Stretch-shortening cycle development and trainability in girls during maturation

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Publications and Presentations from this thesis

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McGarrigal, L.D., Morse, C. I., Sims, D. T., and Stebbings, G. K. '*The development of the slow and fast stretch-shortening cycle in maturing girls*.' Proceedings of the British Association of Sport and Exercise Sciences (BASES) conference (Oral presentation). November 2022.

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List of Abbreviations

Abbreviation	Definition
5max	5 maximal hops
20submax	20 submaximal hops
ACL	Anterior cruciate ligament
CA	Chronological age
CMJ	Countermovement jump
CSA	Cross-sectional area
CV	Confidence intervals
d	Cohen's d
DJ	Drop jump
EMG	Electromyography
ES	Effect size
FT	Flight time
F-V	Force-velocity
GTO	Golgi tendon organs
GCT	Ground contact time
ICC	Insulin-like growth factor
IGF-1	Intraclass correlation coefficient
kN	Leg stiffness
MTU	Musculotendinous unit
PAR-Q	Physical activity readiness questionnaire

PEC	Parallel elastic component
PHV	Peak height velocity
PT	Plyometric training
RFD	Rate of force development
RSI	Reactive strength index
RSR	Reactive strength ratio
SD	Standard deviation
SDD	Smallest detectable difference
SDpooled	Standard deviation pooled
SEC	Series elastic component
SEM	Standard error of mean
SJ	Squat jump
SSC	Stretch-shortening cycle
YPHV	Years from peak height velocity

Abstract

The stretch-shortening cycle (SSC) is an intricate cyclical muscle action fundamental in many explosive sporting movements such as sprinting and jumping. Plyometric training (PT) is often considered the training method of choice when aiming to increase slow (>250 ms) and fast (<250 ms) SSC function, power, jump height and sprinting performance. Maturation appears to affect the SSC through childhood and into adolescence. However, most studies into the effect of maturation in SSC tasks has included boys and not girls. PT is considered the bridge between strength and speed, with the ability to develop force in the shortest time possible. Many neuro-musculoskeletal adaptations can occur following PT, which positively influences athletic ability while mitigating the risk of serious knee injuries, which is more prevalent in girls compared to boys. However, there currently exists limited research examining the effects of maturation and plyometric trainability on the development of SSC in girls.

Study one (Chapter 4) examined the between-device agreement and the inter-day test-retest reliability of the MyJump 2 app (Apple Inc. Cupertino, USA) and the Optojump Next system (Microgate, Bolzano, Italy) during a series of SSC tasks, including squat jump (SJ), countermovement jump (CMJ), reactive strength index (RSI), and its derivatives of jump height and ground contact time (GCT), and leg stiffness, and its derivatives of flight time and GCT. This study involved 34 recreational post-PHV female soccer players. To the author's knowledge, this was the first time such a study has been conducted in this population, which is pertinent given that girls and boys may record differences in SSC function (Pedley et al.,

2020; Pedley et al., 2021) due to anatomical, hormonal and physiological differences between the sexes. It was also novel to measure the reliability of the MyJump 2 app in measuring leg stiffness, which to date has not been measured in any population. Intraclass correlation coefficient (ICC) demonstrated moderate to excellent agreement between the devices (ICC ≥ 0.735 – 0.964) but was dependent on the task involved. Coefficient of variance (CV) values reflected strong agreement and low bias between the MyJump 2 app and the Optojump Next in DJ RSI, leg stiffness and relative leg stiffness (CV ≤ 8.0%) as well as excellent in all other dependent variables (CV ≤ 4.4%). Test-retest reliability of the MyJump 2 app was good-to-excellent in all variables (ICC ≥ 0.856), accept DJ GCT (ICC = 0.682). CV values for the MyJump 2 app were acceptable-to-excellent in all variables (CV 2.0 - 10.7%). The reliability of the Optojump Next was moderate-to-excellent in SJ, CMJ, RSI variables (ICC ≥ 0.730), but not in DJ GCT and flight time during 5 maximal hopping (5max), jump height during 20 submaximal hopping (20submax), relative leg stiffness during a DJ, 5max, and 20submax hopping (ICC ≥ 0.613). CV values were acceptable-to-excellent, with the lower CV during DJ flight time (CV = 3.3%), and the highest during DJ relative stiffness (CV = 12.4%). Bland-Altman plots revealed a systematic bias between the devices, with the MyJump 2 recording greater GCT, RSI, leg stiffness and relative stiffness during DJ, and the Optojump reporting greater measures during a SJ, CMJ, DJ jump height and flight time. Consequently, it was concluded that while the MyJump 2 and Optojump next offered agreement, due to the flexibility of the Optojump Next in terms of instantaneous feedback and the measurement of RSI and leg stiffness during hopping as well as a DJ, this device should be used in all subsequent chapters.

Study two (Chapter 5) compared the measurement of the fast SSC during a DJ and hopping using the Optojump Next involving 34 recreational post- PHV female soccer players. The data demonstrated that while both the 5max and 20submax hopping recorded fast GCTs (≥ 206.4 ms), the 30 cm DJ did not (255 ms). This finding contradicts literature in elite post-PHV female soccer players and other populations, who record GCTs <250 ms during a 30cm DJ. As fast GCTs are an integral determinant of leg stiffness, it was unsurprising that both hopping tests demonstrated significantly greater leg stiffness and relative leg stiffness than the DJ ($P \leq .001$). This finding suggests that strength and conditioning practitioners should test leg stiffness during maximal and submaximal hopping and include these protocols in training. Significantly greater RSI during the DJ compared to both hopping tasks ($P \leq .05$) highlighted that girls can increase RSI values by offsetting slow GCTs with greater jumping heights. Considering that RSI and leg stiffness require effective elastic energy reutilisation and activation of the stretch reflex indicative of the fast SSC, it was deemed that 5max and 20submax hopping should be used in subsequent chapters to measure RSI and leg stiffness, respectively.

Research in the SSC development of girls during growth and maturation is lacking and often contradictory. Study three (Chapter 6) examined the effects of maturation on SJ and CMJ (slow SSC), and RSI, and leg stiffness (fast SSC function) in active girls aged 7-17 years. Peak height velocity (PHV) and years from PHV (YPHV) were used to assess biological maturational status. As expected, height, body mass and leg length increased during maturation (pre-PHV < mid-PHV < post-PHV), with body mass index also greater in the post-PHV subgroup compared to the pre- and mid-PHV subgroups. Unsurprisingly, the post-PHV outperformed the pre-PHV subgroup in all other dependent variables ($P \leq .05$). The mid-PHV subgroup also outperformed the pre-PHV subgroup in 20submax flight time (P ≤ .0.5), with the mid-PHV outperforming both the pre- and post-PHV subgroups in relative leg stiffness (P ≤ 0.05). Unexpectedly, RSI did not increase during maturation. Further analysis based on consecutive YPHV subgroups revealed that the -0.5 YPHV maturity offset subgroup generated greater leg stiffness than the -1.5 YPHV maturity offset subgroup (P = .014), and that the 0.5 YPHV maturity offset subgroup recorded greater relative leg stiffness than the 1.5 YPHV maturity offset subgroup (P = .002). For the first time, in girls based on maturity, results suggested the possible existence of periods of accelerated adaptation in leg stiffness only. This extends what is currently known in the literature, particularly because the data of leg stiffness in maturing girls is sparse and that data comparing the SSC ability of maturing girls rarely includes pre-PHV populations. However, it remained unclear whether exposure to the correct training stimulus during these timeframes would promote adaptation above and beyond that of natural growth alone.

Study four (Chapter 7) examined the development of SSC function in maturing girls following plyometric training (PT). Currently, the literature in this area is sparse and contradictory. To the author's knowledge, this was the first time that PT has been used to increase the slow and fast SSC of maturing recreational female soccer players using CMJ, RSI, leg stiffness, and sprinting. Chapter 7 examined the trainability of pre-, mid-, and post-PHV girls following 8-week (once per week) soccer-only training, followed immediately by 8-week soccer training (once per week) supplemented with 8-weeks vertical and horizontal PT (also once per week). The main findings revealed that exposure to PT resulted all maturity groups making significant improvements in all SSC-related performance variables (P ≤ .05), except for RSI in the pre-PHV group (P = .333) and 20submax flight time in all subgroups ($P \geq .616$). For the first time, this chapter demonstrated that 8-week low frequency PT can have a positive effect on SSC function in recreational female soccer players, and that trainability may not be maturation dependent. The research has enhanced our understanding of the impact of maturity and PT on the SSC function and athletic development in girls who participate in recreational soccer. Additionally, it was identified that the SSC is sensitive to change when exposed to the correct training stimulus, suggesting the possible existence of trainability and 'synergist adaptation', which refers to the symbiotic relationship between the adaptations caused by a training stimulus and the SSC development due to growth and maturation.

In summary, this thesis found that strength and conditioning practitioners working girls and a limited budget, could use a cost-effective app to test the SSC function of this population. However, the versatility of the Optojump Next could be an option for strength and conditioning practitioners working in a professional setting. This thesis also highlighted that strength and conditioning practitioners working with girls should use hopping to test the fast SSC, which is important given the positive impact the RSI and leg stiffness has on athletic ability and in a population who demonstrates a risk of knee injuries compared to males. Additionally, unlike boys, girls may not demonstrate 'accelerated adaptation' in slow and fast SSC function during maturity, but that following PT, girls demonstrate 'synergistic adaptation'. Given that PT studies involving girls, and in particular girls participating in soccer, is limited, this thesis has added valuable information to strength and conditioning practitioners working with girls, particularly in SSC-based variables such as reactive strength, leg stiffness, GCT and speed, which often determine the difference between winning and losing in many sports, including soccer.

Chapter 1

Rationale and background

Sports such as soccer, basketball, hockey and rugby involve repeated bouts of sprinting and jumping. These actions utilise the stretch-shortening cycle (SSC) to increase force production in the shortest time possible (Markovic and Mikulic, 2010). Given that sprinting and jumping often determine the difference between winning and losing on the sports field, strength and conditioning practitioners are interested in monitoring and developing these SSC-based actions in their athletes' through testing and training (Turner et al., 2013a, Turner et al., 2013b; Taylor et al., 2022).

Throughout childhood, the slow (>250 ms) and fast (<250 ms) SSC develops naturally due to several neuromuscular adaptations linked to maturation (Radnor et al., 2018). SSC development can be further amplified by plyometric training (PT), which utilises the eccentric-concentric coupling action of the SSC during exercises such as jumping, hopping, skipping and bounding (Faigenbaum and Chu, 2006). Given that children can improve sprinting, jumping, agility speed, strength, and power following PT during maturation (Peitz et al., 2018; Moran et al., 2018a; Davies et al., 2019; Asadi et al., 2017), it is surprising that this form of exercise is not currently an essential component of many sports training sessions in a youth-based setting. As PT can be undertaken in limited space, with no requirement for additional equipment, is time-efficient and can include large group sizes (Ramirez-Campillo et al., 2023), this form of training should be attractive to strength and conditioning practitioners working in a youth sport setting, where budgets and time are often limiting factors.

Despite the wide-spread popularity of PT, only 10% of 242 PT included in scooping review have included girls aged <18 years (Ramirez-Campillo et al., 2018b). This finding is unexpected considering maturing girls have been shown to improve their athletic ability following PT (Davies et al., 2019; Romero et al., 2019; Moran et al., 2018a), and that PT has been shown to reduce the risk of serious knee injuries in girls (Hewett et al., 1996; Chimera et al., 2004). In recent years, participation of girls playing soccer has increased exponentially, with over 1 million girls aged 5-15 years now regularly playing in England (Football Association, 2024). Research shows that female athletes have a two-to-eight-fold increase in the incident of anterior cruciate ligament (ACL) injuries compared with their males counterparts (Mancino et al., 2024). Unfortunately, soccer poses the highest risk of ACL injuries in adolescent girls compared to any other sport (Childers et al., 2025; Joseph et al., 2013). Additionally, youth female players are more likely to suffer ACL injuries than youth male players during soccer (Childers et al., 2025; Bram et al., 2021; Joseph et al., 2013), due to several anatomical, hormonal and biomechanical sex-differences that occur during maturation (Mancino et al., 2024; Childers et al., 2025). As such, mitigating the risk of ACL injury is of great importance when working with youth female soccer players.

To date, however, only 3 out of 90 studies investigating the use of PT in soccer players included girls (Ramirez-Campillo et al., 2022). It is well-established that a countermovement jump (CMJ), the reactive strength index (RSI), and leg stiffness quantify SSC function (Lloyd et al., 2011c). While the CMJ is often used to test the slow (>250 ms) SSC function and leg power of adult and youth female soccer players following PT (Slimani et al., 2017), to the author's knowledge no studies have aimed to develop the fast (<250 ms) SSC function measures of RSI and leg stiffness in this population following PT. This is unexpected considering developing

RSI and leg stiffness can improve athletic ability and reduce the susceptibility of ACL injury, particularly in youth female athletes (Lehnert et al., 2020).

Several studies have found that once-a-week PT can improve the athletic ability of youth and adult female soccer players (Ramirez-Campillo et al., 2018a; Rubley et al., 2011; Ozbar et al., 2014). However, these studies did not aim to develop both RSI and leg stiffness. Recognising that low frequency PT may help mitigate the risk of ACL injuries and increase the slow (CMJ) and fast (RSI and leg stiffness) in girls is important, considering that this population typically drop out of sport and high school PE and sport due to time conflicts (18%), boredom (14%), or injury (26%) (Stewart and Taylor, 2000). Understanding the minimum PT dose required to observe positive adaptations in maturing girls is important, as this would positively affect the time dedicated by strength and conditioning practitioners to increasing the athletic ability and reducing the risk of injuries in maturing girls. From a practical perspective, low frequency (once-per-week) PT could be of particular interest to strength and conditioning practitioners working in a youth-based setting where practice sessions may be limited.

Chapter 2

Literature review

2.1 Introduction

Sprinting, jumping and hopping are explosive actions that capitalise on an effective and efficient muscle action known as the stretch-shortening cycle (SSC) (Turner and Jeffreys, 2010). The SSC enhances the ability of the musculotendon unit (MTU) to produce maximal force in the shortest amount of time (Bobbert et al., 1996; Rassier and Herzog, 2005; Markovic and Mikulic, 2010). SSC function is governed by the effective interaction between neural, muscular and muscle-tendon structural factors (Radnor et al., 2018). Improvements in these factors may contribute to improved force production, increased rate of force development (RFD), improved stiffness and overall SSC function, leading to improved sprinting and jumping (Radnor et al., 2018; Tumkur Anil Kumar et al., 2021).

The development of SSC function throughout maturation increases muscular force and velocity, enabling children to increase power, jump higher and sprint faster (Malina et al., 2004b). There are many anatomical, physiological and hormonal differences between boys and girls during maturation that affect sex-differences in SSC function and athletic ability (Malina et al., 2004b; Myer et al., 2005). For example, girls develop greater fat mass and less muscle mass during puberty (Malina et al., 2004b), which contributes to sex-differences in body composition, muscle size, muscle and tendon stiffness, and fibre type composition, meaning that while boys develop greater ability in SSC tasks such as sprinting and hopping throughout childhood to adulthood, girls may not (Talukdar et al., 2022a). As these sex-differences in the determinants of SSC function exist, and there is a publication bias towards boys, and so there is a necessity for a female specific review.

For an effective SSC action, three fundamental conditions must exist: pre-activation of the extensor muscle prior to ground contact to prepare the muscles to resist the impending impact; (Figure 2.1 A) a short and fast eccentric action, (Figure 2.1 B) followed by a rapid transition between eccentric and concentric muscle actions (Figure 2.1 C) (Komi, 2000).

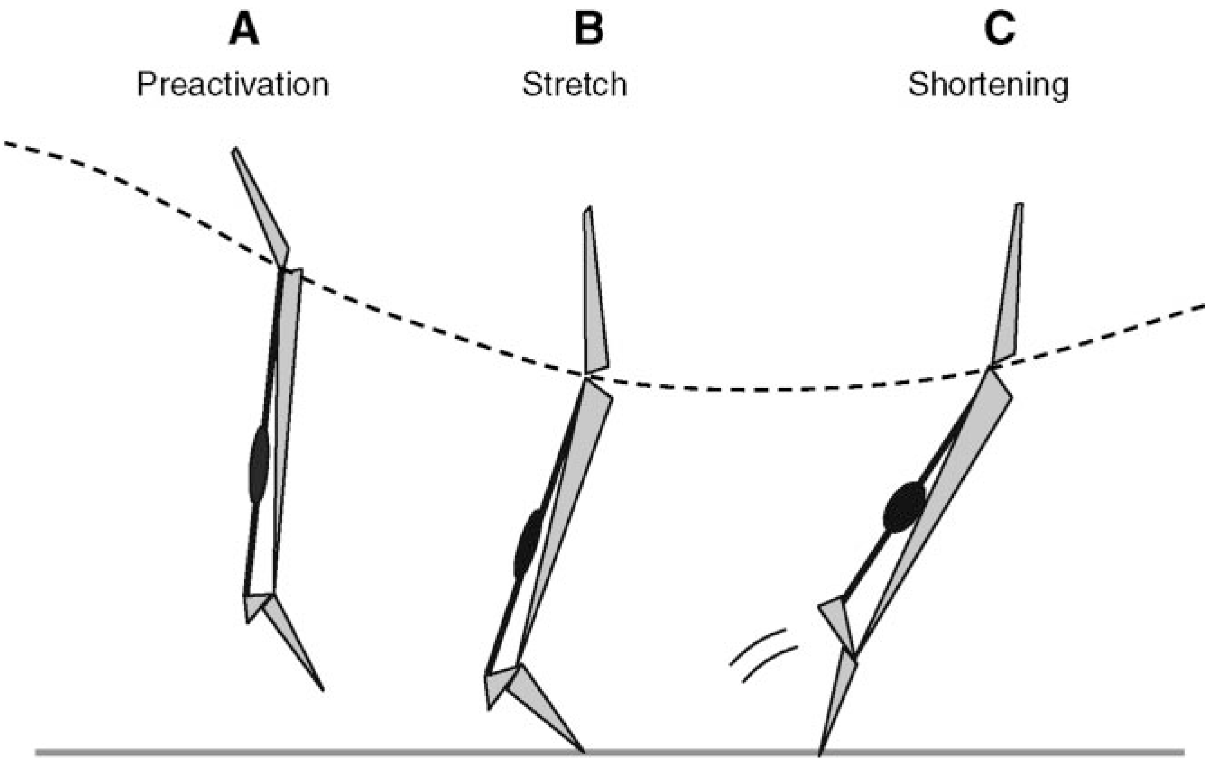

Fig 2.1 Diagrammatic representation of the stretch-shortening cycle (SSC) during human locomotion, incorporating the musculoskeletal components of the lower limb (Komi, 2000).

During SSC actions, a limited amortisation phase is essential, otherwise the energy generated during the eccentric phase will dissipate as heat (Hessel and Nishikawa, 2017) rather than being transferred into mechanical energy to maximise athletic performance with a lower metabolic cost (Bosco et al., 1982; Henchoz et al., 2006). The SSC is influenced by multiple mechanical and neurophysiological mechanisms, including the time available for force development, active state development (described as the number of actin binding sites available for cross-bridge formation), storage and reutilisation of elastic energy, potentiation of the contractile machinery, interaction between the parallel elastic component (PEC) and series elastic component (SEC), contribution of reflexes, and working range (Turner and Jeffreys, 2010; Moir, 2015). During tasks such as jumping, the SEC acts like a spring, where the energy released will generate greater force output (Davies et al., 2015). Although both the SEC and PEC store elastic energy during the eccentric phase of the SSC, it is the energy accumulated within the SEC that contributes 70-75% of the total force enhancement generated during the shortening phase of a SSC action (Albert, 1995), which in turn reduces the work of the contractile components of the muscles during a rebound activity (Blazevich et al., 2012). The relationship between the SEC, PEC and contractile machinery is highlighted in figure 2.2.

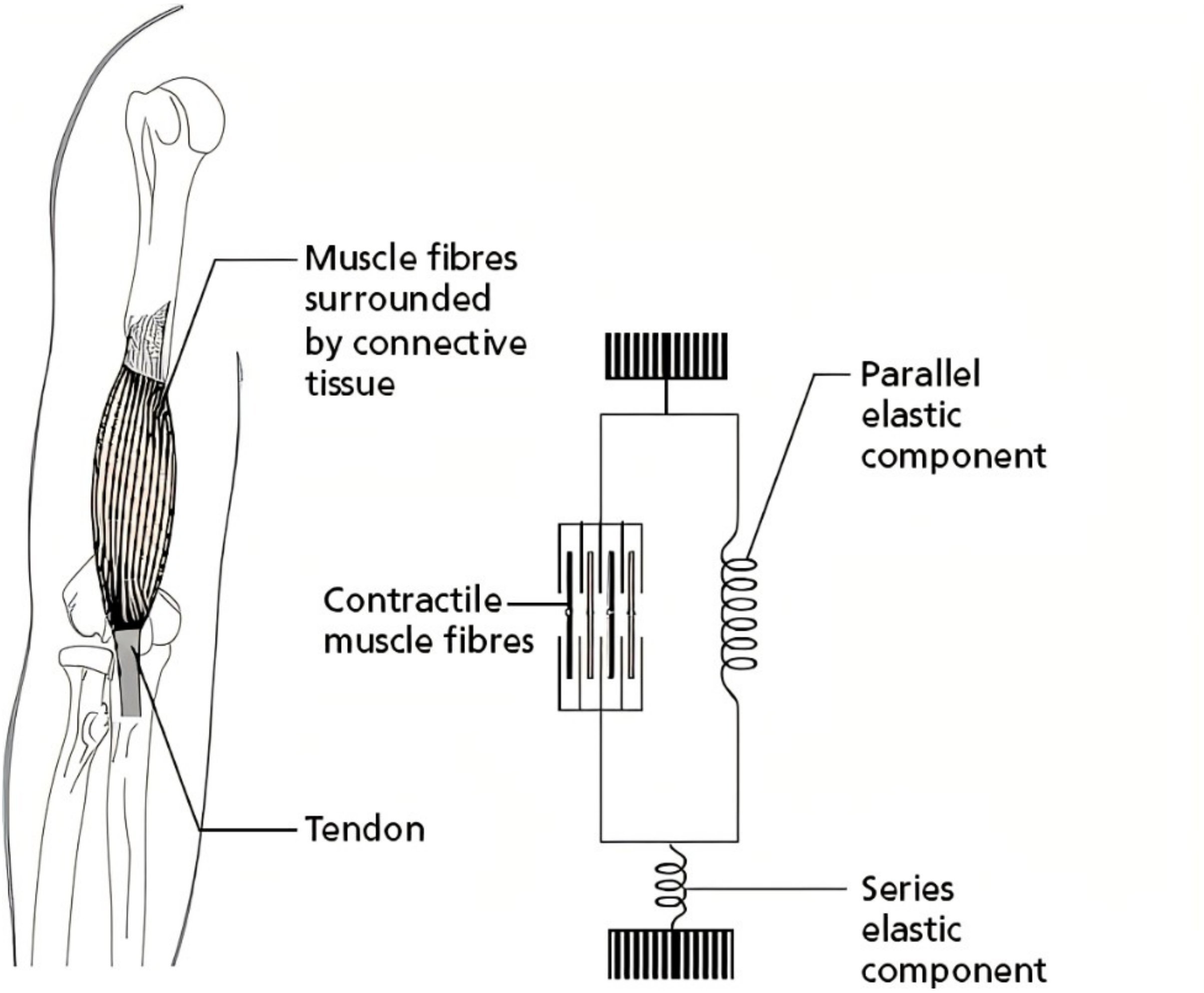

Fig 2.2 Diagrammatic representation of the musculotendinous components that interact during SSC actions

While the debate into the contributing effects of the above-mentioned mechanisms on SSC function continues (Turner and Jeffreys, 2010), it is well understood that the eccentric action enhances the performance of the final concentric phase in comparison to an isolated concentric action only (van Ingen Schenau et al., 1997). For instance, when utilising a preceding eccentric action during a countermovement jump (CMJ), men jump 18–30% higher compared to a squat jump (SJ) (Bosco et al., 1982; Bosco et al., 1987). In younger populations these differences might be lower, as evidence demonstrates the eccentric phase contributed to a 1-5% increase in jump height in boys (Lloyd et al., 2009). Interestingly, women and girls seem to utilise stored elastic energy to a greater degree than men and boys (~90% vs. ~50%) (Komi and Bosco, 1978). Given that female athletes have a more compliant MTU and demonstrate more elastic energy reuse (Granata et al., 2002b; Padua et al., 2005), it could be expected that this population would out jump male athletes, which is not the case (Harrison and Gaffney, 2001; Malina et al., 2004a). This finding suggests that men and women use different SSC mechanisms to increase vertical jump height, given that men jump higher. Additionally, it has been suggested that active state plays a greater role during the CMJ than elastic energy (Bobbert and Casius, 2005; van Ingen Schenau et al. 1997a) and that the storage and reuse of elastic energy may not explain the difference in jump height between the CMJ and SJ (van Ingen Schenau, 1984; van Ingen Schenau et al., 1997al; van Ingen Schenau et al. 1997b; Anderson and Pandy, 1993; Arakawa et al., 2010). In fact, other authors suggest that elastic energy may not be utilised during a slow SSC action such as a CMJ (Winkelman, 2011; Turner and Jeffreys, 2010). Male athletes also demonstrate greater muscle mass following puberty which positively influences jump height (Malina et al., 2004b). Collectively, these findings suggest that the physical characteristics and mechanisms that enhance SSC performance is population-specific and, irrespective of sex, will change according to advancing growth and maturation (Radnor et al., 2018).

