / Dr Rhodri Lloyd

Signed (principle investigator): Date:

CARDIFF METROPOLITAN UNIVERSITY

APPLICATION FOR ETHICS APPROVAL

PHYSICAL ACTIVITY READINESS QUESTIONAIRE (PAR-Q)

Please read the questions carefully with your child and answer each question honestly. Circle your answer and write extra information where appropriate.

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? (if yes, please give details below)	**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? (if yes, please give details below)	**Yes**	**No**
6.	Do you have any bone or joint problems that could be made worse by physical activity? (if yes, please give details below)	**Yes**	**No**
7.	Do you have low or high blood pressure?	**Yes**	**No**
8.	Do you suffer from diabetes, epilepsy, asthma or any allergies? (If yes, please give details below)	**Yes**	**No**
9.	Do you know of any other reason why you should not participate in physical activity? (If yes, please give details below)	**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 a coach at the YPD centre 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 parent/guardian: ……………………………………………………………

Signed (parent/guardian): ……………………………………………………………

Date: ……………………………………………………

DELEGATION OF DUTIES LOG

Effective from May 2020

- This is often referred to as a signature log and is an important document as it is the only one which identifies to whom the Principal Investogator (PI), Researcher or Member of Staff Responsible (MoSR) has delegated project specific duties.
- The PI, Researcher, or MoSR must regularly review the Delegation of Duties log for each study and must:
  - Be satisfied as to the competence of the workers to whom they are delegating duties;
  - Ensure that all workers are informed of their involvement and the duties required of them.
- The log must reflect the current situation, with appropriate worker start/end dates.
- The log must be initialised and signed by each worker that accepts a duty.
- The log must be signed by the PI, Researcher or MoSR at the end of the project.
- A copy must remain in the project box.
- If new workers are recruited, the log must be updated but old versions must not be destroyed.

Legend

Use this legend to complete the General Duties column. For each individual listed in the Name column, enter the letter(s) (e.g. a, c, e) from the legend below that correspond to their protocol-related dutirs in their General Duties Column.

a.	i.	r.
b.	j.	s.
c.	k.	t. d.
l.	u. e.	m.
v. f.	n.	w.
g.	o.	x.
h.	p.	y.

The PI/Researcher/MoSR should sign below when the project is completed.

I have reviewed the information on this log and have found it to be accurate. All delegated duties were performed with my authorisation.

Signature of PI/Research/MoSR: ____ Date: __________________________

Research Project Number:	

PI/Researcher/MoSR:	

Name (print)	**Project Role**	**General Duties**	**Initials**	**Signature**	**Date of Duties**	
					From	**To**