Although a SJ and CMJ have previously been used to determine the SSC capacity in boys and girls (Harrison and Gaffney, 2001; Lloyd et al., 2009), these movements do not include preloading and/or excite a stretch reflex, unlike rebound tasks (Komi and Gollhofer, 1997). As such, the SJ and CMJ do not appropriately represent SSC function (Komi and Gollhofer, 1997), nor do they permit investigation of the fast SSC (Komi and Nicol, 2011). Measuring the fast SSC requires GCTs of less than 250 ms (Schmidtbleicher, 1992; Flanagan and Comyns, 2008), which can be achieved in girls using a drop jump (Jeras et al., 2019; Moeskops et al., 2022), hopping (Laffaye et al., 2016) and sprinting (Talukdar et al., 2021). Despite the SSC being traditionally classified as slow or fast (Schmidtbleicher, 1992; Flanagan and Comyns, 2008; Turner and Jeffreys, 2010), it has been suggested that the SSC of boys aged 7-18 years lies on a continuum, including slow-intermediate-fast SSC (Lloyd et al., 2011c). The continuum proposed by Lloyd et al. (2011b) is highlighted in figure 2.3. This is important as GCT is often used by strength and conditioning practitioners to monitor SSC proficiency (Flanagan and Comyns, 2008; Wilson and Flanagan, 2008) but is predominantly used by practitioners to classify SSC tasks in specific populations.

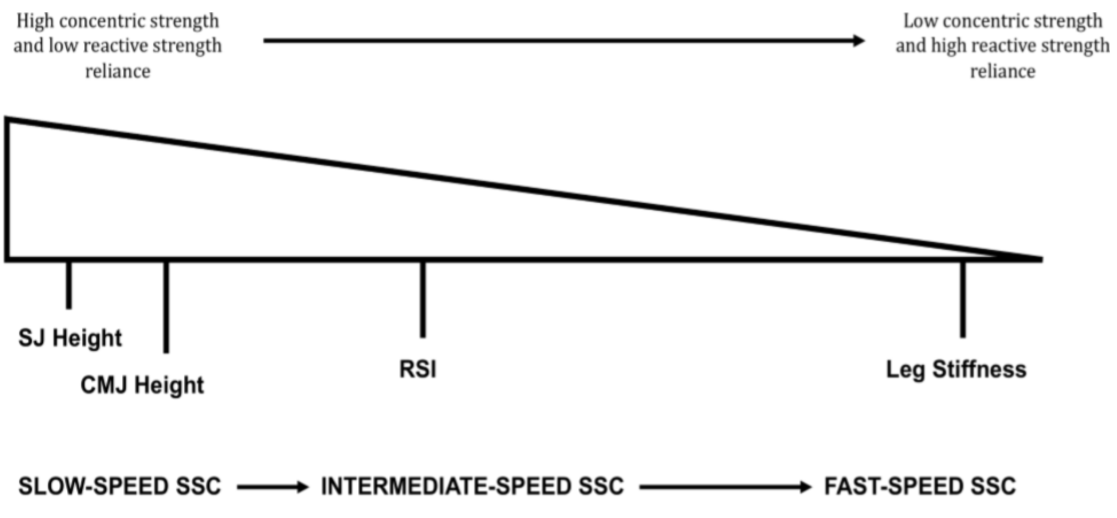

Fig 2.3 Continuum of concentric strength reliance and SSC speed for each jump and rebound-based test (Lloyd et al., 2011c).

In girls, rebound testing is particularly important, as it allows for the assessment of leg stiffness and the reactive strength index (RSI) (Lloyd et al., 2009), which are thought to have a potential role in reducing non-contact anterior cruciate ligament (ACL) injuries (Flanagan and Comyns, 2008; Lehnert et al., 2020; Butler et al., 2003), of which there is a higher prevalence in girls compared to boys (Childers et al., 2025; Mancino et al., 2024). It is important for strength and conditioning practitioners to understand that GCTs during fast actions are controlled by the demands (McMahon, 2018) and technique of the task (Pedley et al., 2017; Struzik et al., 2016), athlete maturity (Lloyd et al., 2012a; Jeras et al., 2019; Lehnert et al., 2020; Lehnert et al., 2022b), and that improvements in slow SSC function may not transfer or improve fast SSC function, and vice versa (Flanagan and Comyns, 2008). Appreciating that specific SSC tasks require varying degrees of GCT implies that testing batteries should include a variety of SSC tests (Taylor et al., 2022; Turner et al., 2011). Comparing the outcome of a variety of SSC tasks that measure the slow and fast SSC would give strength and conditioning practitioners working with girls greater knowledge on the contribution of the SSC during athletic performance and the possible risk of ACL injury, whilst also allowing them to create a more complete SSC profile of their athletes (Lloyd et al., 2011c). Creating a complete SSC profile would help practitioners to design training programmes that benefit the SSC demands of youth female athletes in their chosen sport.

While the RSI and leg stiffness have been extensively studied in boys (Lloyd et al., 2009; Lloyd et al., 2011b; Lloyd et al., 2011c; Lloyd et al., 2012a; Lloyd et al., 2012b), similar studies in girls are limited (Laffaye et al., 2016), particularly following neuromuscular training (Dallas et al., 2020). The greater prevalence of ACL injuries in girls and women (Childers et al., 2025; Mancino et al., 2024) may be attributed to factors such as sub-optimal muscle activation strategies during maturation (Barber-Westin et al., 2006; Barber-Westin et al., 2009; Barber-Westin et al., 2010; Noyes and Barber-Westin, 2018), ovarian hormonal profile (Arendt et al., 2002; Balachandar et al., 2017; Zazulak et al., 2006) and lower leg stiffness (Lehnert et al., 2020; Granata et al., 2002a; Padua et al., 2005; Laffaye et al., 2016). As girls demonstrate lower leg stiffness than boys (Laffaye et al., 2016; Lehnert et al., 2020), it is reasonable to speculate that, during hopping, girls land with less pre-activation and take-off with less stretch reflex activity, which has previously been observed in boys compared to men (Oliver and Smith, 2010). A better understanding of RSI and leg stiffness profiles in girls as they mature may aid strength and conditioning practitioners in reducing the risk of ACL injury and improving fast SSC performances in this population (Lehnert et al., 2020).

2.2 Operational definitions

During this chapter, the author will refer to terms such as childhood, adolescence, youth, growth, maturation, natural development, adaptation, peak height velocity (PHV) and the onset of menarche. *Childhood* represents the developmental period of life from the end of infancy to the beginning of adolescence, whereas the term *children* refers to girls and boys typically aged up to 11 and 13 years, respectively, and to reflect those who have yet to develop secondary sexual characteristics (Radnor et al., 2018). *Adolescence* refers to the period between childhood and adulthood, which occurs typically in girls aged 12-18 years and boys aged 14-18 years (Beunen and Malina, 1988; Malina et al., 2004b). *Youth* is a global term for children and adolescents (Radnor et al., 2018). *Growth* refers to quantifiable changes in body size, body composition, the body as a whole or the size of specific regions of the body (Beunen and Malina, 2008). *Maturation* refers to biological changes, both structural and functional in the body's progress during childhood and adolescence, such as the change of cartilage to bone in the skeleton, appearance of pubic hair or onset of menses (Beunen and Malina, 2008; Malina et al., 2004b). In boys and girls, the timing and tempo of growth and maturation differs, with girls typically maturing 2 years before boys, at age 11-12 years and 13-14 years, respectively. (Malina et al., 2004b). *Natural development* refers to innate development of physical characteristics (such as muscle mass, strength, power and speed) during growth and maturation (Lloyd and Oliver, 2012). *Adaptation* refers to changes in structure or neuromuscular properties prior to, or following, training (Radnor et al., 2018; Lloyd et al., 2011b). *Peak height velocity (PHV)* is a somatic estimation of biological maturity and reflects the maximum acceleration of growth during adolescence (Lloyd et al., 2014a), providing a universal landmark to reflect the occurrence of other body dimension velocities within and between individuals (Mirwald et al., 2002). PHV is an established method of assessing maturation within many paediatric studies (Moran et al., 2017a; Ramirez-Campillo et al., 2023; Asadi et al., 2018), with widely accepted categories classified as pre- (>-1 year from PHV), mid- (-1 year to +1 year from PHV), and post-PHV (> +1 year from PHV) (Emmonds et al., 2018b). The *onset of menarche* is defined as the first menstrual period in a female adolescent, with menarche typically occurring between the ages of 10-16 years, with an average age of onset being 12.4 years (Marques et al., 2022).

2.3 Development of the stretch-shortening cycle during maturation

The SSC is governed by efficient neural regulation, which undergoes significant development during growth and maturation in girls (Jeras et al., 2019; Lehnert et al., 2020; Lehnert et al., 2022b). SSC function is likely influenced by several anatomical, hormonal, neurophysiological, and structural mechanisms which adapt to enhance SSC function specifically during maturation (Radnor et al., 2018; Sahrom et al., 2014; Sahrom et al., 2013). Such adaptations include increases in muscle and tendon cross-sectional area (CSA), fascicle length, tendon stiffness, muscle spindle sensitivity, feed-forward control and leg stiffness (Kubo et al., 2014; Dotan et al., 2012; Grosset et al., 2007; Lloyd et al., 2012a; Oliver and Smith, 2010; Lexell et al., 1992; Lloyd et al., 2011b; O'Brien et al., 2010b; Kubo et al., 2001; Binzoni et al., 2001). These changes lead to a non-linear development of the SSC throughout childhood and adolescence (Radnor et al., 2018).

Insulin-like growth factor (IGF-1) is an important growth hormone in children (Malina et al., 2004b; Malina et al., 2004a; Tonnessen et al., 2015) that peaks during adolescence in boys and girls (Talukdar et al., 2022a). The anabolic nature of IGF-1 positively influences the development of muscle size, strength, speed and power in girls around the onset puberty (Viru et al., 1999). This period, however, also coincides with the onset of menarche during which girls begin to produce higher levels of circulating oestrogen and other female sex hormones, which significantly impacts body composition via greater fat mass accumulation (Malina et al., 2004b; Beunen and Malina, 1988; Viru et al., 1999). This increase in fat mass particularly impacts movements where body-mass is supported, such as running and jumping (Viru et al., 1999). Thus, where the increase in lean mass in boys following a surge in testosterone positively impacts power to weight ratio, the increase in fat mass in girls has the opposite effect (Malina et al., 2004b; Moran et al., 2018a).

Increases in muscle size during growth and maturation can positively impact the capacity to produce force, which typically leads to greater outcomes during SSC activities such as sprinting and jumping (Radnor et al., 2018). Muscle size increases during maturation can produce higher force development during the concentric and eccentric actions integral to the SSC by improvements to muscle and tendon structures (Kubo et al., 2001; O'Brien et al., 2010a; O'Brien et al., 2010b). Greater concentric strength during SSC actions can contribute to greater impulse, and RFD, which promotes greater performances in sprinting and jumping (McLellan et al., 2011; Tillin et al., 2013), while greater strength and speed in eccentric phase of SSC actions may increase the storage and reuse of elastic energy during sprinting and jumping (Komi, 2000). Increases in lean mass and strength, therefore, would have a positive influence on SSC- based tasks where elastic energy reuse is essential to optimal performance (Turner and Jeffreys, 2010).

Knee extensor strength and knee extensor RFD have been shown to significantly correlate with vertical jump height (Paasuke et al., 2001; McLellan et al., 2011; Copic et al., 2014), meaning that children who are stronger (typically boys following the onset of puberty) will out jump and out sprint those who are weaker (typically girls following puberty) (Malina et al., 2004a; Tonnessen et al., 2015; Talukdar et al., 2022a). Girls also experience greater co-contraction of the hamstrings and quadriceps than boys (Hewett et al., 1996), which can lower power output and would exacerbate any vertical jump height differences between the sexes, particularly during adolescence (Barber-Westin et al., 2006). Following the age of menarche, girls experience increases in joint laxity during ovulation (Chidi-Ogbolu and Baar, 2018), as well as reduced neuromuscular control and abnormal landing mechanics which can negatively affect SSC function (Ford et al., 2010). Following PHV, girls also experience an increase in fat mass, which can limit the ability to perform SSC movements optimally and increase their risk of injury, especially ACL injuries (LaBella et al., 2014; Ford et al., 2003; Barber-Westin et al., 2005; Arendt and Dick, 1995; Chaudhari et al., 2007; Wild et al., 2013).

The development of SSC function during maturation increases strength, force production and power output (Radnor et al., 2018). As strength and power are key determinants in the performance of many sports (Cronin and Sleivert, 2005; Cronin and Hansen, 2005), optimising an athlete's power production is of great importance (Asadi et al., 2018; Turner et al., 2011; Turner et al., 2013b; Weldon et al., 2021; Cronin and Hansen, 2005; Taylor et al., 2022; Abernethy et al., 1995; Darmiento et al., 2012; Markovic, 2007). Consequently, monitoring and improving the SSC of girls is often the goal of strength and conditioning practitioners in a youth-based setting (Jeras et al., 2019; Dallas et al., 2020; Moran et al., 2018a; Romero et al., 2019; Ramirez-Campillo et al., 2023). Improvements in power occur when one or both of its components; force or velocity increases (Noffal and Lynn, 2012; Ramirez-Campillo et al., 2015b; Morin and Samozino, 2016). For example, the force-velocity (F-V) slope allows the identification of the mechanical capabilities of musculoskeletal system to produce force, power and velocity (Jaric, 2015; Samozino et al., 2015). When the F-V slope is measured during a complex SSC action such as a vertical jump, the use of the preceding eccentric phase of the task moves the bottom of the F-V slope (where high velocity and low force are observed) to the right, allowing greater impulse and power to be produced during the following concentric phase (Ruddock and Winter, 2016; Aouichaoui et al., 2012).

Although force and velocity are connected concepts, they are independent of each other, such that an increase in force would cause a decrease in velocity, and vice versa, meaning that two athletes could record the same peak power with differing F-V profiles (Jimenez-Reyes et al., 2014). It has been reported, for example, that while cycling peak power increases during maturity in boys (Martin et al., 2003), the predominant factor contributing to this increase for pre-PHV boys is velocity, while force is the predominant factor contributing to this increase for post-PHV boys (Martin et al., 2003). In their study, Marin et al. (2003) reported that enhanced motor control allowed the pre-PHV to improve pedalling frequency to increase peak power, while greater power due to greater pedalling force in the post-PHV were due to increases in lean mass developed during their adolescent growth spurt and muscle strength, attributable to increase in motor-unit activation. This underlines that muscle mass plays a greater role in the development of power during the SSC of post-PHV children, whereas neural adaptations play a major role in the SSC development of pre-PHV children (Lloyd et al., 2015). As the studies by Martin et al. (2003) and Lloyd et al. (2015) only included boys, it remains unclear whether girls would respond in the same way to increase athletic performance during differing periods of maturation.

Prior to adolescence, girls and boys mature at a similar rate (Malina et al., 2004b) and demonstrate similar SSC capabilities in tasks such as sprinting, agility, and vertical and horizontal jumping (Malina et al., 2004a; Talukdar et al., 2022a), which is not the case during adolescence (Malina et al., 2004b; Talukdar et al., 2022a; Tonnessen et al., 2015). As children grow and mature, they experience two periods of accelerated development in strength and power between the ages of 5 and 18 years (Viru et al., 1999), with the first occurring from 5-9 years and the second associated with sexual maturation (Viru et al., 1999; Talukdar et al., 2022a). In girls, the second period of muscle strength development occurs aged 10-15 years, whereas boys demonstrated a second period of muscle strength development aged 13-16 years (Viru et al., 1998). In addition, girls and boys aged 9-13 and 12-16 years, respectively, experience an increase in explosive strength development (Viru et al., 1998). This demonstrates that strength in girls develops earlier but that it plateaus 1-3 years earlier than boys. Indeed, from the age of 12 years, boys consistently out sprint and out jump girls (Malina et al., 2004a), and that while the performance gap between male and female athletes increases to between 10-50% following puberty, this is sport dependent (Hilton and Lundberg, 2021).

Due to the relationship between strength, power and the SSC (Markovic and Mikulic, 2010), it is reasonable to assume that SSC development will coincide with natural periods of accelerated strength and power development (Lloyd et al., 2011b). As the timing of accelerated adaptation differs in boys and girls (Viru et al., 1999; Lloyd et al., 2011b), it is important that sex and maturity data on SSC development exists to allow strength and conditioning practitioners to better understand the SSC performance expectations of girls during periods of growth and maturation. Given the anatomical, physiological and hormonal differences between sexes and the limited research exclusively focusing on girls, caution is warranted when generalising findings from boys to girls, particularly in post-PHV girls compared to post-PHV boys, due to negative adaptations that may adversely affect the SSC of girls (e.g., greater fat mass and less muscle mass than boys). Further research specifically targeting SSC development in girls during different maturation stages is necessary to fill this gap in knowledge.

2.4 The trainability of the stretch-shortening cycle during maturation in girls

Based on the importance of sprinting and jumping in many sports (Markovic, 2007; Markovic et al., 2007; Markovic and Mikulic, 2010; Lockie et al., 2011), an increased emphasis has been placed on monitoring and developing these skills in a youth-based setting (Emmonds et al., 2017b; Emmonds et al., 2018a; Emmonds et al., 2018b). Although several forms of training can increase jumping and sprinting performance (Radnor et al., 2018), plyometric training (PT) is widely considered the training method of choice to enhance SSC development and the explosive power of athletes (Turner and Jeffreys, 2010; Markovic and Mikulic, 2010), as all plyometric exercises capitalise on the SSC (Chmielewski et al., 2006). Lower body PT uses a variety of body-weight exercises such as jumping, bounding and hopping that enhance the ability of the MTU to produce maximal force in the shortest possible time (Markovic and Mikulic, 2010). It has also been state that PT is bridge between pure strength and sports-related speed (Verkhoshanski, 1969; Cordasco et al., 1996), thereby making to transferable to many sports where strength and speed often determine the difference between winning and losing. Indeed, data shows that PT can elicit an overall greater training effect on vertical jump height than resistance training or a combination of strength training and plyometric/speed training (Harries et al., 2012).

Increasing SSC function following PT could be due to several neuro-musculoskeletal adaptations, such as an increased neural drive to the agonist muscles, changes in muscle-tendon and mechanical-stiffness characteristics, alterations in muscle size and/or architecture, changes in single-fibre mechanics, changes in leg muscle activation strategies (or inter-muscular coordination) (Markovic and Mikulic, 2010), as well as changes in the excitability of the stretch reflex (Bishop and Spencer, 2004; de Villarreal et al., 2009).

It has been stated that PT should be preceded by an element of strength training to ensure individuals are capable of sufficient force production (Lloyd et al., 2011a). Previous recommendations suggest that athletes should be able to back squat 1.5-2.5 times their own body weight for 1 repetition or back squat 60% of their own body weight for 5 repetitions prior to starting PT (Rubley et al., 2011). If followed, this recommendation would prevent most children from participating in PT (Rubley et al., 2011). This belief also fails to acknowledge that strength alone does not determine plyometric ability (Jeffreys, 2020), and that children intuitively mimic plyometric exercises during everyday play when they jump, hop and skip (Faigenbaum and Chu, 2006).

Unlike traditional resistance training, PT is a sport-specific, effective, cost-efficient, time-saving and easy to implement training strategy (Asadi et al., 2018; Ramirez-Campillo et al., 2023), making it attractive for strength and conditioning practitioners working in a youth-based setting where space and budget is constrained (Slimani et al., 2017). In children, PT can lead to positive adaptations in muscle power and strength (Thomas et al., 2009); sprinting speed (Beato et al., 2018; Michailidis et al., 2013; Kotzamanidis, 2006); change of direction speed (Meylan and Malatesta, 2009; Saez de Villarreal et al., 2015); rebound jump height (Lloyd et al., 2012b; Moran et al., 2018a); vertical jump performance (Moran et al., 2018a; Slimani et al., 2017); RFD (Matavulj et al., 2001), RSI and leg stiffness (Lloyd et al., 2012b; Dallas et al., 2020; Sylvester et al., 2024), as well as a reduction GCT (Dallas et al., 2020). Consequently, several governing bodies now endorse PT as an effective form of training aimed at children (Lloyd et al., 2014b; Behm et al., 2008; Faigenbaum and Chu, 2006; Faigenbaum et al., 2009a).

It has been suggested that boys experience 'synergist adaptation', which refers to the symbiotic relationship between a training stimulus and the development of the SSC due to growth and maturation (Lloyd et al., 2015). Specifically, Lloyd et al. (2015) found pre-PHV boys benefitted more from the high neural demands of PT, whereas post-PHV boys generated greater gains following a combination of resistance training and PT. One possible reason for this is that pre-PHV boys demonstrate a high level of neuroplasticity (Myer et al., 2013), whereas post-PHV boys may increase jumping and sprinting performance due to hypertrophic adaptation (Lloyd et al., 2015). However, PT studies in girls are limited, making it difficult to draw conclusions if pre- or post-PHV both respond equally well to PT. For example, one meta-analysis including 49 PT studies found that only 21% (38/11) exclusively included youth female athletes (Behm, 2017). In a subsequent scooping review including 242 PT studies, only ~10% included girls aged <18 years [142]. Owing to the lack of PT research in girls, the data found in boys is often applied to girls (Davies et al., 2019). Considering the anatomical, physiological and hormonal differences between boys and girls during maturation (Malina et al., 2004b; Myer et al., 2005), and the limited research exclusively focusing on girls, caution is warranted when generalising findings in youth male athletes to youth female athletes. Indeed, given the sex-differences during maturation, it may be erroneous to superimpose the findings of boys following PT onto girls (Emmonds et al., 2018b; Moran et al., 2018a).

It remains unclear whether girls during specific stages of maturity also experience synergistic adaptation as the few studies that do involve girls are sparse and contradictory (Moran et al., 2018a; Davies et al., 2019; Romero et al., 2019; Dallas et al., 2020; Slimani et al., 2017). For example, a meta-analysis by Moran et al. (2018) reported that girls aged <15 years generated the greatest training improvements in vertical jump height following PT, whereas Slimani et al. (2017) reported no significant difference between age groups (<15 vs. 15–21 vs. <21 years; Q =.98, p = 0.225). However, while Moran et al. (2018) included girls only, Slimani et al. (2017) pooled the findings of male and female soccer players, making it unclear as to which age the girls optimised the benefits of PT. One study also reported that mid-PHV girls generate greater gains in physical attributes following PT than post-PHV girls (Davies et al., 2019), while another similar study stated the opposite (Romero et al., 2019). However, these studies used different measures of SSC and athletic ability, making it difficult to compare the findings of these studies. The above-mentioned research highlights the limited amount of information on the benefits of PT aimed at pre-PHV girls (Lehnert et al., 2022a; Skurvydas and Brazaitis, 2010; Faigenbaum et al., 2009b). Consequently, it remains unclear as to which period of maturity in girls is the best time to introduce PT. The notion that PT gains may be greater in younger girls agrees with several authors who stated that preadolescence may be the optimal period to introduce neuromuscular training (including PT) to reduce the indices of ACL injury in this population (Myer et al., 2011). As the above-mentioned studies included a variety of SSC tests, differing durations (4-16 weeks), volume (<1600 to >1600-foot contacts), and plyometric exercises, there is no consensus as to the most effective PT programme for maturing girls. Future studies involving maturing girls should further examine PT design and aim to optimise several essential components of SSC function, such as reducing GCT, and increasing jump height, sprinting speed, RSI and leg stiffness.

The effectiveness of PT in girls has commonly been assessed by measuring increases in vertical jump height (Moran et al., 2018a; Slimani et al., 2017). While vertical jump testing is a reliable, non-invasive, relatively non-fatiguing method of testing the slow SSC and leg power (Potteiger, 1999; Markovic et al., 2004; Moir et al., 2004; Moir et al., 2008; Moir et al., 2009; Taylor et al., 2012), due to prolonged GCTs and an absence of any pre-loading prior to ground contact, tests such a as SJ and CMJ do not provide an adequate representation of the SSC, nor the fast SSC. Consequently, repeated hopping is often tested to provide a more accurate model of fast SSC (Komi and Gollhofer, 1997; Komi and Nicol, 2011; Lloyd et al., 2009). As a result, Lloyd et al. (Lloyd et al., 2009; Lloyd et al., 2012b; Lloyd et al., 2011b; Lloyd et al., 2011c; Lloyd et al., 2012a), popularised the measurement of RSI and leg stiffness using maximal and submaximal hopping, respectively, prior to and following PT. To the author's knowledge only two studies have examined RSI and leg stiffness following PT in girls, and of the ones that did, these studies included female taekwondo athletes and rhythmic gymnasts aged 8.44 and 13.9 years (Dallas et al., 2020), and post-PHV female volleyball players (Syvester., 2024), which are sports that have differing SSC demands. A lack of research in the development of RSI and leg stiffness following PT, is unexpected, considering that these measures have a positive impact on athlete ability and injury reduction, particularly in girls (Lehnert et al., 2020).

It has been reported that leg stiffness during hopping is governed in part by pre-activation and short-latency stretch reflexes (Hobara et al., 2007), with up to 97% of the variance in leg stiffness explained by the contribution of pre-activation and stretch-reflex response of lower limb extensor muscles (Oliver and Smith, 2010). As girls demonstrate lower leg stiffness than boys (Laffaye et al., 2016; Lehnert et al., 2020), and slower hopping GCTs (Dallas et al., 2020; Pedley et al., 2021), it is reasonable to speculate that girls hop with less pre-activation and lower stretch reflex activity than boys, further highlighting that the findings in boys following PT cannot be transferred to girls. A better understanding of RSI and leg stiffness profiles in girls may aid strength and conditioning practitioners in reducing the risk of ACL injury and improving fast SSC performances in female athletes during maturation (Lehnert et al., 2020).

Research shows that the positive effects of PT may differ depending on the various subject characteristics such as age, maturation, sex, sports activity, familiarity with PT, training history, volume, frequency, direction of a jump, rest intervals between sets and training sessions, and direction of jumping (Davies et al., 2015; Ramirez-Campillo et al., 2022). It is also reasonable to assume that the principle of specificity may influence the positive benefits of PT (Sole et al., 2021; Potach and Chu, 2016; Markovic and Mikulic, 2010; Moran et al., 2021; Ramirez-Campillo et al., 2015a; Asadi et al., 2016). The literature demonstrates that female soccer player might benefit more from PT than their male counterparts (Slimani et al., 2017), and that younger girls may generate greater gains than older girls (Moran et al., 2018a). Following the principle of training specificity, it is possible that horizontal PT may increase sprint speed more than vertical training, that vertical PT may increase jump height more than horizontal PT, and that a combination of horizontal and vertical PT may increase both slow and fast SCC (Ramirez-Campillo et al., 2015b; Moran et al., 2021). Given that most sports involve both horizontal and vertical expressions of power in actions such as sprinting and jumping (Taylor et al., 2022), it is suggested that PT involves exercises in both planes (Markovic and Mikulic, 2010).

Regarding duration, studies have shown 4 weeks (2 sessions per week) of PT can increase the RSI and leg stiffness of boys and girls (Lloyd et al., 2012b; Dallas et al., 2020), whereas 7-8 weeks of PT has been shown to elicit similar gains in vertical jump height as PT >8 weeks (Peitz et al., 2018; Slimani et al., 2017; Moran et al., 2018a). While most authors advocate two or more PT sessions per week aimed at children (Moran et al., 2018a; Lloyd et al., 2011a; Peitz et al., 2018), there appears no significant difference between one or more sessions of PT per week in multiple populations (Bouguezzi et al., 2020; Moran et al., 2018a; Ramirez-Campillo et al., 2020a; Ramirez-Campillo et al., 2018a; Slimani et al., 2017). Indeed, once a week PT has a positive effect on the adaptations of youth female soccer players following 7-14 weeks PT (Rubley et al., 2011; Ozbar et al., 2014). Acknowledging low frequency PT elicits meaningful training gains in slow and fast SSC would allow strength and conditioning practitioners to create the most time-efficient method of training female athletes in youth-based setting. This is important considering girls often drop out of sport due to time conflicts (18%), boredom (14%), or injury (26%) (Stewart and Taylor, 2000).

2.5 Recommendations for future research

Examining both the slow SSC and fast SSC ability of girls during different stages of maturation prior to, and following PT, might enable strength and conditioning practitioners to better identify when PT should be introduced into the training of girls in a youth-based setting. It is possible that practitioners may find that, like boys, girls exhibit accelerated periods of SSC development prior to PT that can be enhanced through synergistic adaptation. Addressing these research gaps might allow for observations of synergistic adaptation in girls following PT, which will enhance our understanding of SSC development in this understudied population but also inform evidence-based training practices tailored to their unique needs and developmental trajectories.

2.6 Conclusion

This review aimed to highlight the differences that sex and maturation can have on the development of the SSC and the effectiveness of PT. In recent years, the participation of girls in such sports as soccer has grown exponentially (Football Association, 2024). Given that SSC actions such as sprinting and jumping are often the determinants of sporting achievement (Lockie et al., 2011; Faude et al., 2012), monitoring and developing the SSC through well-planned training may have a positive effect on the sporting success of youth female athletes. Reportedly, the optimal method to train SSC movement skills is PT, whereby athletes perform a series of jumps to reduce the GCTs and, hence increase the reutilisation of elastic energy and elicit the activation of the stretch reflex. RSI and leg stiffness are often determinants of sports performance and indicators of potential injury. Therefore, RSI and leg stiffness should be monitored and developed in girls, due to their risk of ACL injuries and the need for girls to improve athletic performance.

2.7 Aims

The aims of the proposed thesis are two-fold: Firstly, to identify whether girls aged 7-17 years demonstrate periods of accelerated adaptation in SSC development during maturity, secondly, whether pre-, mid-, and post-PHV recreational female soccer players demonstrate synergistic adaptations and similar increases in slow and fast SSC function, following 8-weeks of progressive PT performed once a week.

2.8 Objectives

- The thesis will be the first time that two field-based applications (MyJump 2 and Optojump Next) for the assessment of slow (SJ and CMJ) and fast (RSI and leg stiffness) SSC function has been examined in post-PHV recreational female soccer players.

- The thesis will determine the most accurate assessment of fast SSC function by comparing GCT during a drop jump and hopping in post-PHV recreational female soccer players.

- The thesis will identify differences and possible periods of accelerated adaptations in slow and fast SSC function in girls, according to biological maturity that could be used to inform subsequent training programmes.

- The thesis will assess the effectiveness of PT in maturing girls to establish if periods of synergistic adaptation exist in slow and fast SSC function.

Chapter 3

Methodology

3.1 Philosophical perspectives

It is important to emphasise that the author of this thesis was a male sports scientist working in a female space. Therefore, the author required a research approach that was non-invasive, both physically and emotionally. Tanner secondary sexual characteristics, for example, was not a method that would have been appropriate to assess biological maturity (Lloyd et al., 2014a). The research paradigm framework of this thesis necessitates an ontological and epistemological approach.

Ontology is defined as ‘the study of being’, (Crotty, 1998, p. 10), with an ontological perspective being concerned with the nature of reality. The ontological approach of this thesis was realism (a subgroup of objectivism), by researchers assume the existence of cause and effect in the physical world.

Epistemology is concerned with ‘the nature and forms of knowledge’ (Cohen et al., 2007, p. 7). The epistemological approach of this thesis was positivism, which emphasises engaging in research where variables can be controlled and manipulated. Positivism considers that knowledge can only be based on what can be objectively observed and experienced through empirical data. As such, positivism uses measurable quantitative data to draw conclusions using statistical analysis. From a data analysis perspective, this is achieved via establishing an experimental hypothesis relating to the effect of a dependent variable on an independent variable.

3.2 Study design

This thesis includes a series of cross-sectional studies examining the development of slow (>250 ms) and fast (<250 ms) stretch-shortening cycle (SSC) function in pre-, mid-, and post-peak height velocity (PHV) female participants aged 7-17 years with and without a plyometric training (PT) intervention. This chapter includes all the measurements and interventions used throughout the thesis. However, not all measurements, participants, or interventions included in the method chapter were included in each experimental chapter. Thus, where appropriate, references to subsequent chapters will be included.

3.3 Participants

3.3.1 Participant recruitment

Throughout the experimental chapters a total of 209 girls aged 7-17 years were recruited from a soccer club (Chapters 4, 5 and 7) or school (Chapter 6) based in the UK. The sample size (range 34 – 130) was calculated using statistical power 0.8 and alpha 0.05 means using G*Power 3.1.9.4 (Table 3.1).

Table 3.1 Number of participants in each research chapter

Chapter number	Research study	Sample size
Chapter 4	Agree and reliability of the MyJump and Optojump Next	34*
Chapter 5	Drop jump and hopping in the measurement of fast SSC	34*
Chapter 6	SSC development of schoolgirls during maturation	130
Chapter 7	Effectiveness of plyometric training in the development of female soccer players during maturation	45

* Included the same participants

Written informed parental and participant consent were obtained prior to each chapter. All participants and their parents/legal representatives were fully informed about the aims and experimental protocols and their potential risks and benefits prior to each chapter (Hammami et al., 2020). Prior to each chapter, parents/guardians completed a Physical Activity Readiness Questionnaire (PAR-Q) on behave of their daughters (Comyns et al., 2018). If any potential participant reported an injury prior testing, they were excluded from the research. Participants were advised to maintain their normal levels of activity throughout the duration of the testing intervention, which included two physical education sessions per week, each lasting one hour. None of the participants self-reported as being engaged in any resistance-based or plyometric training prior to the research. All procedures were approved by the Manchester Metropolitan University ethical committee for the use of human participants. This thesis was also in accordance with the latest version of the Declaration of Helsinki (World Medical Association, 2013).

3.3.2 Anthropometry

Standing and sitting height were measured to the nearest 0.1 cm with the use of a free-standing stadiometer (Seca 213 stadiometer, Seca GmbH, Hamburg, Germany), with participants measured barefoot. Sitting height was measured using the stadiometer, with the participants sitting up straight in a chair, with their feet flat on the floor (Franklin et al., 2024; Carr et al., 1989; Massard et al., 2019). Leg length was calculated by subtracting the sitting height from the standing height. Body mass was measured to the nearest 0.1 kg using calibrated digital scales (Seca 813, Seca GmbH, Hamburg, Germany) with participants barefoot and wearing light clothing (shorts and a t-shirt). Body Mass Index (BMI) was calculated as body mass in kg divided by the square of height in metres (Sharma et al., 2017).

3.3.3 Age and maturational status

Chronological age (CA) was calculated as the difference between the date of birth and the date of assessment (Emmonds et al., 2017a). As CA does not account for biological changes associated with maturational processes (Malina et al., 2004b), such is the large interindividual variation in magnitude, timing, and tempo of the adolescent growth spurt (Stratton and Oliver, 2020), different approaches have been applied to assess the biological age of children (Peitz et al., 2018). For example, biological maturity can be estimated using skeletal, sexual and somatic maturity indicators (Malina et al., 2004b; Lloyd et al., 2014a; Baxter-Jones et al., 2005).

In this thesis, maturity status was estimated from anthropometric measurements, using the method proposed by Mirwald et al. (2002; Equation 3.1), where standing height, sitting height, leg length, body mass, age and the interaction between these variables are used to predict maturity offset and peak height velocity (PHV). Lloyd et al. (2014) described PHV as the period where the maximum rate of growth occurs. Although skeletal age via x-ray analysis is the 'gold-standard' when assessing biological maturity (Malina et al., 2004; Lloyd et al., 2014), this method requires access to a certified practitioner to administer and examine x-rays (Lloyd et al., 2014). Similarly, determination of maturational status according to Tanner staging by observing a child's secondary sexual characteristics requires an appropriately qualified clinician, without which it would be unethical and inappropriate to adopt this approach (Malina et al., 2004; Lloyd et al., 2014a). As such, a somatic method using anthropometric measures is often used in paediatric studies, given its ease of use in the field (Lloyd et al., 2014).

Two popular valid, nonintrusive, inexpensive, and simple methods of estimating biological maturity using somatic measures are the equations by Mirwald et al., (2002) and Khamis and Roche (1994). In this thesis, the reliable (SEE = 0.5 years) Mirwald equation (SEE = 0.5 years) of estimating maturity was used, primarily because collecting a father's and mother's height in a youth-based setting (schools and youth-clubs) was not always possible. Additionally, the Mirwald method has been used previously in multiple studies involving female athletes (Emmonds et al., 2017a;, Davies et al., 2021; Romero et al. 2019). Crucially, the Mirwald method uses a different equation for boys and girls (Stratton and Oliver, 2020; Lloyd et al., 2014a). Using a female-specific equation to estimate PHV [Equation 3. 1] is important because the average age for biological maturity differs in boys and girls (13.7 ± 1.4 and 12.1 ± 1.4 years, respectively) (Granados et al., 2015).

$$Eq. 3.1)\ \text{Female maturity offset} = -9.376 + (0.0001882 \cdot (\text{leg length} \cdot \text{sitting height})) - (0.0022 \cdot (\text{age} \cdot \text{leg length})) + (0.005841 \cdot (\text{age} \cdot \text{sitting height})) - (0.002658 \cdot (\text{age} \cdot \text{Body mass})) + (0.07693 \cdot (\text{Body mass} \div \text{stature})) \cdot 100$$

where stature, leg length and sitting height is measured in cm, body mass is measured in kg, and age is chronological age in years and months and the time of testing (Mirwald et al., 2002).

Years from PHV (YPHV) of each participant was calculated by subtracting the age at PHV from their chronological age (Emmonds et al., 2017a). To examine the effects of maturation in girls, participants were categorised into three pre-defined groups based on PHV; Pre-PHV (< 1 years YPHV), Mid-PHV (-1 to +1 YPHV) and Post-PHV (> +1 YPHV), which is consistent with previous paediatric literature (Cunha et al., 2015; Hammami et al., 2016; Rumpf et al., 2014; Rumpf et al., 2015). It has been established that mid-PHV reflects the age at which maximum rate of growth occurs during the adolescent growth spurt (Lloyd et al., 2014a; Malina et al., 2004b). PHV is often used as a reference landmark to reflect the development of natural strength, speed, power, and 'windows of training adaptability' in children (Balyi and Hamilton, 2004; Lloyd and Oliver, 2012). Given the associated error in the Mirwald equation (Mirwald et al., 2002), it is noteworthy to state that girls of the same CA could be classified as pre-, mid- or post-PHV due to differences in the anthropometric variables used in the Mirwald equation (Table 3.2).

Table 3.2 Peak height velocity (PHV) status using fictitious data

	Pre	Mid	Post
Age (Years)	12.0	12.0	12.0
Height (cm)	135	160	170
Body mass (kg)	35	50	60
Leg length (cm)	69	77	83
Sitting height (cm)	66	82	87
Years from peak height velocity	-1.1	+0.5	+1.2

3.4 Testing

Prior to testing, participants attended two familiarisation sessions over two weeks, separated by 7 days. During these sessions, the lead researcher (who has experience of testing, performing, and observing jump tests in youth populations) demonstrated and coached participants how to correctly perform each jump and hopping protocol used during testing. The lead researcher observed the participants and made sure the performance of each task was satisfactory (e.g., in accordance with the procedures outlined in 2.2.4) and until no further improvements in performance were observed (e.g., no increase in jump height or a reduction of GCT). All familiarisation and testing sessions included a 5-minute warm up comprising bodyweight squats, heel flicks, high knees and repeated countermovement jumps (CMJ) in place for 2 sets of 10 repetitions each. Participants were asked to wear the same clothing and footwear through each chapter, and to avoid drinking, eating, and exercising one hour before each familiarisation and testing session (Lloyd et al., 2009).

To minimise the influence of external factors (e.g. weather, surface interaction, and interrater inconsistences), all jumping and hopping tests were completed at same temperature controlled indoor venue by the lead researcher, on a hard wooden surface (Ramirez-Campillo et al., 2015b). All sprinting tests were performed on same outdoor G4 artificial surface. Due to the sensitive nature of assessing menstrual status and phase in adolescent participants (Lloyd et al., 2014a), beyond maturation status, no further data on menstrual phase or status is reported. It should be noted that the menstrual cycle impact on maximum bilateral, triple extension movements are not negatively impacted by menstrual variation (Julian et al., 2017; Romero-Moraleda et al., 2019; Blagrove et al., 2020). For example, Blagrove and colleagues (2020) noted the effect of the menstrual cycle on jump performance is minimal (Hodges g = 0.04 to 0.03 over different phases of the menstrual cycle), with similarly no significant menstrual effect on aspects that could influence the SSC such as tendon properties (Burgess et al., 2009). In contrast, large significant effects are reported for circadian variations in jump performance (Kusumoto et al., 2021). Within this thesis, circadian variation was controlled for by conducting each PRE- and POST testing session at the same time of day ± 1 (Atkinson and Reilly, 1996).

3.4.1 Instrumentation

The valid and reliable (Sharp et al., 2019; Gencoglu et al., 2023b) MyJump 2 app (Apple Inc. Cupertino, USA) was used in Chapter 4 of this thesis to measure a squat jump (SJ), countermovement jump (CMJ), and drop jump (DJ) jump height, GCT, and flight time, reactive strength index (RSI), and leg stiffness. In accordance with the designers, the lead researcher lay prone 1.5 m away from each participant and filmed their landing and take-off time

(Balsalobre-Fernandez et al., 2015; Figure 3.1) using the slow-motion capabilities of an Apple 12 iPhone (Apple Inc., Cupertino, USA). In accordance with the app's instructions, body mass (kg), leg length (cm), and squatting height (cm) was entered into the MyJump 2 software prior to testing.

The Optojump Next system (Microgate, Bolzano, Italy) was used to measure several jumping and hopping variables (i.e., SJ, CMJ, DJ, jump height, flight-time, and GCT, leg stiffness). This device was chosen because it has proven to offer near perfect reliability and validity compared to a force platform in SJ and CMJ jump height and flight time in children aged 15-17 years (Casartelli et al., 2010; Castagna et al., 2013; Slomka et al., 2017) and adults (Attia et al., 2017; Glatthorn et al., 2011; Sirico et al., 2016; Bosquet et al., 2009; Castagna et al., 2013), GCT and RSI during a DJ and hopping (Healy et al., 2016; Magrum et al., 2018; Comyns et al., 2019b), and leg stiffness during continuous hopping (Ruggiero et al., 2016) in adult males.

The Optojump Next system consisted of two 1-metre-long photoelectric bars, with one bar responsible for transmitting light from 96 light emitting diodes towards the receiving unit that was positioned 1-metre away (Figure 3.1). Due to the design of the device, the diodes were placed in a parallel arrangement 0.003 m above the ground, (Healy et al., 2016; Glatthorn et al., 2011). Prior to testing, the body mass (kg) and height (m/cm) of each participant was entered into the Optojump Next software. During each trial participants were required to stand between the two bars, except for a DJ, where participants started from a 30 cm box positioned 10 cm outside the bars before dropping to a position inside the bars. The light emission was interrupted by a participant's foot during a take-off and landing, and flight-time was measured in seconds as the time between these light disturbances, with an accuracy as 0.001 seconds (1 Hz) (Healy et al., 2016; Glatthorn et al., 2011). Both the MyJump 2 app and the Optojump Next used the flight time method proposed by Bosco et al. (1983) in the calculation of jump height during each trial (Equation 3.2).

$$\text{(Eq. 3.2) Jump height (cm)} = \frac{\text{gravity (9.81 ms) x flight time (ms)}^2}{8}$$

(Bosco et al., 1983)

Fig 3.1 Standard set up for the MyJump 2 app and the Optojump Next device

Figures 3.2 - 3.5 demonstrates each jumping and hopping protocol using during this thesis, and the positioning of the Optojump Next device during each trial.

Fig 3.2 Illustration of the participant's start position, take-off and landing during a squat jump (SJ).

Fig 3.3 Illustration of the participant's start position, landing and take-off during a countermovement jump (CMJ).

Fig 3.4 Illustration of the participant's start position, landing and take-off during a drop jump (DJ) from a 30 cm step.

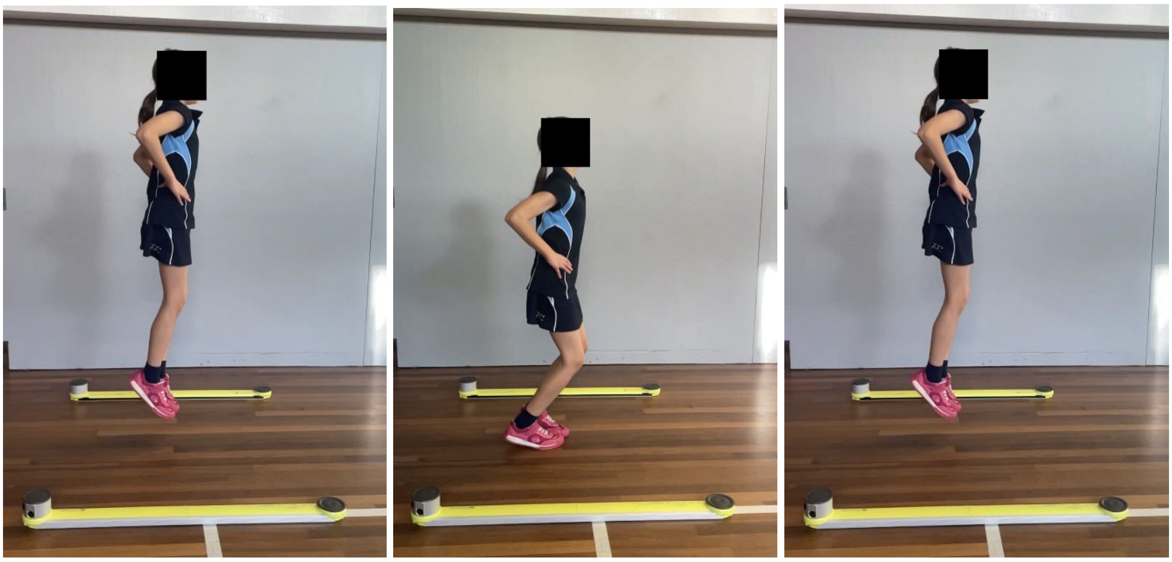

Fig 3.5 Illustration of the participant's start position, landing and take-off during 5 maximal (5max) and 20submaximal (20submax) hopping.

Throughout this thesis, all jumps and hops were performed with body mass only (Lloyd et al., 2009; Laffaye et al., 2016; Lehnert et al., 2020). Following each test, the best score of three trials (SJ, CMJ, RSI) was used for further analysis (Lloyd et al., 2009), with only one test of 20submax hopping used to measure leg stiffness tested (Lloyd et al., 2009). Using the best score is common practice in the assessment of jumping and hopping, so as not to analyse subpar efforts (Lephart et al., 1991; McGill et al., 2012; Lloyd et al., 2009). In addition, it has been shown that when three or more SJ and CMJ jumps are performed, a high degree of test-retest correlation (R = 0.95) is achieved (Bosco et al., 1983). Testing order for each chapter is highlighted in Table 3.3.

Table 3.3 Testing order of all SSC tests in chapter

Chapter	**Testing order**
4	SJ, CMJ, DJ, 5max, 20submax
5	DJ, 5max, 20submax
6	SJ, CMJ, 5max, 20submax
7	CMJ, 5max, 20submax, 20 m sprint

3.4.2 Squat jump

The squat jump (SJ) served as a representation of concentric strength and maximal concentric vertical jump height (Lloyd et al., 2011b; Lloyd et al., 2011c). Prior to jumping, each participant adopted a foot stance shoulder-width apart, with their hands on their hips, and in a flexed knee position at 90° (Glatthorn et al., 2011). Once achieved, participants held this position for 2 s before jumping vertically for maximum height on the command of the lead researcher. In accordance with previous research, each participant was visually observed during the SJ to ensure that no countermovement was implemented (Bobbert et al., 1996). Participants performed a SJ three times, with the highest jump height used for further analysis (Lloyd et al., 2009). The SJ has been found to be reliable test of vertical jump height in men (Cronbach's alpha = 0.97) (Markovic et al., 2004) and boys and girls aged 11-13 years (ICC = 0.97) (Dantas et al., 2020).

3.4.3 Countermovement jump

A maximal countermovement (CMJ) was used to assess leg power and slow (> 250 ms) SSC function (Lloyd et al., 2011c; Turner and Jeffreys, 2010). Prior to jumping, each participant adopted a foot stance shoulder-width apart, with their hands on their hips (Glatthorn et al., 2011). On command, participants lowering themselves from an initial standing position to a self-selected squat position, followed immediately by a rapid upward movement before take-off (Lloyd et al., 2009). Participants were encouraged to perform the countermovement phase of the jump as quickly as possible, with the depth of the eccentric phase being self-selected by the participant to maximize jump height (Cormack et al., 2008). Participants performed a CMJ three times, with the highest jump height used for further analysis (Lloyd et al., 2009). The CMJ has been shown to be a valid and reliable test of vertical jump height in men (Cronbach's alpha = 0.98) (Markovic et al., 2004) and girls and boys aged 11–13 age years (ICC = 0.97) (Dantas et al., 2020).

3.4.4 Drop jump

During the drop jump (DJ) participants stood on a 30 cm step positioned 10 cm from the edge of the Optojump Next system with their hands on their hips (Healy et al., 2016). A 30 cm drop height was selected in line with other studies involving maturing girls (Pedley et al., 2021; Jeras et al., 2019; Moeskops et al., 2022). To control for homogenous drop height distance, participants were instructed to "step out onto an invisible box and drop directly downward." (Pedley et al., 2020), promoting participants to; "drop off" the step (Stratford et al., 2020b); avoiding stepping down (e.g., excessively bending their trail leg); lifting their centre of gravity (e.g. jumping off); and performing a tucking motion in the air (Costley et al., 2018; Baca, 1999; Barr and Nolte, 2011). Prior to execution, participants were instructed "jump as high as possible, as fast as possible" (Young, 1995). Participants then stepped off the step with their preferred foot (Ambegaonkar et al., 2011) before landing with two feet simultaneously between the Optojump Next bars (Healy et al., 2016). As soon as ground contact was made, participants immediately performed a maximal vertical rebound jump (Flanagan et al., 2008) by jumping as high as possible with minimal contact time (Lloyd et al., 2009). Following their rebound jump, participants were instructed to stick the landing in the same position as they had taken off from. (Pedley et al., 2020). Trials were excluded and data recollected if the subjects visibly stepped down from or jumped off the box rather than stepping out (Pedley et al., 2020), or if they did not jump or land two feet simultaneously. Participants performed a DJ three times. Determinants of RSI (flight time, jump and GTC) were also analysed during the DJ.

3.4.5 Maximal hopping

The 5 maximal hopping (5max) protocol was performed in the same manner as previously described in paediatric literature (Lloyd et al., 2009; Lehnert et al., 2020). The 5max test involved participants performing 5 bilateral maximal hops in place, with their hands on their hips, standing between the Optojump bars (Chaabene et al., 2019; Davies et al., 2019). The first hop served as a CMJ (impetus) and was not included in the analysis. The four remaining hops were averaged for further analysis of RSI and leg stiffness (Lloyd et al., 2009). Participants were instructed to maximise jump height, whilst minimising ground contact time (GCT) (Dalleau et al., 2004; Ruggiero et al., 2016). The 5max test was performed three times, with the highest RSI and leg stiffness values used for further analysis (Lloyd et al., 2009). The derivatives of 5max hopping (jump height, GCT, and flight time) were also recorded for further analysis (Flanagan et al., 2008). Using this method, Lloyd et al. (2009) reported validity and reliability of ICC = 0.75-0.90 and CV = 13.98% in boys aged 13.5 ± 0.5 years using a jump mat, while Comyns et al. (2018) reported high inter-day reliability (ICC = 0.98, CV =7.5 %) in female collegiate team athletes sport using the Optojump.

3.4.6 Submaximal hopping

During the 20submax test, a hopping frequency 2.5 Hz was selected to ensure participants conformed to the spring-mass model and would maintain the required hopping frequency (Hobara et al., 2008; Farley et al., 1991), while also allowing the participants to demonstrate greater consistency of movement coordination (Lloyd et al., 2009). Hopping frequency of 2.5 Hz was maintained throughout the 20submax test using an auditory signal from a digital quartz metronome (SQ50V; Seiko, Tokyo, Japan) (De Ste Croix et al., 2017). Standing between the Optojump Next bars, with their hand on their hips, participants perform 20 consecutive bilateral hops in place (Lloyd et al., 2009), with the mean of the ten consecutive hops closest to the designated metronome was used for further analysis (Lloyd et al., 2009; Dallas et al., 2020). In accordance with Lloyd et al. (2009), a single 20submax was performed.

3.4.7 Reactive strength index

Reactive strength index (RSI) was calculated using equation first proposed by Young (1995; Equation 3.3) using inbuilt Optojump Next software.

$$\text{(Eq. 3.3) RSI} = \frac{\text{Jump height (mm)}}{\text{Contact time (ms)}}$$

(Young, 1995)

In this thesis, RSI was calculated during a DJ, 5max and 20submax hopping (Chapters 4 and 5), and using the 5max only in Chapters 6 and 7.

3.4.8 Absolute leg stiffness

Absolute leg stiffness was calculated using a validated and reliable (R = 0.94-0.98) field-based equation first proposed by Dalleau et al. (2004; Equation 3.4).

$$(\text{Eq. 3.4})\,\text{Leg stiffness} = \frac{\text{Body mass} \times \pi\ (\text{flight time} + \text{contact time})}{\text{contact time}^2 \times \left(\left(\frac{\text{flight time} + \text{contact time}}{\pi}\right) - \left(\frac{\text{contact time}}{4}\right)\right)}$$

Dalleau et al. (2004)

where body mass is measured in kg, and flight time and contact time are measured in ms.

In this thesis, absolute leg stiffness was measured during a DJ, 5max and 20submax hopping by modelling the vertical ground reaction force, based on the flight time, GCT, and body mass (Chaouachi et al., 2014; Dalleau et al., 2004; Lloyd et al., 2009). This method during hopping has been found to be reliable in adolescent boys aged 13.5 ± 0.5 years (typical error of estimate [TEE] = 7.5%; CV = 10.2%) and in girls aged 12-18 years (ICC = 0.75-0.91; CV = 8.2%) by Lloyd et al. (2009) and De Ste Croix et al. (2017), respectively.

3.4.9 Relative leg stiffness

Leg stiffness was normalised relative to leg length and body mass (Equation 3.5) outlined previously by McMahon and Cheng (1990)

$$(\text{Eq. 3.5})\ \text{Realtive leg stiffness} = \frac{\text{Leg siffness x leg length(mm)}}{\text{body mass 9kg) x gravity (9.81)}}$$

(McMahon and Cheng, 1990)

To control for the potential effects of arm swing on jump height, landing, and movement neuro-mechanics (Ashby and Delp, 2006; Chaudhari et al., 2005; Cowling and Steele, 2001), participants were instructed to keep their hands on their hips throughout each jump (Ambegaonkar et al., 2011). To minimise lateral and horizontal displacement during performance, participants were instructed to jump and land on the same spot; land with legs fully extended (i.e. triple extension at the acetabulofemoral joint, femorotibial joint, and the talocrural joint); and to look forward at a fixed position to aid balance maintenance (Lloyd et al., 2009). Adherence to these instructions was carefully monitored by the lead researcher during all testing sessions. If a participant failed to comply with these instructions, the trial was deemed invalid and discarded. Following an invalid trial, the participant was reminded of the protocol and asked to perform the trial again following adequate rest (Lloyd et al., 2009; De Ste Croix et al., 2017). In accordance with previous literature, rest periods between each jumping and hopping test were set a 60 s (Lloyd et al., 2009). To avoid any residual effects of fatigue, 3 minutes recovery was given between different tests (Read and Cisar, 2001).

3.4.10 Sprinting

Sprint testing was performed after the completion of all jump tests. Participants perform 2 x 20 m sprints (Loturco et al., 2013). During this test, two Brower Speed Trap II times gates (Brower Timing Systems, Utah, USA) were positioned 20 m apart, with each transmitter and receiver positioned 5 m apart at standing height 0.91-m (Bond et al., 2017). Participants started 5 m behind the first timing gate using a two-point stance (Romero-Franco et al., 2017) and ended 10 m beyond the final timing gate, marked by a red cone (Loturco et al., 2013). To begin each trial, participants were given the instructions “ready” and “go” and were encouraged verbally throughout each trial to promote maximal effort (Meyers et al., 2015). All sprint tests were undertaken individually (Meyers et al., 2015). A sprint of 20 m was chosen as soccer players routinely perform linear sprints between 10 and 20 m (Haugen et al., 2014; Faude et al., 2012). To minimise the effect of fatigue and allow the phosphagen energy system to fully resynthesize (Harris et al., 1976), 4 minutes rest between each sprint was permitted (Koral et al., 2018; Meyers et al., 2015). All sprint tests were conducted on an outdoor 4G pitch, with participants wearing astro turf boots. The weather conditions during each testing session were dry with minimal wind. The fastest trial (s) completed by each participant were used for further analysis (Loturco et al., 2013; Lloyd et al., 2016).

3.4.11 Statistical analysis

Throughout this thesis, measures for dependent variables are presented as mean standard deviation (SD). All statistical analyses were performed in SPSS version 28 (SPSS Inc., Chicago, IL, USA) and Microsoft Excel (version 2016, Microsoft Corp., Redmond, WA, USA). In all studies (Chapters 4-7). statistical significance was classified as a *p*-value ≤ 0.05 (Moeskops et al., 2018), while the effect sizes (ES) using the modified Cohen's d were classified as ≥4.0 extremely large; 2.0–4.0 very large; 1.2–2.0 large; 0.6–1.2 moderate; 0.2–0.6 small; ≤0.2 trivial (Hopkins, 2002). All other statistical analyses information is described in each individual research chapter. All research chapters (chapters 4-7) will use a variety of approaches to analysis the data. All statistical analysis procedures are described in detail in relevant sections of each research chapter.

3.5 Plyometric Training

Many team sports require a high level of aerobic and anaerobic capacity (Turner et al., 2013a; Taylor et al., 2021). From a practical perspective, strength and conditioning practitioners must monitor a diverse range of factors to improve the fitness of soccer players. In soccer, for example, 67% of goals are scored due to SSC actions such as linear short sprints, jumping, and change of direction (Faude et al., 2012). Therefore, these SSC-based movements should be tested by strength and conditioning practitioners on a regular basis.

Due to the limited training time of youth soccer players, it is of vital importance that strength and conditioning practitioners design training programmes that are time efficient. While reviewing the literature, it was apparent that plyometric training (PT) offered a safe, time efficient modality to effectively train and develop the SSC in adults and children (Flanagan and Comyns, 2008; Lloyd et al., 2011a). The aims of this thesis were to measure the SSC of girls during maturation (Chapter 6), and to improve the slow and fast SSC of maturing female soccer players using PT 9 (Chapter 7). The measurement of both RSI and leg stiffness appears to be fundamental not only in the testing of SSC capability, but also in the monitoring of a plyometric programme and injury prevention (Lehnert et al., 2020). It is hoped that the author’s research may help in adding to the research in this area while also providing useful applied information to the strength and conditioning practitioners working with youth female soccer players, with consideration given to maturation.

PT has consistently been shown to increase sprinting, jumping, and hopping ability in boys and girls at various stages of biological maturity (Moran et al., 2018a; Asadi et al., 2017; Moran et al., 2017b). In this thesis, soccer-only training (1 per week/ 8-weeks) was compared to soccer training supplemented with PT (1 per week/ 8-weeks (Table 3.4). Although PT twice a week PT has been shown to increase jump height, RSI, leg stiffness and/or sprinting (Lloyd et al., 2012b; Dallas et al., 2020; Lloyd et al., 2016; Moran et al., 2017c), there appears no significant difference between PT performed between one and more sessions per week in youth female athletes (Slimani et al., 2017; Moran et al., 2018a; Ramirez-Campillo et al., 2020a). Additionally, previous literature has found one session per week for 8 and 14 weeks was sufficient to increase jump height in youth female soccer players aged 13 and 18 years, respectively (Ozbar et al., 2014; Rubley et al., 2011). PT commonly lasts between 4-16 weeks (Lloyd et al., 2012b; Dallas et al., 2020; Lloyd et al., 2016; Moran et al., 2017c). While a meta-analysis by Moran et al. (2018) involving girls aged 10-17 years suggested that 8 weeks PT generated greater training improves than less PT, a subsequent meta-analysis found that ≤ 8 weeks PT elicited a greater effect on jump height that PT ≥ 8 weeks (Ramirez-Campillo et al., 2020a). One systematic review also found that most PT interventions in youth participants last 7.1 ± 1.4 weeks (Peitz et al., 2018).

The PT programme was used as a substitute for the low-intensity technical-tactical soccer drills at the beginning (i.e., first 10-20 minutes) of the usual 60-minute soccer practice (Ramirez-Campillo et al., 2015b). Each session commenced with standardised warm-up consisting of light jogging, jumping jacks and high knee drills in place. The intensity of the programme was increased in accordance with previous plyometric training guidelines aimed at children and adolescents (Lloyd et al., 2011a), with intensity determined based on the magnitude of eccentric loading of each exercise (Lloyd et al., 2011a; Meylan et al., 2012). PT was progressed over the course of the 8-week intervention by increasing volume and including horizontal exercises (Ramirez-Campillo et al., 2015b). Training volume was defined by the number of foot contacts made during each session (Ebben et al., 2010), starting with 80 contacts in Week 1, increasing to 190 contacts in Week 7, and a tapering to 60 contacts in Week 8 (Ramirez-Campillo et al., 2020b). A contact was identified each time the lower extremities perform one attempt of each exercise. Plyometric drills lasted approximately 5-10 s, and 90 s minutes rest was allowed after each set between difference tasks (Meylan and Malatesta, 2009). This work-rest ratio was enforced to optimise repetition velocity, enable full-recovery, and retain maximal motor unit recruitment throughout the training session (Lloyd et al., 2011a). Progressive volume-based PT was used because it appears more advantageous that non-progressive PT (Ramirez-Campillo et al., 2020b; Ebben et al., 2010). Tapering PT volume during the final week was used as reducing volume prior to testing has been shown to reduce the effects of fatigue during the post-test and increase jump performance (Miller et al., 2006; Ebben et al., 2010). Specifically, a > 40% reduction in volume has been shown to have a greater effect size (ES) on jump capacity than tapering volume ≤ 40% (effect size [ES] = 1.18 and 0.61, respectively) (Ramirez-Campillo et al., 2020a). Owing to a lack of PT familiarity, verbal feedback focused on correct take-off and landing mechanics (Lloyd et al., 2012b). The training intervention was supervised by the lead researcher who is experienced strength and conditioning practitioner experienced in performing and coaching PT. Exercise quality was carefully observed to ensure proper execution and limit the risk of injury (Sylvester et al., 2024). No injuries occurred during the intervention.

Table 3.4 8-week progressive plyometric training programme

	Week 1	Week 2	Week 3	Week 4	Week 5	Week 6	Week 7	Week 8
Submaximal bilateral hopping	2 x 20	2 x 10	2 x 10	3 x 10	2 x 20	3 x 20	3 x 20	2 x 20
Maximal bilateral hopping	5 x 6	2 x 10	2 x 10	2 x 10	2 x 10	2 x 10	3 x 10	2 x 5
Countermovement jumps	1 x 10	2 x 10	2 x 10	2 x 10	2 x 10	2 x 10	2 x 10	1 x 10
Unilateral vertical hopping		2 x 10	2 x 10	2 x 10	2 x 10	2 x 10	2 x 10	
Bilateral horizontal hops		2 x 10	2 x 10	2 x 10	2 x 10	2 x 10	2 x 10	
Unilateral horizontal hops			2 x 10	2 x 10	2 x 10	2 x 10	2 x 10	
Bounding					2 x 10	2 x 10	2 x 10	
Sprinting	20 m x 2	10-m x 3	15-m x 2	20 m x 2	30-m x 2	50-m x 2	50-m x 3	20 m x 2
Total foot contacts per leg (excluding sprints)	80	100	120	130	160	180	190	60

All exercises are represented in sets x reps.
All exercises were performed as rapidly as possible, with maximum effort

To increase horizontal force required for sprinting (Markovic and Mikulic, 2010; Brughelli et al., 2011; Morin, 2013) and the vertical force to improve jump height (Ramirez-Campillo et al., 2015a; Ramirez-Campillo et al., 2015b) the PT intervention included both vertical and horizontal plyometric exercises (Loturco et al., 2015; Moran et al., 2021; Ramirez-Campillo et al., 2020a; Talukdar et al., 2022b). All vertical drills were performed with arms akimbo (Floria and Harrison, 2013), whereas participants were encouraged to use arm swings to increase momentum during horizontal exercises (Ashby and Heegaard, 2002). To maintain motivation and variety, the order of exercises was randomised for each training session (Ramirez-Campillo et al., 2015b). All groups performed PT on the same surface (G4 artificial grass), in conditions with minimal wind and a dry surface. Due to lack of prior plyometric experience in the participant groups, the PT programme used a tester-to-participant ratio of 1:5, with attention paid to demonstration, correct execution, verbal feedback, focus on correcting posture, linearity of jumping kinematics and take-off and control of landing mechanics (Cronin and Radnor, 2020). To maximise fast elastic recoil and stretch reflex utilisation (Lloyd et al., 2012b), all PT exercises were performed in a cyclical nature and as rapidly as possible (Potach and Chu, 2016; Turner and Jeffreys, 2010).

Sprint training was also included in the PT programme (Markovic et al., 2007), as sprinting, alongside hopping, is considered one of the purest expressions of plyometric action (Hansen and Kennelly, 2017; Komi and Nicol, 2011). For example, mid- and post peak PHV girls have shown to sprint with GCTs of 170 ms (Talukdar et al., 2021). By performing repeated CMJs, hopping and sprinting during the PT, the intervention adhered to principle of training specificity, which predicts that the closer the training routine is to the requirements of the desired outcome, the better the outcome will be (Sale and MacDougall, 1981; Sale, 1988).

Chapter 4

Agreement and reliability of the MyJump 2 app and the Optojump Next in the measurement of stretch-shortening cycle function in adolescent female soccer players

4.1 Introduction

Soccer is an intermittent team sport which incorporates submaximal aerobic tasks with a variety of explosive actions such as sprinting and jumping (Taylor et al., 2022). Such actions utilise the stretch-shortening cycle (SSC), which consists of an eccentric action, quickly followed by a concentric action (Turner and Jeffreys, 2010). Three important measures of SSC function are the maximal countermovement jump (CMJ), the reactive strength index (RSI) and leg stiffness (Lloyd et al., 2009). The CMJ assesses leg power and slow SSC function (>250 ms), whereas the RSI and leg stiffness measure the fast (<250 ms) SSC (Lloyd et al., 2009). RSI and leg stiffness have important implications for both sports performance and the risk of injury as increasing these metrics can lower the indices of anterior cruciate ligament (ACL) rupture (Lehnert et al., 2020; Butler et al., 2003; Flanagan and Comyns, 2008). Reducing ACL injuries is of particular importance to strength and conditioning practitioners working with adolescent female soccer players as they are more likely to suffer from ACL injuries than their male counterparts (Childers et al. 2024; Shea et al., 2004; Clausen et al., 2014). Crucially, girls who play soccer are also 150% more likely to sustain an ACL injury compared to high school female athletes participating in any other sport (Childers et al., 2025).

The ‘gold-standard’ when measuring vertical jump height, RSI and leg stiffness is a laboratory-based force platform (Linthorne, 2001; Arampatzis et al., 2001b; Ferris and Farley, 1997). Owing to their price, complexity, and lack of transportability (Balsalobre-Fernandez et al., 2015; Hojka et al., 2018), strength and conditioning practitioners working in a youth-based setting often seek reliable, ecologically valid, low-cost, time-efficient, user-friendly, portable alternatives to measure SSC function (Bogataj et al., 2020b). Such devices allow for the testing of large numbers of performers simultaneously quickly, which would be suitable when testing soccer players in the field (Hulse et al., 2013). Two such alternatives are the MyJump 2 app (Apple Inc. Cupertino, USA) and the Optojump Next photoelectric system (Microgate, Bolzano, Italy). Although there is a plethora of studies testing the validity and reliability of both devices in a variety of SSC-based tasks (Glatthorn et al., 2011; Casartelli et al., 2010; Rago et al., 2018; Sirico et al., 2016; Attia et al., 2017; Healy et al., 2016; Ruggiero et al., 2016; Gencoglu et al., 2023a; Sharp et al., 2019; Haynes et al., 2018) only 14% (6/43) of all known studies have involved girls aged <18 years. In addition, only one study measured the RSI in girls, and of the one that did, only the MyJump 2 app was used (Rogers et al., 2018). Owing to the anatomical, physiological, biomechanical and hormonal differences between girls and boys following puberty (Bini et al., 2000; Handelsman, 2017) (Huston and Wojtys, 1996; Ford et al., 2003), the data found in trained and untrained men and boys using MyJump 2 and Optojump Next might not be transferable to adolescent female soccer players.

To date, only one study has examined the ability of the Optojump Next to measure leg stiffness compared to the gold-standard (Ruggiero et al., 2016), while no studies have done so using the MyJump 2 app in any population (Haynes et al., 2018). Establishing the agreement of these devices in the slow (SJ and CMJ) and fast (RSI and leg stiffness) SSC function of adolescent female soccer players may allow strength and conditioning practitioners working with this cohort to create normative data and a more complete SSC profile of adolescent female players. As the app costs £10 and the Optojump Next costs £3,500, finding high agreeability between the devices may offer strength and conditioning practitioners working in a youth-based setting the opportunity to monitor the SSC function using a low-cost and accessible device.

When monitoring SSC function and the performance characteristics of youth female soccer players, reliability is important, as it allows strength and conditioning practitioners to evaluate the effectiveness of training programmes, optimising physical development and talent identification (Hulse et al., 2013). Reliability is the consistency of an individual's performance during a testing (Thomas et al., 2017a; Atkinson and Nevill, 1998). Frequent between-day reliability is essential to allow practitioners to monitor the potential changes to athletic performance (Petre et al., 2023). Although all tests include some degree of measurement error. Consequently, reliability should be considered as the amount of measurement error that is deemed acceptable for effective practical use of a test and the equipment used. Establishing what is an 'acceptable level' is might of great importance to strength and conditioning practitioners testing the effectiveness of a training programme (Hulse et al. 2013). Between-day reliability of a test referring to its ability to produce consistent results from day-to-day (Hopkins, 2000). It is important that a test has good between-session reliability, as this gives strength and conditioning practitioners the confidence that changes in performance are 'real' and 'meaningful' and not due to daily variations in the test (Franklin et al., 2024). Therefore, aim of the chapter was two-fold: firstly, to establish the inter-device agreement between the MyJump 2 app and the Optojump Next system, and secondly examine the between-session reliability of various measures of slow and fast SSC function, including SJ, CMJ, DJ, RSI, leg stiffness, and relative leg stiffness, and their derivatives using both devices.

4.2 Methods

4.2.1 Participants

Detailed descriptions of participant recruitment and assessment of anthropometric, maturation, and SSC variables are detailed in Chapter 3. In this chapter 34 post-PHV recreational adolescent female soccer players (age: 14.7 ± 0.4 yrs; +2.1 ± 0.5 PHV; height: 1.65 ± 0.06 m; body mass: 56.7 ± 9.6 kg; body mass index [BMI]: 20.7 ± 3.26 kg·m^{-2}: training age: 4.2 ± 2.5 years) volunteered to participate in the agreement study, with 24 of these same participants (age: age: 14.7 ± 0.4 years; +2.1 ± 0.5 PHV; height: 1.65 ± 0.06 m; body mass: 55.6 ± 11.0 kg; BMI: 20.4 ± 3.6 kg·m^{-2}; training age: 4.4 ± 2.5) also taking part in the reliability study.

4.2.2 Testing

All SSC dependent variables are detailed in Chapter 3 but described briefly here. Jump height (cm) was measured using a squat jump (SJ) and countermovement jump (CMJ). RSI and its determinants of jump height (mm) and GCT measured in ms, and leg stiffness and its determinants of flight time (ms) and GCT (ms) were measured during a drop jump (DJ), 5 maximal (5max) hopping (5max) and 20 submaximal (20submax) hopping. Relative leg stiffness was also calculated. All DJ tests were carried out using the MyJump 2 app and Optojump Next optical measurement system, with the latter also measuring RSI and leg stiffness during 5max and 20submax hopping. RSI and leg stiffness during a DJ and 5max hopping was measured three times, with the best values used for further analysis. A single test of 20submax measuring RSI and leg stiffness was used for further analysis.

4.2.3 Statistical analysis

Testing session measures for dependent variables are presented as mean standard deviation (SD). All statistical analyses were performed in SPSS version 28 (SPSS Inc., Chicago, IL, USA) and Microsoft Excel (version 2016, Microsoft Corp., Redmond, WA, USA). Bland–Altman with upper (+1.96) and lower (-1.96) limits of agreement (LOA) plots were also used to detect systematic bias between the two devices (Bland and Altman, 1999). Agreement and reliability measures for the MyJump 2 and Optojump Next system also included intraclass correlation coefficient (ICC; two-way mixed effects, average measures, absolute agreement) with 95% confidence intervals (CI), coefficient of variation (CV; Equation 4.1) with 95% CI, standard error of measurement (SEM; Equation 4.2) to examine absolute reliability (Bailey, 2023; Shechtman, 2013), the smallest detectable difference (SDD; Equation 4.3) of the mean of sessions 1 and 2 (Angst et al., 2001), standard deviation pooled (SDpooled; Equation 4.4) (Lakens, 2013), with effect size (ES; Equation 4.5) calculated using a modified Cohen's d (Hopkins, 2002), which were all calculated via Microsoft Excel. The calculations for reliability measures were as follows (Franklin et al., 2024):

(Eq.4.1) $\text{Coefficient of variation } (\text{CV\%} = \text{SD}/\text{mean x } 100)$

(Eq. 4.2) $SEM = SD(pooled)\ x\ \sqrt{1 - ICC}$

(Eq. 4.3) $\text{SDD} = SEM\ x\ \sqrt{2}\ x\ 1.96$

(Eq. 4.4) $\text{SDpooled} = \sqrt{\frac{\left((Mean_1 - 1)\ s_1^2 + (Mean_2 - 1)\ s_2^2\right)}{(Mean_1 + Mean_2 - 2)}}$

(Eq. 4.5) $\text{Cohen's d effect size} = \text{session 1 mean} - \text{session 2 mean/SD(pooled)}$

SDD was used to determine real and meaningful changes between the sessions and CV% and SEM were used to determine the variability between the two sessions (Franklin et al., 2024). ICCs were interpreted as follows: >0.9 excellent; 0.75–0.9 good; 0.5–0.75 moderate; <0.5 poor (Koo and Li, 2016). CV% was classified as ≤5% excellent; 5–10% good; 10–15% acceptable; ≥15% unacceptable (Shechtman, 2013). Effect sizes (*d*) were classified as ≥4.0 extremely large; 2.0–4.0 very large; 1.2–2.0 large; 0.6–1.2 moderate; 0.2–0.6 small; ≤0.2 trivial (Hopkins, 2002). and CV% was classified as ≤5% excellent; 5–10% good; 10–15% acceptable; ≥15% unacceptable (Shechtman, 2013). Statistical significance was classified as a p-value of 0.05 (Moeskops et al., 2018).

4.3 Results

Agreement

Descriptive statistics and agreement measures containing ICC, CV%, Δ%, *p* values, and ES are presented in Table 4.1. The MyJump 2 app demonstrated higher values in SJ height, DJ GCT, DJ RSI, DJ leg stiffness, and DJ relative stiffness compared to the Optojump Next (Table 4.1).

However, paired sample t-tests p-values showed no significant differences between the devices in any variable (p ≤ .123; Table 4.1). The devices demonstrated excellent inter-device agreement in SJ, CMJ, and DJ height, and DJ flight time (ICC ≥ .964; Table 4.1) and good CV values in SJ, CMJ, DJ height DJ jump height, DJ GCT, and DJ flight time (CV ≤ 4.4%; Table 4.1). DJ GCT, DJ RSI, demonstrated good agreement (ICC ≥ .839; Table 4.1), while DJ leg and relative stiffness demonstrated moderate agreement (ICC ≤ .735; CV ≥ 7.7%; Table 4.1). DJ RSI also demonstrated moderate CV (7.7%; Table 4.1). Bland-Altham (B-A) plots with mean difference and 95% LOA are highlight in figures 4.1 to 4.8. Systemic bias ranges from -0.356 to 2.85, with any positive values demonstrating greater values on average using the app. While most athletes were scattered randomly within the upper and lower LOA, 2 athletes fell above the upper LOA during for SJ height (Figure 4.1) and relative leg stiffness (Figure 4.8), while 1 athlete fell above the upper LOA for RSI (Figure 4.5) and leg stiffness (Figure 4.7). DJ GCT showed 1 athlete fell above the upper LOA and another below the lower LOA (Figure 4.4).

Reliability

Descriptive statistics and reliability measures containing ICC, CV%, Δ%, SEM, SDD, P values, and ES for the MyJump 2 app and the Optojump Next are presented in Table 4.2 and Table 4.3, respectively. Using the MyJump 2 app, significant session 2 SJ height was significantly greater than session 1 (P = .002; ES = 0.29; Table 4.2), with no significant between-session differences in all other variables (P ≥ .229; ES ≤ 0.17; Table 4.2). Between-session reliability using the app was excellent in DJ leg stiffness (ICC = 0.934; Table 4.2), and good in all variables (ICC ≥ .856; Table 4.2), bar DJ GCT, which showed moderate reliability (ICC = .682; Table 4.2). DJ flight time demonstrated an excellent CV value (CV = 3.5%; Table 4.2), while SJ height, CJ height, DJ height, and DJ GCT demonstrated good CV values (CV ≤ 0.74; ES ≥ 0.05; Table 4.2). RSI, leg stiffness and relative leg stiffness demonstrated acceptable CV values (CV ≤ 10.7; Table 4.2). ES values demonstrated small-to-trivial effect sizes in all variables (d ≤ 0.29; Table 4.2).

Using the Optojump Next, SJ height, 5max leg stiffness, 5max relative leg stiffness, and 20submax GCT were significantly greater in session 1 compared to session 2 (P ≤ .029; ES ≥ 0.33; Table 4.3), while CMJ height, 5max GCT and 5max flight time were significantly greater in session 1 compared to session 2 (P ≤ .038; ES ≥ 0.30: Table 4.3). All other variables showed no significant difference between day 1 and day 2 (P ≥ .203; Table 4.3). Between-session reliability was excellent in 5max RSI (ICC = .921; Table 4.3), good in SJ, CMJ, and DJ jump height, DJ RSI, DJ flight time, 5max leg stiffness, and 20submax leg stiffness (ICC ≥ .811; Table 4.3), and moderate in all other variables (ICC ≥ .618; Table 4.3). CV were excellent in DJ flight time, 5max GCT, 20submax GCT, and 20submax flight time (CV ≤ 4.7%; Table 4.3), and good in all other variables (CV ≤ 9.9%; Table 4.3), bar DJ RSI, DJ leg stiffness, DJ relative leg stiffness, and 20submax height, which were deemed acceptable (CV ≤ 12.4%; Table 4.3). ES were small-to-trivial in all variables (ES ≤ 0.53: Table 4.3).

Table 4.1: Descriptive statistics (Mean ± SD) of agreement between the MyJump 2 app and the Optojump Next

	MyJump 2	Optojump Next				
Variable	**Mean ± SD**	**Mean ± SD**	**Δ%**	**ICC (95% CI)**	**CV% (95% CI)**	**ES**
SJ height (cm)	22.7 ± 5.3	22.6 ± 4.9	-0.4	**.988 (.917 - .979)[a]**	3.5 (2.4 - 4.7)	0.02
CMJ height (cm)	23.2 ± 5.3	23.3 ± 5.0	0.4	**.966 (.934 - .986)[a]**	3.7 (2.8 - 4.5)	0.02
DJ height (cm)	19.8 ± 5.2	20.0 ± 4.8	1.0	**.966 (.933 - 9.83)[a]**	4.4 (3.4 - 5.4)	0.05
DJ GCT (ms)	257.8 ± 42.6	255.0 ± 35.0	-1.1	**.839 (.703 - .916)[a]**	4.2 (2.7 - 5.8)	0.07
DJ RSI (mm/ms)	0.82 ± 0.30	0.80 ± 0.25	-2.4	**.867 (.751 - .931) [a]**	7.7 (5.0 - 10.4)	0.05
DJ flight time (ms)	398.0 ± 51.8	401.6 ± 48.6	0.9	**.964 (.930 - .982)[a]**	2.0 (1.5 - 2.5)	0.07
DJ leg stiffness (kN)	13.22 ± 5.74	12.94 ± 3.73	-2.1	**.748 (.552 - .866)[a]**	7.7 (4.1 - 11.2)	0.06
DJ relative leg stiffness ($kN·kg^{-1}·m^{-1}$)	19.29 ± 6.43	18.73 ± 4.38	-2.1	**.735 (.533 - .858)[a]**	8.0 (4.3 - 12.3)	0.10

Abbreviations: SJ, squat jump; CMJ, countermovement jump; DJ, drop jump; 5max, 5 maximal hops, 20submax, 20 submaximal hops; JH, jump height, GCT, ground contact time; RSI, reactive strength index; FT, flight time; SD, standard deviation; intraclass correlation coefficient; 95% CI, confidence intervals; CV, coefficient of variance; ES, effect size using Cohen's d

[a] p <.001 **(Bold)**

Table 4.2 Between-session reliability for all SJ, CMJ, and DJ variables for the MyJump 2 app

	Session 1	Session 2	Between-Session Reliability Statistics					
Variable	**Mean ± SD**	**Mean ± SD**	**Δ%**	**ICC (95% CI)**	**CV% (95% CI)**	**SEM**	**SDD**	**ES**
SJ height (cm)	22.7 ± 4.7	**24.2 ± 5.2**[a]	6.6	**.885 (.607 - .958)**[b]	6.2 (4.6 - 7.8)	1.27	4.66	0.29
CMJ height (cm)	25.0 ± 5.4	24.3 ± 5.4	-2.8	**.883 (.752 - .948)**[b]	5.4 (2.7 - 7.2)	1.28	3.55	0.17
DJ height (cm)	20.7 ± 4.7	20.9 ± 5.6	1.0	**.861 (.706 - .938)**[b]	7.0 (4.3 - 9.8)	1.89	4.12	0.05
DJ GCT (ms)	241.6 ± 50.0	246.8 ± 44.2	2.2	**.682 (.393 - .849)**[b]	7.4 (4.2 - 10.6)	17.72	49.11	0.17
DJ RSI (mm/ms)	0.92 ± 0.3	0.91 ± 0.34	-1.1	**.875 (.732 - .944)**[b]	10.7 (7.2 – 14.2)	0.08	0.22	0.03
DJ flight time (ms)	408.8 ± 45.4	409.4 ± 55.5	0.2	**.856 (.695 - .935)**[b]	3.5 (2.1 - 4.9)	14.90	41.30	0.02
DJ leg stiffness (kN)	13.71 ± 5.23	13.21 ± 4.75	-3.7	**.934 (.855 - .971)**[b]	10.5 (6.3 - 14.8)	1.17	3.26	0.11
DJ relative leg stiffness ($kN \cdot kg^{-1} \cdot m^{-1}$)	20.56 ± 7.75	19.83 ± 6.72	-3.6	**.884 (.753 - .948)**[b]	10.1 (6.1 - 14.1)	1.69	4.69	0.14

Abbreviations: SJ, squat jump; CMJ, countermovement jump; DJ, drop jump; GCT, ground contact time; RSI, reactive strength index; FT, flight time; SD, standard deviation; ICC, intraclass correlation coefficient; CI (95%) confidence intervals; CV%, coefficient of variation; SEM, standard error of measurement; SDD, smallest detectable difference; ES, effect size using Cohen's d

[a] $P<.05$ Difference between Day 1 and Day 2 **(Bold)**

[b] $P<.001$ **(Bold)**

Table 4.3 Between-session reliability for all SJ, CMJ, and DJ variables for the Optojump Next

	Session 1	Session 2	Between-Session Reliability Statistics					
Variable	**Mean ± SD**	**Mean ± SD**	**Δ%**	**ICC (95% CI)**	**CV% (95% CI)**	**SEM**	**SDD**	**ES**
SJ height (cm)	22.3 ± 4.7	**23.5 ± 5.2**[a]	5.4	**.899 (.695 - .961)**[b]	5.6 (3.9 - 7.3)	1.19	3.29	0.33
CMJ height (cm)	25.0 ± 5.1	**23.9 ± 5.1**[a]	-4.4	**.886 (.731 - .951)**[b]	5.3 (3.4 - 7.2)	1.19	3.31	0.30
DJ height (cm)	20.5 ± 4.7	20.7 ± 5.4	1.0	**.879 (.741 - .946)**[b]	6.4 (4.2 - 8.5)	1.33	3.68	0.06
DJ GCT (ms)	241.6 ± 43.9	250.2 ± 37.7	3.6	**.613 (.295 - .811)**[b]	7.3 (4.4 - 10.2)	16.72	46.34	0.32
DJ RSI (mm/ms)	0.88 ± 0.27	0.85 ± 0.29	-3.4	**.834 (.657 - .924)**[b]	11.2 (7.7 - 14.7)	0.09	0.24	0.12
DJ flight time (ms)	406.7 ± 45.7	407.8 ± 53.9	-0.3	**.880 (.743 - .946)**[b]	3.3 (2.1 - 4.4)	13.20	36.59	0.03
DJ leg stiffness (kN)	14.14 ± 5.12	13.23 ± 4.17	-6.4	**.730 (.477 - .873)**[b]	12.1 (7.1 - 17.1)	1.50	4.17	0.31
DJ relative leg stiffness ($kN·kg^{-1}·m^{-1}$)	20.98 ± 6.30	19.29 ± 4.85	-8.1	**.636 (.327 - .823)**[b]	12.4 (7.4 - 17.4)	2.02	5.61	0.51
5max jump height (cm)	20.4 ± 4.5	19.5 ± 4.0	-4.4	**.792 (.578 - .904)**[b]	7.8 (4.8 - 10.8)	1.28	3.54	0.32
5max GCT (ms)	217.5 ± 23.7	**210.6 ± 22.9**[a]	-3.2	**.753 (.491 - .888)**[b]	4.0 (2.3 – 4.6)	7.98	22.11	0.43
5max RSI (mm/ms)	0.96 ± 0.28	0.95 ± 0.26	-1.0	**.921 (.826 - .965)**[b]	6.8 (4.5 - 9.2)	0.06	0.16	0.07
5max flight time (ms)	407.0 ± 42.6	**385.7 ± 57.0**[a]	-5.2	**.666 (.339 - .884)**[b]	5.6 (2.6 – 8.6)	23.00	63.76	0.49
5max leg stiffness (kN)	16.30 ± 3.78	**17.56 ± 4.93**[a]	7.7	**.811 (.570 - .918)**[b]	7.2 (4.1 – 10.4)	1.55	4.29	0.36
5max relative leg stiffness ($kN·kg^{-1}·m^{-1}$)	24.26 ± 3.96	**25.91 ± 4.36**[a]	6.8	**.614 (.278 - .814)**[b]	7.3 (4.2 - 10.4)	1.95	5.40	0.53
20sub max jump height (cm)	15.4 ± 3.4	15.6 ± 3.6	1.3	**.686 (.396 - .851)**[b]	10.3 (6.7 - 13.9)	1.42	3.93	0.09
20submax GCT (ms)	200.0 ± 22.6	**206.6 ± 20.3**[a]	3.3	**.768 (.506 - .896)**[b]	4.1 (2.8 - 5.4)	6.97	19.31	0.45
20submax RSI (mm/ms)	0.79 ± 0.22	0.77 ± 0.21	-2.5	**.790 (.574 - .903)**[b]	9.9 (6.2 - 13.7)	0.07	0.19	0.12
20submax flight time (ms)	352.0 ± 40.1	350.0 ± 42.3	-0.6	**.754 (.509 - .886)**[b]	4.7 (3.1 - 6.4)	41.05	14.81	0.06
20submax leg stiffness (kN)	19.32 ± 4.66	18.47 ± 4.29	-4.4	**.812 (.615 - .914)**[b]	9.0 (6.5 - 11.5)	3.61	1.30	0.28
20submax relative leg stiffness ($kN·kg^{-1}·m^{-1}$)	28.71 ± 4.93	27.51 ± 4.36	-4.2	**.618 (.304 - .813)**[b]	8.9 (6.4 - 11.4)	5.22	1.88	0.39

Abbreviations: SJ, squat jump; CMJ, countermovement jump; DJ, drop jump; GCT, ground contact time; RSI, reactive strength index; FT, flight time; SD, standard deviation; ICC, intraclass correlation coefficient; CI (95%) confidence intervals; CV%, coefficient of variation; SEM, standard error of measurement; SDD, smallest detectable difference; ES, effect size using Cohen's d

[a] $P<.05$ Difference between Day 1 and Day 2 **(Bold)**

[b] $P<.001$ **(Bold)**

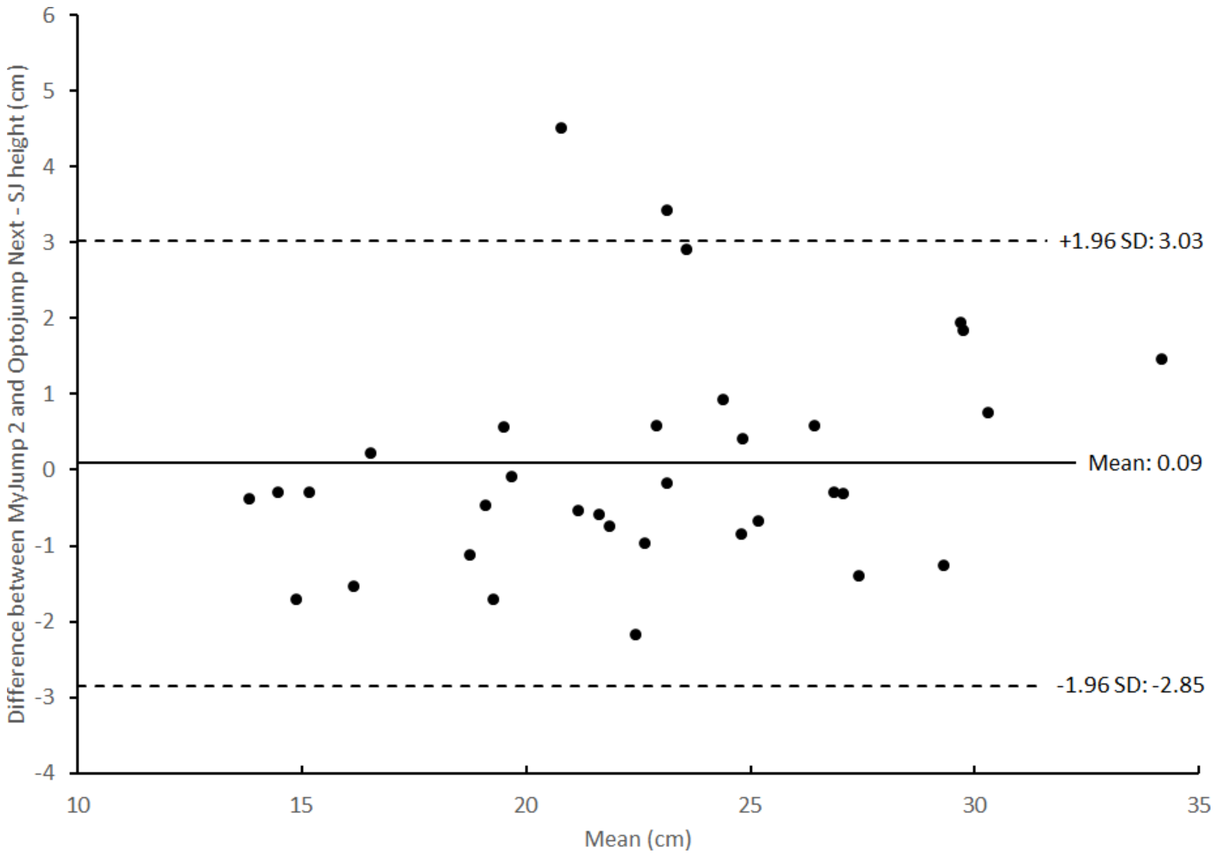

Fig 4.1 Bland-Altman limits of agreement between the MyJump 2 app and Optojump Next for Squat jump (SJ) height (cm) with 95% (+1.96) upper and 95% lower (-1.96) limits (dotted lines) and mean difference (solid line).

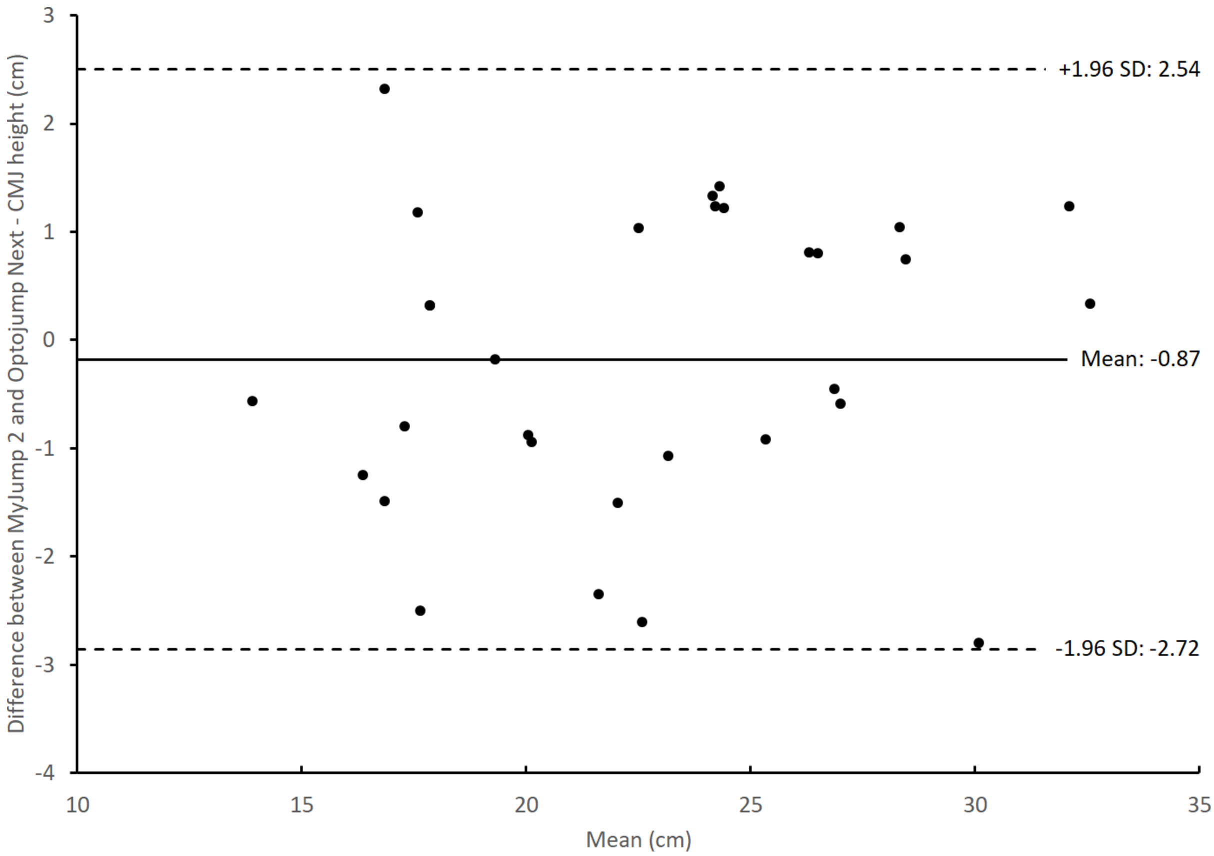

Fig 4.2 Bland-Altman limits of agreement between the MyJump 2 app and Optojump Next for countermovement jump (CMJ) height (cm) with 95% (+1.96) upper and 95% lower (-1.96) limits (dotted lines) and mean difference (solid line).

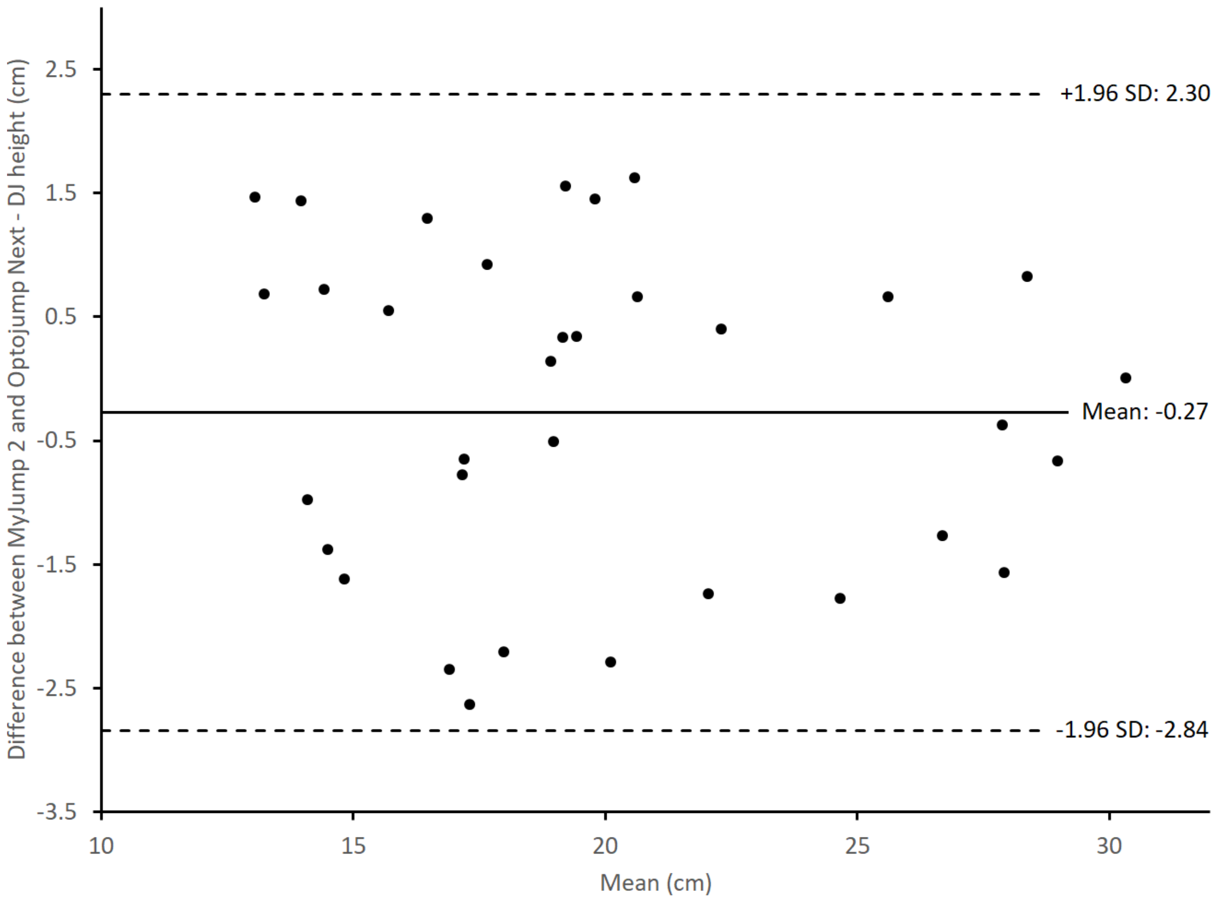

Fig 4.3 Bland-Altman limits of agreement between the MyJump 2 app and Optojump Next for drop jump (DJ) height (cm) with 95% (+1.96) upper and 95% lower (-1.96) limits (dotted lines) and mean difference (solid line).

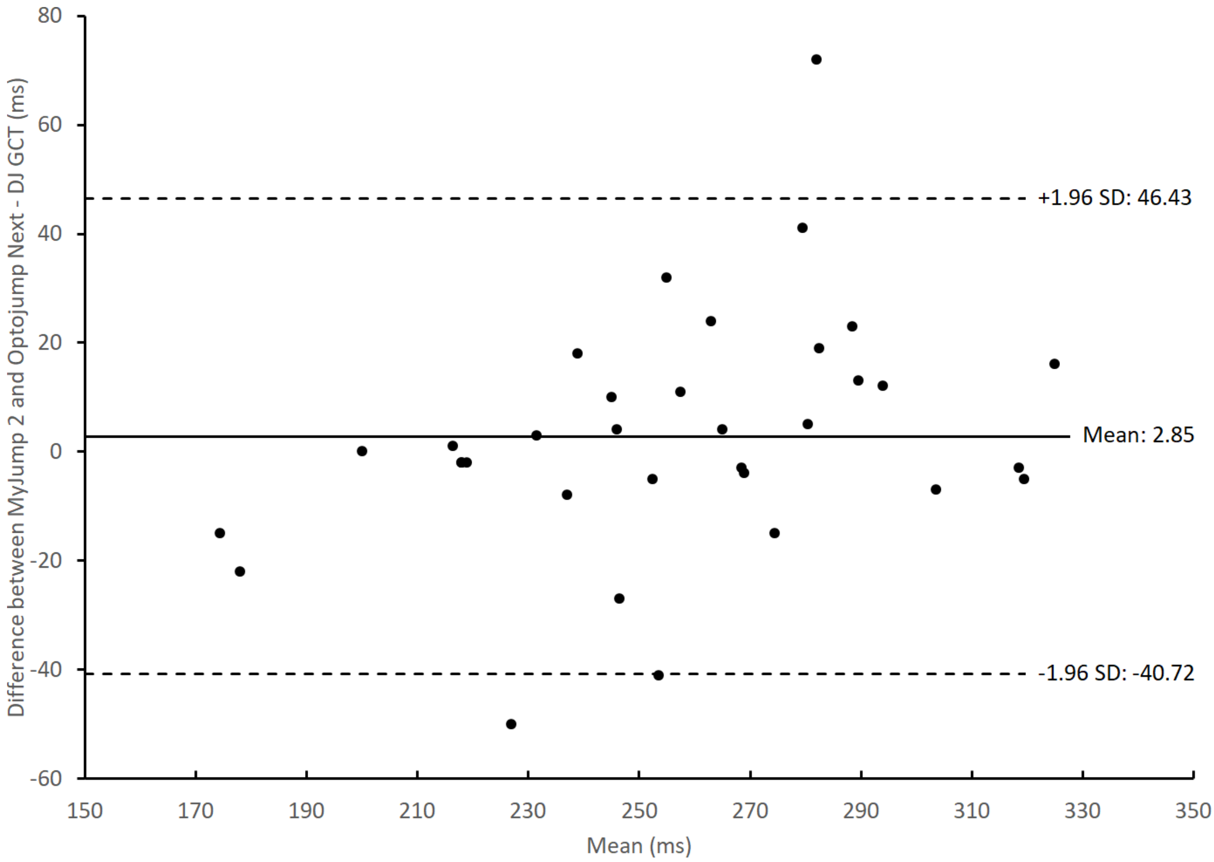

Fig 4.4 Bland-Altman limits of agreement between the MyJump 2 app and Optojump Next for drop jump (DJ) ground contact time (GCT) (ms) with 95% (+1.96) upper and 95% lower (-1.96) limits (dotted lines) and mean difference (solid line).

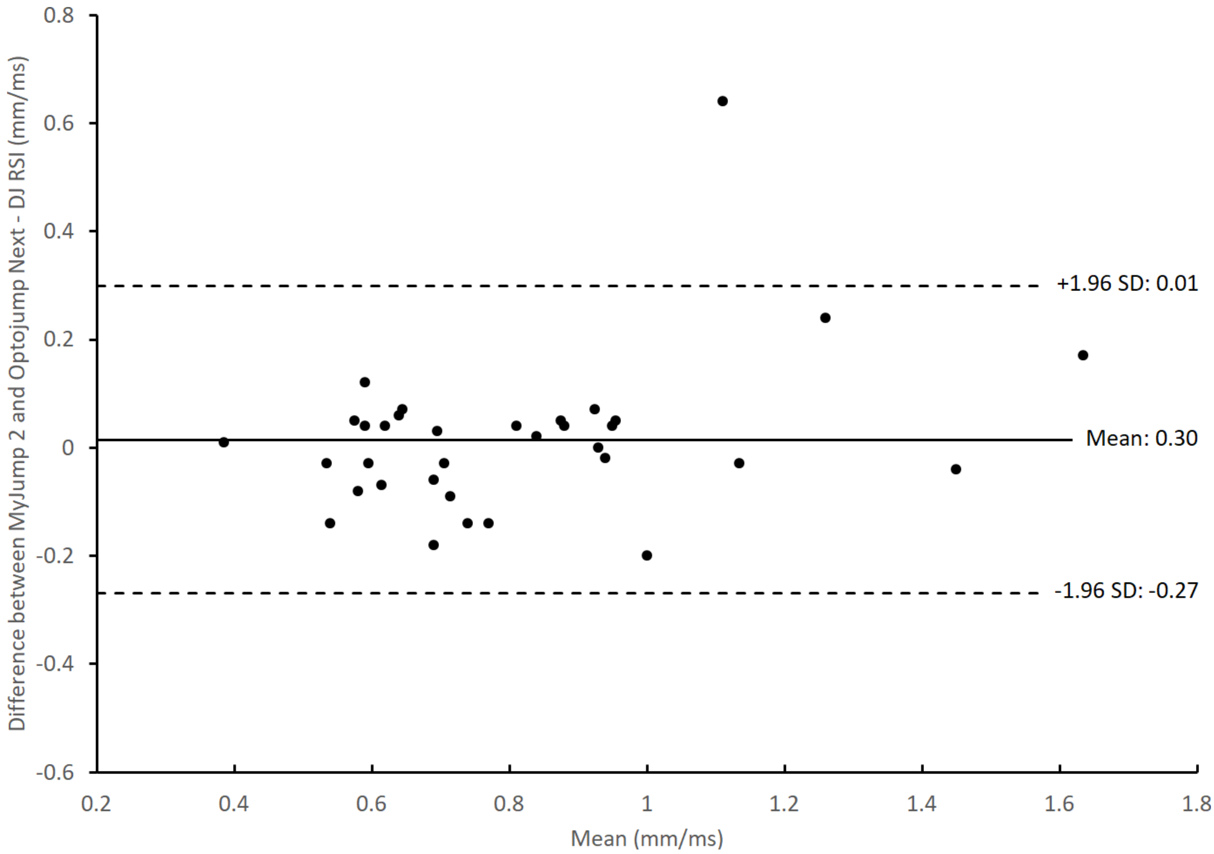

Fig 4.5 Bland-Altman limits of agreement between the MyJump 2 app and Optojump Next for drop jump (DJ) reactive strength index (RSI) (mm/ms) with 95% (+1.96) upper and 95% lower (-1.96) limits (dotted lines) and mean difference (solid line).

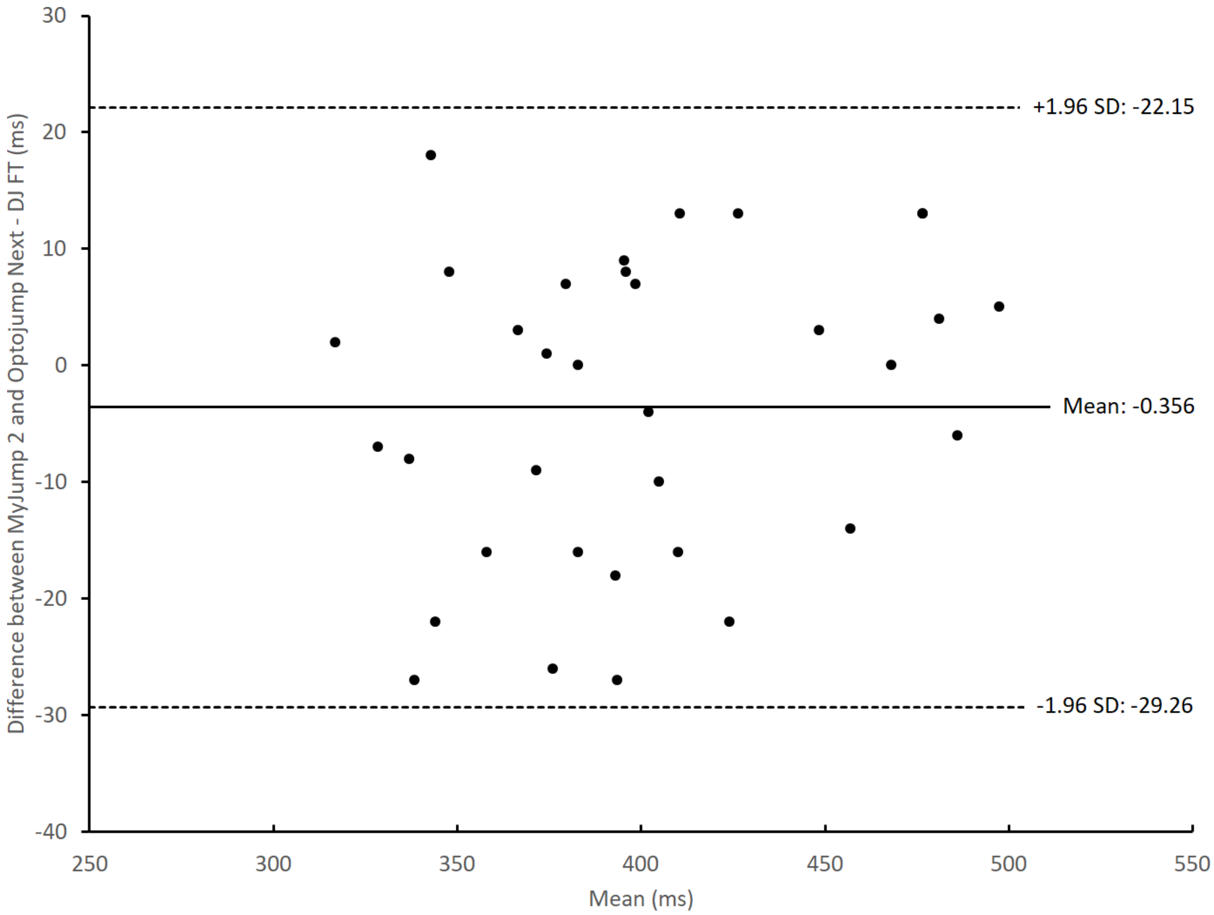

Fig 4.6 Bland-Altman limits of agreement between the app and Optojump Next for (A) drop jump (DJ) flight time (FT) (RSI) (ms) and (B) DJ leg stiffness (kN) with 95% (+1.96) upper and 95% lower (-1.96) limits (dotted lines) and mean difference (solid line).

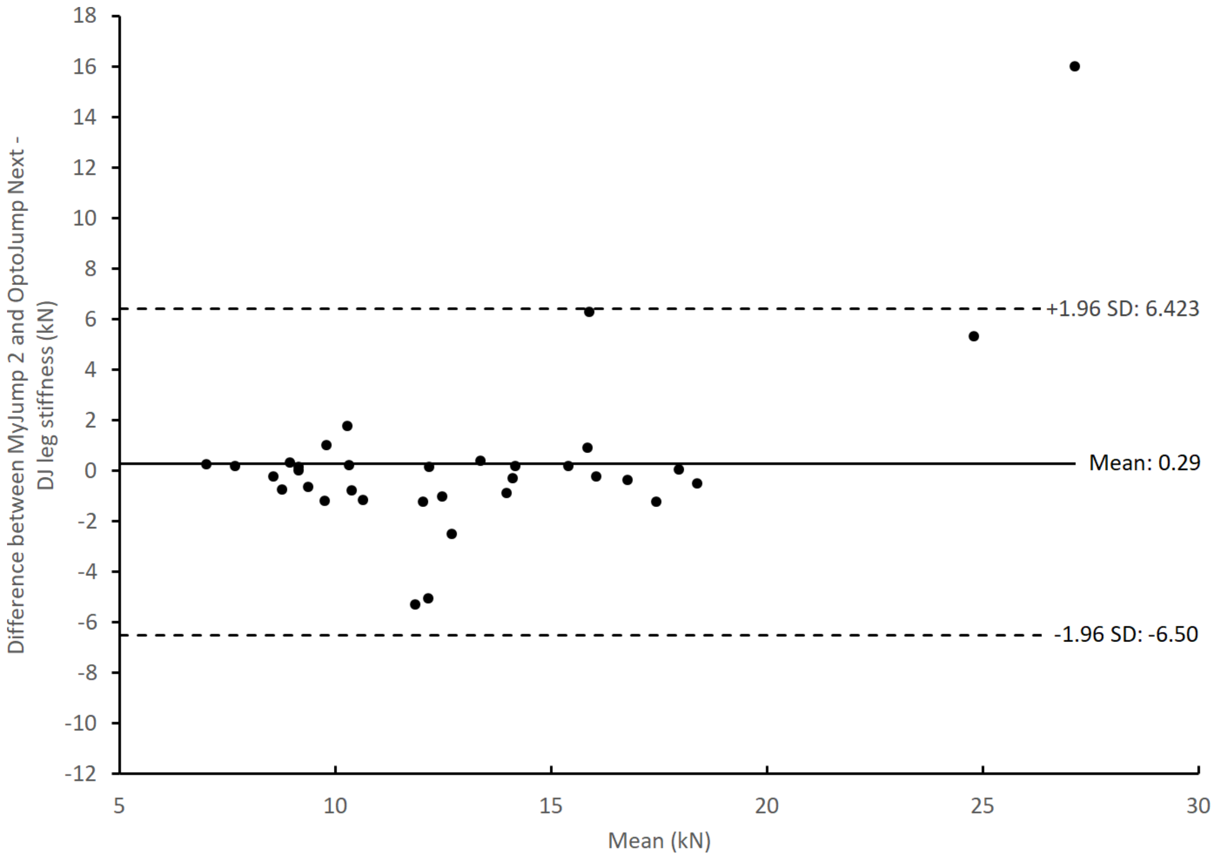

Fig 4.7 Bland-Altman limits of agreement between the MyJump 2 app and Optojump Next for leg stiffness (kN) with 95% (+1.96) upper and 95% lower (-1.96) limits (dotted lines) and mean difference (solid line).

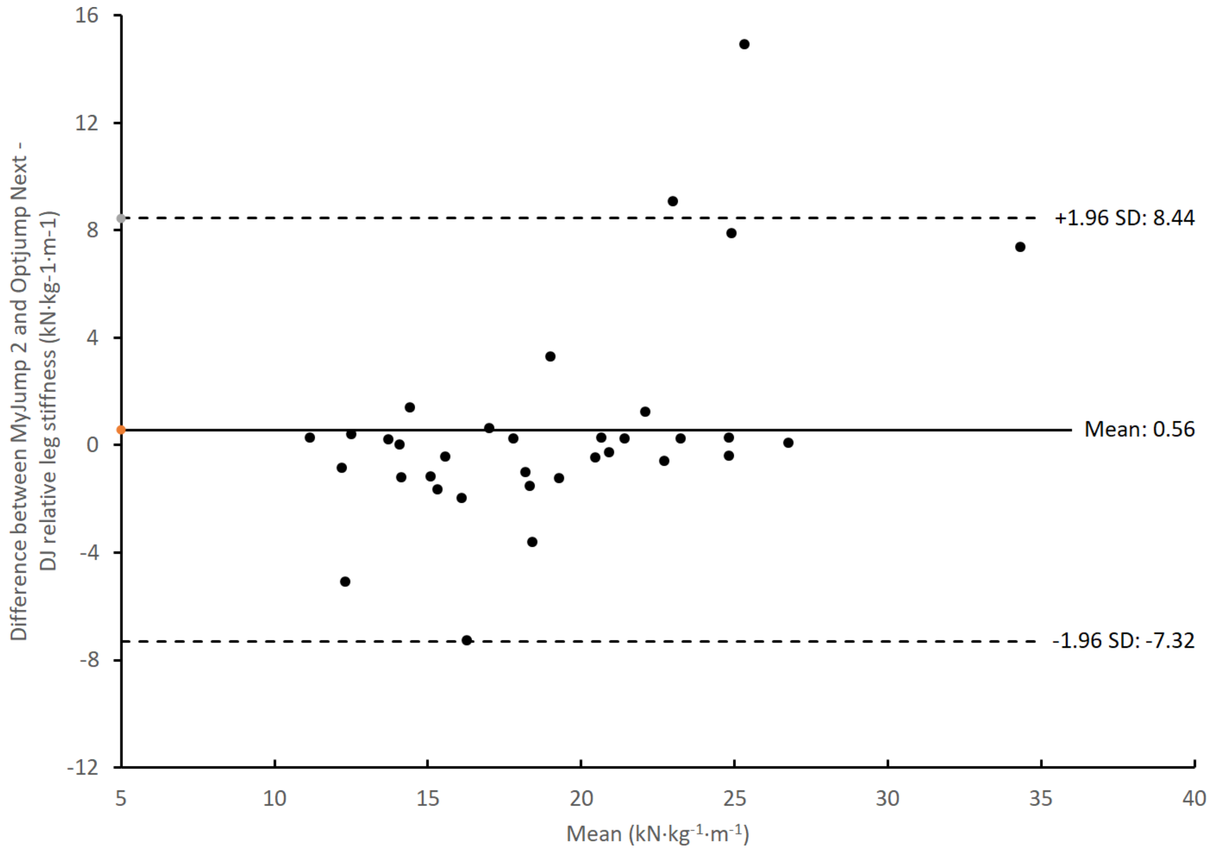

Fig 4.8 Bland-Altman limits of agreement between the MyJump 2 app and Optojump Next for relative leg stiffness (kN·kg^{-1}·m^{-1}) with 95% (+1.96) upper and 95% lower (-1.96) limits (dotted lines) and mean difference (solid line).

4.4 Discussion

The aim of this chapter was two-fold; to test the agreement between the MyJump 2 app and Optojump Next in the measurement of various SSC tasks and their derivatives involving adolescent female soccer players, and to test the between-session reliability of each device in the measurement of slow and fast SSC function, separated by one-week. The main findings were that the devices demonstrated good-to-excellent agreement in all dependent variables (range -2.1 to 1.0%). While this may suggest that the devices may be used interchangeably, Bland-Altman results demonstrated a systematic bias between the devices, most notably in the DJ GCT (2.85 ms). Thus, it is suggested strength and conditioning practitioners should aim to use the same device throughout testing (Glatthorn et al., 2011). One novelty of this research was that it was the first to examine the reliability of leg stiffness using the MyJump 2 app in any population. The main finding was that both MyJump 2 and the Optojump Next demonstrated good-to-excellent agreement of leg and relative leg stiffness during a DJ.

The between-session reliable data revealed good-to-excellent reliability in all variables using the MyJump 2 app (range -3.7 to 6.6%), and moderate-to-good reliability in all variables using the Optojump Next (range -8.1 to 7.7%), except 5max RSI, which was deemed to have excellent reliability (-1.0%). The between-session findings of the current research concur with several authors who found the SJ and CMJ to be reliable using the app and Optojump Next (Glatthorn et al., 2011; Balsalobre-Fernandez et al., 2015). Greater jump heights in the CMJ compared to the SJ, and greater jump heights in the CMJ and SJ compared to the DJ agrees with several previous studies involving trained and untrained children (Bassa et al., 2012; Harrison and Gaffney, 2001; Gerodimos et al., 2008).

In the current research, all ICC values were lower than other studies using the MyJump app (Sharp et al., 2019; Gencoglu et al., 2023b; Hanley and Tucker, 2019) and the Optojump Next (Glatthorn et al., 2011; Healy et al., 2016; Ruggiero et al., 2016). Greater reliability during the above-mentioned studies might suggest that the athletes in these studies were more accustomed to performing SSC tasks and, therefore, did not demonstrate a high degree of variance in their DJ and/or hopping performances between Day 1 and Day 2. It may also imply that the current athletes changed their jumping strategies due to a learning effect in Day 2 or that they were less motivated during the retest session (Turner et al., 2015). This partly agrees with previous literature (Rogers et al., 2018), who observed that reactive strength ratio (RSR) and RSI values decreased during the retest session. Possible changes in jumping and landing strategies could suggest that different verbal cues (Comyns et al., 2019a), and greater motivational feedback (Flanagan and Comyns, 2008) is needed to demonstrate greater repeatability during the DJ and hopping. It may also indicate that athletes should perform specific jump training such as plyometric training prior to testing to greater familiarise themselves with the demands of rebounding. In addition, researchers may wish to test the SSC over three rather than two days (Southey et al., 2023) and include more habituation sessions prior to testing to allow athletes to become more familiar with each SSC task (Baker et al., 2022).

To the author's knowledge, only five studies have directly compared the MyJump app to the Optojump Next (Bogataj et al., 2020b; Rago et al., 2018; Bogataj et al., 2020a; Stojiljkovic et al., 2024; Montalvo et al., 2018). However, only one involved youth female athletes and of the one that did, only a SJ, CMJ and CMJ with arm swing was examined (Bogataj et al., 2020b), thereby limiting the ability to create a complete profile of the SSC (Lloyd et al., 2011c). In their study, Bogataj and colleagues (2020b) found that tests of SJ and CMJ height recorded using MyJump 2 were highly correlated to the Optojump Next ($R = 0.70\text{-}0.99$; $P = 0.001$) in primary school boys and girls aged 11-14 years. Rago et al. (2018), however, found that the app recorded greater CMJ flight time (+7.5%) and CMJ height (+17%) compared to the Optojump Next in men aged 27 years, which is markedly greater than the 0.4% difference in CMJ in the current chapter. Nonetheless, Rago et al. (2018) reported that both the MyJump app and the Optojump Next offer the most accurate measure of flight time and jump height during a CMJ.

In their original MyJump study, Balsalobre-Fernandez et al. (2015) found that the app overestimated jump hight by 1 cm compared to a force platform, whereas the Optojump Next has been found to underestimate jump height by 1 cm compared to the gold standard (Glatthorn et al., 2011). The discrepancies between earlier literature involving MyJump 2 are likely because the authors used an iPhone at 120 Hz (Balsalobre-Fernandez et al., 2015; Rago et al., 2018), which is associated 3% greater error than the newer iPhone 12 model used in present research (Samozino, 2018), which records at 240 Hz (Gallardo-Fuentes et al., 2016; Bogataj et al., 2020b). The continued development of smart phone camera technology means that future studies using the app may use higher recording frequencies, thereby reducing measurement error further (Rago et al., 2018). Practitioners using MyJump 2 recording at either frequency regularly, however, should still be able to track intra and inter session changes reliably, provided there exists minimal tester error (Balsalobre-Fernandez et al., 2015; Gallardo-Fuentes et al., 2016).

Despite very large agreement between the devices (ICC = .735 - .988), any differences found between the MyJump 2 app (overestimating jump height) and Optojump Next (underestimating jump height) could be due to device design. The app, for instance, measures take-off and when investigator identifies any part of either foot leaving the floor and GCT and when any part of either foot touched down using the slow-motion camera feature of the iPhone (Balsalobre-Fernandez et al., 2015). In contrast, the design of Optojump Next device means that the transmitter and receiver units are positioned 0.003 m above the floor (Healy et al., 2016), resulting in overestimation of GCT, and an underestimation of flight time and, hence, lower jump height (Healy et al., 2016). Based the importance of flight time and GCT in calculate of leg stiffness (Dalleau et al., 2004) and jump height and GCT in RSI (Flanagan et al., 2008), overestimating GCT would limit both the RSI and leg stiffness values obtained from the Optojump Next.

Both the 5max and 20submax demonstrated good reliability in the measurement of RSI (ICC ≥ .790; CV ≤ 9.9%), implying that either the 5max or 20submax test could be used to measure the fast SSC function of the current cohort. The notion that the 5max test could be used to measure leg stiffness, however, disagrees with Lloyd et al (2009), who reported the 5max demonstrated ‘unacceptable’ CV values of 36.41%, 21.37%, and 13.98% for GCT, RSI and leg stiffness (De Ste Croix et al., 2018), respectively, in boys using a jump mat. Acknowledging that either the 5max and 20submax can measure RSI and leg stiffness in a single test, however, might be advantageous in a youth-based setting, where training time in often limited.

The MyJump 2 app demonstrated reliability in RSI and leg stiffness during a DJ (ICC ≥ .875; CV ≤ 10.7%), which was slightly better than the Optojump Next in these same measures (ICC ≥ .730; CV ≤ 12.1%). While this may suggest the MyJump 2 can be used in future studies assessing RSI and leg stiffness during a DJ, it is important to state that the app has several limitations. Specifically, MyJump 2 relies on the strength and conditioning practitioners being able to pinpoint the exact landing and take-off frames (Haynes et al., 2018), which could lead to human error. To limit this, future studies may wish to test the between-session reliability of the app using a second tester using the same recording frequency (Southey et al., 2023). In addition, scrolling through a series of frames to select take-off and landing is both time inefficient and logistically difficult during testing, particularly when working with many athletes during several trials. Specifically, during this chapter filming 34 participants for three SJ, CMJs, DJs, 5mas and a single 20submax test meant the lead researcher recorded 442 videos. Consequently, analysis of the data obtained using MyJump 2 app is often performed after the event, which lacks the instantaneous performance feedback offered by the Optojump Next. Immediate feedback during jumping tasks is important as it allows practitioners to offer better coaching instruction, education, and motivation to increase performance outcomes (Flanagan and Comyns, 2008). Real-time feedback also means that strength and conditioning practitioners can also alter their verbal cue, to generate greater jump height and/or lower GCT (Comyns et al., 2019a), thereby allowing athletes to perform tasks based on the specific SSC demands of their sport, such as greater jump height for basketball players and limited GCT in sports which require a higher level of sprinting, such as soccer.

Unlike the Optojump Next device, the MyJump 2 app does not yet allow practitioners to test RSI and leg stiffness during hopping, which is a popular protocol often using by practitioners working with children (Lloyd et al., 2009; Lloyd et al., 2011b; Lloyd et al., 2011c; Dallas et al., 2020; Lehnert et al., 2020). Based on abovementioned limitations of the app and the greater versatility of the Optojump Next, the latter was chosen to be the measurement device moving forward in this thesis.

4.5 Practical Applications

To identify meaningful changes during testing, minimal measurement error between devices and repeatability are vital to creation of a test battery (French and Torres Ronda, 2022). The Optojump Next device and the MyJump 2 app demonstrated moderate to excellent agreement, while showing that they are both reliable tools for the assessment of vertical jump height, GCT, RSI, and leg stiffness. These findings allow strength and conditioning practitioners a more accessible option to measure SSC function, which are not constrained by location or venue (i.e., a laboratory). Strength and conditioning practitioners can, therefore, use either device with confidence to detect within-group changes in test-retest research (e.g., to verify the effectiveness of a specific training programme and to quantify possible alterations during the competitive season) (Maffiuletti et al., 2002) and between-group differences in cross-sectional comparisons (e.g., during talent identification or to explore differences between athletes of different levels) (Di Cagno et al., 2009).

Understanding that a cost-effective iPhone app can reliably record the fast and slow SSC function of children is highly relevant to strength and conditioning practitioners working with children, where budget is often a limiting factor. Additionally, while the MyJump 2 app was used to test SSC function in post-PHV recreational female soccer players in this study, this technology can also be used to evaluate the physical conditioning of professional athletes, making it attractive to strength and conditioning practitioners working at an elite level. As a final thought, the MyJump 2 app is available on both the iPhone and Android (Alphabet, Mountain View, California, USA), thus ensuring that results pertaining to the app’s usefulness are spread to a wider strength and conditioning practitioner market. Nevertheless, when working with a large cohort athletes, strength and conditioning practitioners should acknowledge that, unlike the Optojump Next device, the MyJump 2 app does not provide instantaneous feedback, which may limit the motivation and competition between, athletes.

4.6 Conclusion

When comparing the devices, there was agreement in all SSC variables. Both devices also offered acceptable-to-excellent reliability in vertical jump height, RSI, and leg stiffness, as well as their determinants. The results mean that strength and conditioning practitioners can use either device and/or protocol with confidence that test-retest results will be accurate. Atkinson and Nevill (1998) defined reliability as the consistency of an individual's performance on a test. Given the SSD was greater than the SEM in almost all tests (except 20max leg stiffness using the Optojump Next), strength and conditioning practitioners will be able to calculate the smallest detectable change (changes outside of 'noise'). Ultimately, strength and conditioning practitioners are advised to be consistent with the instrumentation used to assess athletes, including when using either the MyJump 2 or Optojump Next given the small yet detectable bias between these devices.

Chapter 5

A comparison between drop jumping and repeated hopping in the measurement of the fast stretch-shortening cycle in adolescent female soccer players

5.1 Introduction

The reactive strength index (RSI) and leg stiffness are two measures used as indicators of the fast (<250 ms) stretch-shortening cycle (SSC) function (Lloyd et al., 2009). Both the RSI and leg stiffness can be obtained from a single of rebound task such as a drop jump (DJ) and continuous hopping (Flanagan and Comyns, 2008; Wilson and Flanagan, 2008; Lloyd et al., 2009). The RSI is calculated by dividing jump height by ground contact and has been described as a measure of an athlete's ability to change from an eccentric to a concentric contraction (Flanagan and Comyns, 2008). High RSI values are associated with greater reactive strength (Young, 1995), (Flanagan and Comyns, 2008; Lloyd et al., 2009), acceleration (Lockie et al., 2011), 60-m sprint performance (Nagahara et al., 2014), and change of direction speed (Young and Murray, 2017). Conversely, low RSI values indicate poor SSC function (Lloyd et al., 2009; Flanagan and Comyns, 2008; Pedley et al., 2020) and may increase the likelihood of anterior cruciate ligament (ACL) injury (Toumi et al., 2006; Raschner et al., 2012).

Leg stiffness, which acts as a representation of the spring-mass model (Butler et al., 2003), describes how the entire leg generates strength and resists deformation to lengthen once ground reaction forces are applied (Brughelli and Cronin, 2008a; Serpell et al., 2012). Greater leg stiffness positively correlates with hopping frequency (Hobara et al., 2008; Ferris and

Farley, 1997), running economy (Dalleau et al., 1998), jump height (Arampatzis et al., 2001b), and maximum sprint speed (Chelly and Denis, 2001; Bret et al., 2002; Meyers et al., 2019), whereas lower leg stiffness has been shown to reduce the ability to sustain impact loads, thereby increasing the risk of soft tissue and ACL injury (Lehnert et al., 2020; Butler et al., 2003).

Leg stiffness and RSI are indicators of the SSC capability to stabilise the knee joint and absorption of tensile forces exerted on the muscle-tendon complex, respectively (Hughes and Watkins, 2006). Deficiencies in either parameter might result in excess stress on the soft tissues beyond their load capacity during high-intensity tasks, which can lead to mechanical failure and injury (Kalkhoven et al., 2020). The role of the RSI and leg stiffness in reducing ACL and soft tissue injury is of particular importance to youth female soccer players, who are more likely to suffer from such injuries than their male counterparts (Shea et al., 2004; Clausen et al., 2014). Additionally, high school female soccer players are also 150% more likely to suffer from ACL rupture than adolescent females participating in other sports (Childers et al., 2025). Greater knowledge of RSI and leg stiffness values of adolescent female soccer players, therefore, could provide strength and conditioning practitioners working with this population a better understanding of SSC efficiency, performance enhancement and injury management strategies (Lehnert et al., 2020; Lehnert et al., 2022b).

Despite the popularity of the DJ (Jeras et al., 2019; Bishop et al., 2019; Pedley et al., 2021; Moeskops et al., 2022) and repeated hopping in the measure of SSC function in girls (Lehnert et al., 2020; De Ste Croix et al., 2017; Dallas et al., 2020), comparative studies between the two protocols are sparse. Of the studies, a DJ was either compared to 10/5 hopping or 10 second hopping in male athletes (Healy et al., 2016; Stratford et al., 2020a), rather than maximal and submaximal hopping tests popularised by Lloyd et al. (2009). In addition, no studies have aimed to examine whether the DJ or hopping can both measure the fast SSC function in adolescent female soccer players. Comparing these modalities may allow strength and conditioning practitioners working with this population to select the most optimal method of measuring and training the fast SSC, which is important given the direct association between fast SSC function (RSI, leg stiffness), sporting performance and the risk of ACL injury (Butler et al., 2003; Lehnert et al., 2020). The aim of this study, therefore, was to examine whether both a DJ and repeated hopping can measure fast SSC in adolescent female soccer players, whilst also comparing the RSI and leg stiffness values obtained during each test.

5.2 Method

5.2.1 Participants

Detailed descriptions of participant recruitment and assessment of anthropometric, maturation and SSC variables are detailed in Chapter 3. In this study 34 recreational post-peak height velocity (PHV) adolescent female soccer players (age: 15 ± 1 yrs; height: 1.65 ± 0.06 m; body mass: 55.6 ± 11.0 kg; soccer training age: 4.4 ± 2.5 years; Table 1) volunteered to take part in this research. Participants engaged in one hour of organised soccer practice per week, one competitive match, and two hours of physical education per week. Any volunteer who suffered an injury within the preceding 6 months was excluded from testing.

5.2.2 Testing

All SSC dependent variables are detailed in Chapter 3. In brief, RSI and its determinants of jump height (mm) and GCT (ms), and leg stiffness (kN) and its determinants of flight time (ms) and GCT were measured during DJ, 5 maximal hopping (5max) and 20 submaximal hopping (20submax). Relative leg stiffness was also calculated. All tests were carried out using the Optojump Next optical measurement system. RSI and leg stiffness during a DJ and 5max hopping was measured three times, with the best values used for further analysis. A single test of 20submax measuring RSI and leg stiffness was used for further analysis.

5.2.3 Statistical analysis

Data are presented as mean ± standard deviation (SD). Normality was confirmed using the Shapiro-Wilk test. Repeated measures analysis of variance (ANOVA) was used to analyse the differences between each modality in the measurement of jump height, GCT, RSI, leg stiffness and relative leg stiffness. If there was a significant difference between the variables, pairwise comparisons were analysed for significance. Effect size using Cohen's d (d) were classified as trivial (<0.20), small (0.2-0.6), moderate (0.6-1.2), large (1.2-2.0), very large (2.0-4.0), and extremely large (>4.0) (Hopkins, 2002). The statistical significance level was set at $P < 0.05$ (Moeskops et al., 2018). Statistical analyses were performed with a statistical package IBM SPSS version 28 (IBM Corporation, New York, USA).

5.3 Results

Repeated-measures ANOVA revealed significant differences in each variable ($P < .001$; Table 5.1). Pairwise comparisons revealed significantly greater jump height, GCT, RSI, and flight time during the DJ than both hopping tests ($P \leq .043$; $ES \geq 0.33$; Table 5.1), but greater leg stiffness and reactive stiffness in the 5max and 20submax hopping compared to the DJ ($P \leq .001$; $ES \geq 1.21$; Table 5.1). When comparing different hopping modalities, the 5max test demonstrated significantly greater jump height and RSI only ($P \leq .043$; $ES \geq 0.21$; Table 5.1), whereas the 20subax test revealed significantly greater leg stiffness and relative leg stiffness compared to the 5max test ($P \leq .046$; $ES \geq 0.25$; Table 5.1), with no other differences in any other variable ($P \geq 0.068$; $ES \leq 0.22$; Table 5.1). Further analysis showed that only 14/34 participants recorded GCTs <250 ms (range 182-322 ms) during the DJ, whereas all participants did in both the 5max (range 160-249 ms) and 20sbmax hopping tests (range 165-249 ms), respectively.

Table 5.1 Descriptive statistics (Mean ± SD) and ANOVA pairwise comparison (P values) and Effect size (ES) Cohen's d between the drop jump, 5max and 20submax hopping

				Pairwise comparison (Cohen's d)		
Variables	**DJ**	**5max**	**20submax**	**DJ vs. 5max**	**DJ vs. 20submax**	**5max vs. 20submax**
Jump height (cm)	20.0 ± 4.8	14.8 ± 3.4	13.7 ± 4.4	**< .001 (1.24)**[b]	**< .001 (1.34)**[b]	**0.043 (0.30)**[a]
GCT (ms)	255.0 ± 35.0	206.4 ± 22.0	204.5 ± 21.2	**< .001 (1.66)**[b]	**< .001 (1.75)**[b]	0.707 (0.09)
RSI (mm/ms)	0.80 ± 0.25	0.73 ± 0.19	0.69 ± 0.24	**.043 (0.33)**[a]	**.004 (0.48)**[a]	**0.012 (0.21)**[a]
Flight time (ms)	401.6 ± 48.6	341.2 ± 42.0	330.7 ± 53.4	**< .001 (1.33)**[b]	**< .001 (1.39)**[b]	0.068 (0.22)
Leg stiffness (kN)	12.94 ± 3.7	18.47 ± 5.27	19.69 ± 4.6	**< .001 (1.21)**[b]	**< .001 (1.61)**[b]	**0.046 (0.25)**[a]
Relative leg stiffness ($kN{\cdot}kg^{-1}{\cdot}m^{-1}$)	18.73 ± 3.73	26.92 ± 5.74	28.95 ± 5.54	**< .001 (1.60)**[b]	**< .001 (2.05)**[b]	**0.024 (0.36)**[a]

GCT, ground contact time, RSI, reactive strength index

[a] P <. 05 **(Bold)**

[b] P < .001 between DJ and 5max and 20submax hopping **(Bold)**

5.4. Discussion

To the author's knowledge, this is the first study comparing the GCT, RSI, and leg stiffness obtained via a DJ, 5max and 20submax hopping in adolescent female soccer players. The main finding was that that only 41% of participants performed a DJ with GCTs less than 250 ms, whereas 100% of participants did during both the 5max and 20submax test. This finding concurs with Lloyd et al. (2009), who found that the 5max and 20submax test measures the fast SSC in boys aged 13.5 years (≤ 219 ms). In contrast, Dallas et al. (2020) found that youth female athletes aged 8.44 years and 13.9 years were unable to rebound using the fast SSC during 5max and 20submax hopping prior to or following, plyometric training (≥ 302 ms). This demonstrates that hopping does not always generate fast GCTs in girls, and that differences exist in the rebound capabilities between the sexes during youth (Laffaye et al., 2016; Pedley et al., 2021; Pedley et al., 2020). Based on the GCTs found in the current research, strength and conditioning practitioners may wish to test the fast SSC using hopping.

In the present study, the DJ demonstrated slower GCTs (~19%) and higher jumps heights (26.0 - 31.5%) compared to 5max and 20submax hopping, respectively. Slower GCTs and higher jump heights observed during the DJ, compared to the hopping, may suggest that 59% of participants used mechanisms indicative of the slow SSC such as greater time to generate force production (van Ingen Schenau et al., 1997), active state development (Bobbert and Casius, 2005; Bobbert et al., 1996), and greater impulse (Ruddock and Winter, 2016), while 41% of participants in the DJ likely used the fast mechanisms of elastic energy and the stretch reflex to reduce GCT (Flanagan and Comyns, 2008).

Observing that the DJ was performed with prolonged contact times >250 ms concurs with several studies involving untrained pre-PHV boys and girls aged 9-11 years (Bassa et al., 2012), non-professional female volleyball players aged 15-32 (Ruffieux et al., 2020), and pre-, mid- and post-PHV elite male youth academy soccer players aged, 12, 14 and 15 years, respectively (Pedley et al., 2020). In contrast, Jeras et al. (2019) found that adolescent female soccer players aged 15-17 years performed a DJ using the fast SSC. The female participants of that study, however, were elite academy players who trained 4-6 hours per week, compared to recreational players of this chapter who trained for 1 hour per week (60 mins). Considering that SSC tasks (e.g. sprinting, jumping, change of direction, and kicking) play a major role during soccer (Taylor et al., 2022), it is reasonable to assume that the participants of the Jeras et al. (2019) study outperformed the players of the present chapter due to greater training volume and a higher exposure to SSC-based actions performed during regular soccer training. The current findings also disagree with Moeskops et al. (2022) also observed that recreational, regional and elite/national level gymnasts recorded GCTs representational of the fast SSC, thereby highlighting that regular rebound training can reduce GCTS during a DJ.

Both a DJ and hopping require feedforward (preprogrammed) and feedback (reflex) mechanisms (Taube et al., 2012; Lloyd et al., 2012a). Hypothetically, however, the demands of the DJ and continuous hopping are not the same (Stratford et al., 2020a), with differences likely neurophysiological and mechanical in nature (Komi and Nicol, 2011). For example, McMahon et al. (2018) reported that a DJ requires greater musculotendinous unit (MTU) compliance, whereas hopping requires greater MTU stiffness. In addition, vertical hopping relies heavily on the triceps surae musculature, the calcaneal tendon of the lower legs, and ankle stiffness (Farley and Morgenroth, 1999; Lamontagne and Kennedy, 2012), whereas the knee joint plays a more active role during a DJ (Pedley et al., 2017).

Hopping also has a greater overall preparatory period due to the repetitive nature of the assent and descend prior to ground contact, whereas the DJ is characterised by lower preparation time, as the athlete only descends from a platform prior ground contact (Stratford et al., 2020a). During a DJ, athletes are also able to pre-plan prior to executing the movement, which might not be the case during fast repetitive hopping (Stratford et al., 2020a). Faster GCTs during hopping also implies that participants demonstrated less leg deformation required to maintain hopping rhythm (Healy et al., 2017; Lloyd et al., 2009), which leads to lower GCTs and hence, increased leg stiffness (McMahon et al., 2012; Lazaridis et al., 2010; Arampatzis et al., 2001a).

From a biomechanical perspective, two types of DJs have been identified: the bounce-DJ and the countermovement jump-DJ (CMJ DJ) (Struzik et al., 2016; Bobbert et al., 1987; Ball et al., 2010). The bounce-DJ requires limited flexion of the knees and hips and maximises ankle flexion and ankle stiffness (Bobbert et al., 1987; Holcom et al., 1996) to generate stiffer landings and lower GCTs (Ball et al., 2010). Contrastingly, a CMJ-DJ is characterised by greater triple flexion of the hips, knees, and ankles, leading to prolonged GCTs, lower RSI (Struzik et al., 2016) and less leg stiffness (McMahon et al., 2012). As to whether the participants performed either a CMJ-DJ or a bounce-DJ remains unknown. In future, researchers using the Optojump Next device may wish to utilise the inbuild video analysis and biomechanical software to determine the exact joint flexion of the hips, knees, and ankles during a DJ to determine which form of DJ is being performed (Pedley et al., 2017).

Previous research shows that DJ technique is often influenced instructions (Pedley et al., 2017; Struzik et al., 2016; Xu et al., 2024) and drop height (Pedley et al., 2017). Optimal drop height during a DJ, however, varies based on an individual's SSC capabilities (Flanagan and Comyns, 2008). For example, it has been reported that DJ box height should coincide with an athlete's own maximal CMJ height (Flanagan and Comyns, 2008; Baker et al., 2022) or be 10 cm less than their individual CMJ height (Byrne et al., 2017). In children, however, several authors found that DJ performance and its derivatives (jump height and GCTs) did not change in trained and untrained boys and girls aged 9-11 years when performing a DJ from heights of between 10 and 50 cm (Bassa et al., 2012), suggesting that the participants of this study were unable to effectively utilise the SSC during a DJ from any drop height (Sahrom et al., 2013).

In line with other paediatric literature, this chapter used a standardised drop height of 30 cm (Lloyd et al., 2022; Pedley et al., 2021; Pedley et al., 2020; Moeskops et al., 2022). However, landing from a 30 cm box may have been too great for most participants to rebound with fast GCTs, suggesting the drop height should have been individualised based on optimal CMJ height or lower (Byrne et al., 2017; Flanagan and Comyns, 2008; Lees and Fahmi, 1994). During a standardised DJ, some athletes tend to increase or decrease their centre of gravity before dropping from a box, resulting in inconsistent drop height distances (Baca, 1999). Whilst ideal, standardising or monitoring the actual fall height from a box in the field is difficult, meaning that landing forces, GCTs, RSI and leg stiffness values might be negatively or positively affected depending on performance strategies (Pedley et al., 2017; Pedley et al., 2021). During double leg DJs there is a tendency to touch down each foot at different times, indicating that one leg may dominate performance more than the other, which may affect force output and, therefore, jump height and GCT (Ball and Scurr, 2009; Hay et al., 2006). High impact on one foot may also increase the likelihood of injury, due to the high impact ground forces exhibited in post-PHV girls (Bates et al., 2013b; Hewett et al., 2005).

Individualising drop height would prevent excessive eccentric overloading that may activate the protective, inhibitory drive of the Golgi tendon organs GTO (Komi and Gollhofer, 1997), leading to less force production (Chimera et al., 2004; Goodwin and Jeffreys, 2016), which could ultimately nullify any benefits associated with fast SSC mechanism (Komi and Gollhofer, 1997; Wilson et al., 1994). Excitation of the GTO may also reduce the ability of the elastic components of the muscles to undergo a greater stretch (Chimera et al., 2004), limiting the activation of the stretch reflex required to increase motor-unit recruitment and enhance force production during the ensuing concentric contraction (Chimera et al., 2004). Using a smaller drop height with less eccentric stress would presumably dampen the protective effect of the GTO, which may trigger the stretch reflex and increase force production, provided GCTs were minimised (Komi and Gollhofer, 1997). Despite the benefits of individualising DJ height, doing so is impractical when testing large teams in a field-based setting when time is a limiting factor (Stratford et al., 2020a).

In rebound SSC tasks such as a DJ or hopping, the aim is to maximise jump height and minimise GCT (Flanagan and Comyns, 2008; Lloyd et al., 2009; Pedley et al., 2017). In this chapter, maximising jump height during the DJ led to significantly slower GCTs, but greater RSI compared to 5max and 20ssubmax hopping (8.8 and 13.8%, respectively). In contrast, jump height was sacrificed in favour of faster GCTs during the 5max and 20submax tests, leading to suboptimal RSI values. Greater RSI in the DJ demonstrates that slower GCTs can be offset by greater jump heights to improve RSI (Flanagan and Comyns, 2008; Baker et al., 2022). The findings of the current chapter may suggest that strength and conditioning practitioners working with recreational post-PHV female athletes should consider improving both jump height and GCTs in both the DJ and hopping, using a safe and effective training programme directly linked to improving the fast SSC, such as plyometric training (Lloyd et al., 2011a; Markovic and Mikulic, 2010).

In is noteworthy, however, to state that reducing GCT during a DJ may exceed the eccentric capabilities of an athlete, resulting in undesirable stiffening strategies, such as landing with a much more extended knee and hip, which places greater stress on skeletal structures rather than the muscle-tendon unit (Pedley et al., 2017). High eccentric stress may also increase agonist-antagonist co-contraction, thereby further limiting the force generated during the rebound phase of a DJ (Frost et al., 1997; Lambertz et al., 2003; Croce et al., 2004). As co-contraction was not measured, this is speculative and requires further research. Reducing GCTs during a DJ may also increase peak vertical ground reaction forces, reducing the time to impact, and increase landing impulse, which have demonstrated to be a contribution factor to a high-risk profile of ACL injury (Bates et al., 2013a; Krosshaug et al., 2007; Hewett et al., 2016). This is of particular importance in post-PHV female athletes who demonstrate a greater predisposition to ACL injury during a DJ compared to male athletes (Hewett et al., 2005; Noyes et al., 2005).

Greater ACL indices in post-PHV girls may be due to several anatomical, physiological and hormonal factors including; hormonal fluctuations due to menstruation (Wojtys et al., 2002); sub-optimal muscle activation strategies (Huston and Wojtys, 1996); a disparity neuromuscular control; greater knee adduction; higher ground reaction forces (Barber-Westin et al., 2010; Ford et al., 2003; Hewett et al., 2007); and lower levels of strength relative to males (Bini et al., 2000; Handelsman, 2017). As such, hopping is an appealing test for strength and conditioning practitioners as it does not create as high eccentric forces as a DJ (Southey et al., 2023). Consequently, strength and conditioning practitioners may wish to test the fast SSC function of female athletes during different stages of maturity using the less impact-inducing, safer, hopping method (Dallas et al., 2020; Lehnert et al., 2020).

In this chapter, the 20submax hopping generated significantly greater leg stiffness values that both DJ and 5max test (52.2% and 6.6%, respectively). Unsurprisingly, relative leg stiffness was also significantly greater in the 20submax test compared to the DJ and 5max test (54.6% and 7.5%, respectively). Similarly, the 5max test generated significantly greater leg stiffness (42.7%) and relative leg stiffness values than the DJ (43.7%). Variances between hopping and DJ leg stiffness values are certainly due to differing GCTs, as faster GCTs have a profound impact on leg stiffness (Lloyd et al., 2009; Arampatzis et al., 2001b; Arampatzis et al., 2001a). For instance, when using the Dalleau et al. (2004) equation, an athlete with a body mass of 60 kg, a flight time of 400 ms, and a GCT of 150 ms would generate a 66% greater leg stiffness value than the same athlete, with the same flight time, but a GCT of 200 ms (33.5 kN vs. 20.1 kN, respectively).

It has been demonstrated that leg stiffness is governed in part by pre-activation (feed-forward motor control) coupled with short stretch reflexes reliance, with research indicating that up to 97% of the variance in leg stiffness can be explained by the contribution of pre-activation and stretch-reflex response of lower limb extensor muscles (Oliver and Smith, 2010). While it is reasonable to suggest that all participants used feed-forward and excitation of the stretch reflex during hopping to rebound faster and increase leg stiffness beyond that of the DJ, it would be desirable for future research to test this theory using electromyography (EMG) analysis (Lloyd et al., 2012a; Oliver and Smith, 2010).

Hopping intuitively uses a spring-like behaviour (Lloyd et al., 2009; Blickhan, 1989), which describes the relationship between ground force reaction and the centre of mass displacement during ground contact (Pedley et al., 2021). According to the spring-mass model used in the measurement of leg stiffness, a reduction in GCT would facilitate greater elastic energy reutilisation to maintain centre of mass displacement (McMahon and Cheng, 1990) and greater stretch-reflex activity (Oliver and Smith, 2010; Lloyd et al., 2012a). While spring-like behaviour is also evident during a DJ, Pedley et al. (2021) recently observed female athletes, based on ground forces and spring-like behavior, demonstrated 'poor' SCC function at prepubertal (79.6%), pubertal (77.3%), and post-pubertal (65.5%) stages of maturity during a 30 cm DJ (Pedley et al., 2021). In contrast, Pedley et al., (2020) found that 65-90% of youth male academy players of English professional soccer clubs demonstrated moderate-to-good SSC function during a DJ from the same 30 cm DJ protocol (Pedley et al., 2020). Taken together, these findings lend credence to the theory that the data found in boys should not be superimposed onto girls.

Interestingly, in a recent study, Moeskops et al. (2022) reported 94.8% of pre-, mid- and post-PHV gymnasts, regardless of competitive level (recreational, regional, elite/national), demonstrated moderate-to-good SSC function during a 30 cm DJ. This finding implies that the rebound-based training inherent in gymnastics is beneficial for enhancing the SSC function of pre-to-post PHV female athletes. However, while the above-mentioned findings suggest that a 30 cm DJ is an appropriate test of fast SSC function in elite youth male and female athletes (Pedley et al., 2020; Jeras et al., 2019, Moeskops et al., 2022), this test may not be appropriate in the examination of SSC function in grassroots, recreational female soccer players without prior knowledge of specific rebound-based training. Therefore, strength and conditioning practitioners should be mindful of prior rebound training when assessing SSC function in youth female athletes before drawing any comparisons with previous literature which have demonstrated that this population can demonstrate good levels of GCT, jump height, and RSI in sports such as soccer and gymnastics (Jeras et al., 2018; Moeskops et al., 2022).

Finding that hopping measured the fast SSC in all the current cohort, whereas a DJ did not, may impact future testing and training, particularly as fast SSC function with limited GCTs generate greater elastic energy reuse (Kopper et al., 2014). In their study, Kopper et al. 2014) observed that if range of motion is not restricted (larger flexion), the use of elastic energy is minimal at the beginning of joint extension, whereas if movement amplitude is restricted (smaller flexion), elastic energy use if significant at the beginning of joint extension. Greater elastic energy reuse is desirable, given many sporting actions such as sprinting and jumping require efficient accumulation and reutilisation of elastic energy during the eccentric the concentric phase, respectively, to increase muscle force and power (Flanagan and Comyns, 2008; Wilson and Flanagan, 2008).

Although it could be assumed that greater leg stiffness values may lower the injury rate of post-PHV girls (Lehnert et al., 2020), to much or too little leg stiffness can increase the risk of bony and soft tissue injuries, respectively (Moir, 2015; Butler et al., 2003; McMahon et al., 2012). Thus, strength and conditioning practitioners working with girls should adhere to the 'Goldilocks Principle', whereby a girl utilises 'just the right amount' of leg stiffness during specific SSC-based tasks such as a DJ, hopping and sprinting (McMahon, 2018). What constitutes 'optimal' leg stiffness, however, is debatable, unresolved and complex (Butler et al., 2003; Brughelli and Cronin, 2008a; Brughelli and Cronin, 2008b).

5.5 Practical Applications

Strength and conditioning practitioners, who are limited on time and resources, but are interested in evaluating their athletes' reactive strength, should consider using a DJ or a repeated hopping test. Although a DJ demonstrated significantly greater RSI, hopping tests overcome issues such as standardisation of fall height from the box, which is a significant limitation associated with DJ testing. Additionally, unlike a DJ, hopping does not require set up of an individualised box height or a lengthy familiarisation period, making it time-efficient, which is important to strength and conditioning practitioners working with children where time is often limited. During a DJ, post-PHV girls often demonstrate compromised landing mechanics (knee-valgus and high peak landing force) (Barber-Westin et al., 2006; Pedley et al., 2021), which is less likely during hopping, given that hopping is a natural movement performed in everyday play (Faigenbaum and Chu, 2006).

Due to the greater jump height and RSI during the DJ and faster GCTs during repeated hopping, the results of the study indicate that an athlete's reactive strength qualities and GCT are task-dependent, and that strength and conditioning practitioners should not use these assessments interchangeably when longitudinally monitoring changes in an athlete's RSI. The ability to record the fast GCT is essential to the measurement of RSI and leg stiffness. From a practical perspective, therefore, strength and conditioning practitioners should be advised to use a repeated hopping test rather than a DJ to measure the fast SSC.

5.6 Conclusion

This was the first study to compare the DJ and hopping in the measurement of the RSI and leg stiffness in adolescent female soccer players. Although the DJ generated a greatest jump height, flight time, and RSI, due to the prolonged GCTs registered, it may not be the best test to represent fast SSC function in the current cohort. Conversely, 5max test and 20submax hopping generate superior leg stiffness values compare to the DJ, primary because all participants rebounded with GCTs of <250 ms. Fast SSC actions are important in several sporting movements such as sprinting and jumping. Thus, monitoring and developing the fast SSC using an appropriate protocol is essential. As RSI and leg stiffness are indicators of fast SSC function (Flanagan and Comyns, 2008; Lloyd et al., 2009), it is recommended that hopping should be used to test the RSI and leg stiffness of recreational adolescent female footballers. When interpreting the RSI and leg stiffness scores, practitioners should examine the component parts of jump height, flight time, and GCTs to understand how greater RSI and leg stiffness was achieved. Additionally, based on the results of this chapter and the findings of Lloyd et al. (2009), the 5max should be used to measure RSI, and the 20submax test should be used to measure leg stiffness (Lloyd et al., 2009; Dallas et al., 2020; Lehnert et al., 2020).

Chapter 6

Stretch-shortening cycle development in maturing girls

6.1 Introduction

The stretch-shortening cycle (SSC) is defined as a muscle action that involves pre-activation prior to ground contact, with a fast eccentric action followed by a rapid transition between the eccentric and concentric actions (Komi, 2000). An effective SSC enhances neural transmission and the ability of the musculotendinous units to produce maximal force in the shortest amount of time (Markovic and Mikulic, 2010). The SSC is advantageous to athletes who routinely perform explosive actions such as sprinting, jumping, and hopping (Lloyd et al., 2009; Lloyd et al., 2011c), and can be categorised as slow (>250 ms) or fast (<250 ms) based on GCTs (Schmidtbleicher, 1992). Consequently, a countermovement jump (CMJ) is classified as a slow SSC (Lloyd et al., 2009; Lloyd et al., 2011c), whereas rebound actions, such as hopping and sprinting, which adhere to spring-mass behaviour, can be used to measure the fast SSC (Lloyd et al., 2009).

Leg stiffness and reactive strength index (RSI) are indicators of fast SSC, and capacity to stabilise the knee joint and absorption of the tensile forces exerted on the musculotendinous unit, respectively (Hughes and Watkins, 2006). Despite leg stiffness and RSI being extensively researched in boys (Lloyd et al., 2009; Lloyd et al., 2011b; Lloyd et al., 2011c; Lloyd et al., 2012a; Lloyd et al., 2012b), similar research in girls is limited (Laffaye et al., 2016). This is surprising given that girls are more susceptible to anterior cruciate ligament (ACL) injury than boys (Childers et al., 2025; Shea et al., 2004), and that development of RSI and leg stiffness can protect against ACL injury during functional tasks in girls (Lehnert et al., 2020).

During growth and maturation several neuromuscular, physiological, and anatomical factors (Radnor et al., 2018) such as tendon stiffness (Kubo et al., 2014), the stretch reflex, and pre-activation (Grosset et al., 2007; Lloyd et al., 2012a) develop to increase the force production capabilities of the SSC (Radnor et al., 2018). During maturation, periods of accelerated adaptation in slow and fast SSC function have been described in boys (Lloyd et al., 2011b). However, due to the sex dimorphism relating to body size and composition, among other phenotypes, which become apparent during maturation (Malina et al., 2004b), it is erroneous to suggest SSC data from boys can be transferred to girls (Emmonds et al., 2018b). Consequently, more research into the role of maturity on SSC tasks in girls is necessary, as a better understanding of the influence of maturation on the slow and fast SSC development of girls could be advantageous to strength and conditioning practitioners looking to optimise and enhance the physical training and injury prevention of girls according to their own maturity and physiology. This is pertinent given there has been an exponential rise in the popularity, participation, and professionalism of female sport (Scheadler and Wagstaff, 2018; Emmonds et al., 2019), in addition to female athletes having a two to eight times greater incidence of non-contact ACL injury compared to males athletes (Mancino et al., 2024), which coincides with a requirement for more ACL reconstructions in girls aged 15-19 years compared to age-matched boys (Renstrom et al., 2008). As the development of the SSC can reduce ACL injuries in girls (Lehnert et al., 2020) and increase athletic performance (Butler et al., 2003; Radnor et al., 2018), the aim of this study was to examine the innate development of the SSC in girls using a variety of slow and fast SSC-based tests, according to maturity.

6.2 Method

6.2.1 Participants

Detailed descriptions of participant recruitment and assessment of anthropometric, maturation and SSC variables are detailed in Chapter 3. In this chapter, 130 schoolgirls aged 7-17 years (age: 12.8 ± 2.4 years; maturity offset: 0.7 ± 2.0 years; height 1.56 ± 0.13 m; mass 47.8 ± 12.8 kg; body mass index 19.2 ± 3.0 kg·m^{-2}; leg length: 0.77 ± 0.07 m) volunteered to take part in this research. Participants were categorised as pre-, mid-, or post-peak height velocity (PHV), as well as years from PHV (YPHV) divided into further subcategories, with PHV and YPHV described in Chapter 3.

6.2.2 Testing

All SSC dependent variables are detailed in Chapter 3. Jump height (cm) was measured during squat jump (SJ) and a countermovement jump (CMJ). Reactive strength (RSI) and its determinants of jump height (mm) and ground contact time (GCT) (ms) were measured during 5 maximal (5max) hopping, while leg stiffness and its determinants of flight time (ms) and GCT (ms) were measured during 20 submaximal (20submax) hopping. Relative leg stiffness (kN.m.kg^{-1}) was also calculated. All tests were carried out using the Optojump Next optical measurement system. SJ and CMJ height, and RSI were measured three times, with the best values used for further analysis. A single test of 20submax measuring leg stiffness was used for further analysis.

6.2.3 Statistical analysis

Statistical analyses were performed with statistical package IBM SPSS version 28 (IBM Corporation, New York, USA). Normality and homoscedasticity assumptions were checked with Shapiro-Wilk and Levene's tests, respectively. When assumptions of parametricity were met for at least two of the maturity status (pre-, mid-, and post-PHV) subgroups and at least four of the maturity offset (-2.5 to 2.5 YPHV) subgroups and Skewness and kurtosis charts where checked, a one-way analysis of variance (ANOVA) test was completed to identify any main effects. To compare the maturity status or maturity offset subgroups, between-group analysis was conducted only. When these assumptions of parametricity were not met, a Kruskal-Wallis test was used to compare between-group differences (Ostertagová et al., 2014). When a main effect as observed, non-parametric comparisons were conducted to identify the between-group differences in all variables. Effect size (ES) was determined using the modified Cohen's d scale, with ≤ 0.2 classified as trivial, 0.2-0.6 small, 0.6-1.2 a moderate, 1.2-2.0 large, 2.0-4.0 very large, and ≥ 4.0 extremely large effect (Hopkins, 2002). Statistical significance level was set at $P < 0.05$ (Moeskops et al., 2018) and data are presented as mean ± standard deviation (SD).

6.3 Results

Maturity status subgroups

Age, maturity status, height, body mass, BMI, and leg length was significantly greater in the post-PHV subgroup compared to the pre-PHV and mid-PHV subgroups (Post > Mid > Pre; $P < .001$; ES ≥ 1.08; Table 6.1). The mid-PHV subgroup also demonstrated greater age, maturity status, height, body mass and leg length compared to the pre-PHV subgroup ($P \leq .010$; $ES \geq 1.75$; Table 6.1). The post-PHV subgroup demonstrated significantly greater SJ, CMJ, 5max jump height, and absolute and relative leg stiffness compared to the pre-PHV subgroup ($P \leq .05$; $ES \geq 0.55$; Table 6.1). The pre-PHV subgroup demonstrated significantly faster 5max GCT compared to the post-PHV subgroup ($P < .001$; $ES = 0.42$; Table 6.1), with no significant differences in GCTs values between the pre- and mid-PHV subgroups ($P = .157$; $ES = 0.70$; Table 6.1), or between the mid- and post-PHV subgroups in 5max GCT ($P = .239$; $ES = 0.45$ Table 6.1). There was no significant difference between any group in RSI ($P \geq .590$; $ES \leq 0.33$; Table 6.1). The pre-PHV subgroup demonstrated greater 20submax flight time compared to the mid- and post-PHV subgroups ($P \leq .028$; $ES \geq 0.62$; Table 6.1), while 20submax flight time was greater in the post-PHV subgroup compared to the mid-PHV subgroup ($P = .033$; $ES = 0.62$; Table 6.1).

The mid-PHV subgroup demonstrated faster 20submax GCT than the post-PHV subgroup ($P < .001$; $ES = 0.75$; Table 6.1), while there was no difference between the pre- and post-PHV subgroups or the pre- and mid-PHV subgroups ($P \geq .285$; $ES \leq 0.46$; Table 6.1). The mid-PHV subgroup demonstrated greater leg stiffness than the pre-PHV subgroup ($P < .001$; $ES = 1.99$; Table 6.1), with the leg stiffness of the mid- and post-PHV subgroups similar ($P = .706$; $ES = 0.23$; Table 6.1). The mid-PHV subgroup demonstrated significantly greater relative leg stiffness than the pre- and post-PHV subgroups ($P \leq .001$; $ES \geq 0.69$; Table 6.1). Additionally, there were no differences between the pre- and the mid-PHV subgroups in SJ, CMJ, and 5max jump height, ($P \geq .58$; $ES \leq 0.70$; Table 6.1) and there were no differences between the mid-and post-PHV subgroups in SJ, CMJ, 5max jump height, and absolute leg stiffness ($P \geq .208$; ES ≤ 0.37; Table 6.1).

Maturity offset subgroups

The anthropometric and physical characteristics of the current cohort by maturity offset are presented in Table 6.2 and the P values and ES for anthropometric and physical characteristics between consecutive maturation groups are shown in Table 6.3. One-way ANOVA revealed significant differences in age ($P < .001$; ES ≥ 1.65; Table 6.3) and height ($P \leq .040$; ES ≥ 0.72; Table 6.3) between all consecutive maturity offset subgroups. Subsequent pairwise comparisons between consecutive maturity offset subgroups observed significantly greater body mass in the -1.5 YPHV maturity offset subgroup compared to the -2.5 YPHV maturity offset subgroup ($P = .018$; ES = 1.70; Table 6.3), and significantly greater body mass and in the 0.5 YPHV maturity offset subgroup compared to the 1.5 YPHV maturity offset subgroup ($P = .005$; ES = 1.39; Table 6.3). The -1.5 YPHV maturity offset subgroup demonstrated significantly greater leg length than the -2.5 YPHV maturity offset subgroup ($P < .001$; ES = 1.77; Table 6.3), with no other consecutive maturity offset subgroup differences in anthropometric measures demonstrated ($P \geq .135$; ES ≤ 1.10; Table 6.3). There were no significant differences between consecutive maturity offset subgroups in all performance variables ($P \geq .054$; ES ≤ 1.22; Table 6.3), apart from greater leg stiffness demonstrated in the -0.5 YPHV maturity offset subgroup compared to the -1.5 YPHV subgroup ($P = .014$; ES = 2.05; Table 6.3), and the greater relative leg stiffness shown in the 0.5 YPHV maturity offset subgroup compared to the 1.5 YPHV group ($P = .002$; ES = 1.16; Table 6.3).

Table 6. 1 Mean ± SD for anthropometry, maturational status, performance results, pairwise comparisons (P values) and Effect size (ES) using Cohen's d with 95% confidence intervals (95% CI) between peak height velocity (PHV) subgroups.

	Maturity status subgroups			**ES (95% (CI)**		
	Pre-PHV (n = 30)	**Mid-PHV** (n = 31)	**Post-PHV** (n = 69)	**Pre vs. Mid**	**Pre vs. Post**	**Mid vs. Post**
Age (years) *	9.3 ± 1.1	**12.0 ± 0.7[a]**	**14.7 ± 1.0[ab]**	2.93 (2.42 to 3.45)	5.10 (4.66 to 5.53)	2.80 (2.37 to 3.22)
Maturity offset (Years from PHV)	-2.3 ± 0.8	**-0.0 ± 0.6[a]**	**2.3 ± 0.6[ab]**	3.35 (2.83 to 3.86)	4.68 (4.25 to 5.12)	2.44 (2.01 to 2.87)
Height (m)	1.37 ± 0.06	**1.53 ± 0.06[a]**	**1.65 ± 0.06[ab]**	2.43 (1.91 to 2.94)	4.76 (4.33 to 5.20)	2.10 (1.67 to 2.53)
Body mass (kg) *	31.5 ± 6.1	**42.8 ± 6.2[a]**	**57.2 ± 7.7[ab]**	1.83 (1.31 to 2.33)	3.52 (3.09 to 3.96)	1.97 (1.54 to -2.40)
Body mass index ($kg \cdot m^{-2}$)	16.6 ± 2.0	18.1 ± 2.2	**20.9 ± 2.7[ab]**	0.72 (0.20 to 1.23)	1.70 (1.26 to 2.13)	1.08 (0.65 to 1.51)
Leg length (m)	0.68 ± 0.05	**0.76 ± 0.05[a]**	**0.81 ± 0.04[ab]**	1.75 (1.23 to 2.26)	3.16 (2.73 to 3.60)	1.24 (0.81 to 1.67)
SJ height (cm)	19.3 ± 3.1	20.7 ± 3.9	**22.1 ± 4.3[a]**	0.38 (-0.14 to 0.89)	0.70 (0.27 to 1.13)	0.35 (-0.08 to 0.77)
CMJ height (cm)	19.8 ± 3.9	22.2 ± 3.9	**22.7 ± 4.2[a]**	0.63 (0.12 to 1.14)	0.71 (0.28 to 1.14)	0.11 (-0.32 to 0.54)
5max jump height (cm)	16.3 ± 2.9	19.0 ± 4.5	**20.8 ± 5.1[a]**	0.70 (0.19 to 1.21)	0.97 (0.54 to 1.41)	0.37 (-0.06 to 0.80)
5max GCT (ms)	207.0 ± 32.4	226.3 ± 43.2	**244.3 ± 45.9[a]**	0.45 (-0.06 to 0.97)	0.42 (-0.02 to 0.85)	0.70 (0.32 to 1.18)
5max RSI (ms/ms)	0.81 ± 0.20	0.90 ± 0.30	0.88 ± 0.25	0.33 (-0.18 to 0.85)	0.30 (-0.14 to 0.73)	0.05 (-0.38 to 0.48)
20submax flight-time (ms)	280.8 ± 58.3	**205.7 ± 56.0[a]**	**242.7 ± 61.4[ab]**	1.31 (0.80 to 1.83)	0.63 (0.20 to 1.06)	0.62 (0.19 to 1.05)
20submax GCT (ms)	186.7 ± 18.2	177.6 ± 21.5	**197.6 ± 28.6[b]**	0.46 (-0.06 to 0.97)	0.42 (-0.01 to 0.85)	0.75 (0.32 to 1.18)
Absolute leg stiffness (kN)	13.2 ± 2.5	**22.1 ± 5.7[a]**	**23.3 ± 5.1[a]**	1.99 (1.48 to 2.50)	2.23 (1.80 to 2.67)	0.24 (-0.19 to 0.67)
Relative leg stiffness ($kN \cdot kg^{-1} \cdot m^{-1}$)	29.4 ± 5.4	**39.6 ± 7.6[ab]**	**33.8 ± 8.8[a]**	1.54 (1.03 to 2.05)	0.55 (0.11 to 0.98)	0.69 (0.26 to 1.12)

PHV, Peak height velocity; BMI, Body mass index; SJ, Squat jump; CMJ, Countermovement jump; 5max, 5 maximal hops; 20submax, 20 submaximal hops; GCT, Ground contact time; RSI, Reactive strength index

[a] $P < 0.05$ denotes difference from pre-PHV maturity group **(Bold)**

[b] $P < 0.05$ from mid-PHV maturity group **(Bold)**

Table 6.2 Mean ± SD for anthropometry and performance results based on maturity offset subgroups, based on years from peak height velocity (YPHV)

	Maturity offset subgroups (YPHV)					
	-2.5 (n = 18)	**-1.5** (n = 12)	**-0.5** (n = 18)	**0.5** (n = 13)	**1.5** (n = 27)	**2.5** (n = 42)
Age (years)	8.8 ± 1.03	10.1 ± 0.4	11.6 ± 0.5	12.7 ± 0.5	13.9 ± 0.5	15.3 ± 1.0
Maturity offset (years from PHV)	-2.8 ± 0.6	-1.6 ± 0.2	-0.4 ± 0.3	0.6 ± 0.2	1.6 ± 0.3	2.7 ± 0.5
Height (cm)	1.34 ± 0.05	1.43 ± 0.04	1.50 ± 0.06	1.58 ± 0.04	1.63 ± 0.05	1.67 ± 0.05
Body mass (cm)	28.3 ± 3.2	36.4 ± 6.4	40.2 ± 5.0	46.3 ± 6.3	54.5 ± 5.6	58.9 ± 8.4
Body mass index ($kg \cdot m^{-2}$)	15.9 ± 1.3	17.6 ± 2.5	17.8 ± 2.2	18.6 ± 2.2	20.5 ± 2.3	21.1 ± 2.9
Leg length (m)	0.65 ± 0.04	0.72 ± 0.03	0.74 ± 0.05	0.78 ± 0.03	0.80 ± 0.04	0.82 ± 0.03
SJ height (cm)	19.1 ± 3.2	19.7 ± 3.0	20.8 ± 3.6	20.5 ± 4.4	21.3 ± 4.1	22.6 ± 4.3
CMJ height (cm)	19.3 ± 4.3	20.5 ± 3.3	21.9 ± 4.0	22. 8 ± 3.9	21.8 ± 4.2	23.3 ± 4.1
5max jump height (cm)	16.0 ± 3.3	16.8 ± 2.3	19.6 ± 4.1	18.2 ± 5.0	20.0 ± 4.8	21.3 ± 5.3
5max GCT (ms)	203.6 ± 35.8	212.2 ± 27.1	213.8 ± 27.2	243.6 ± 55.2	234.7 ± 33.7	250.5 ± 51.8
5max RSI (ms/mm)	0.81 ± 0.18	0.83 ± 0.22	0.96 ± 0.27	0.81 ± 0.32	0.87 ± 0.23	0.89 ± 0.27
20submax flight time (ms)	286.4 ± 62.2	272.3 ± 53.4	221.2 ± 32.2	184.2 ± 74.3	255.3 ± 71.9	242.7 ± 64.4
20Submax GCT	182.6 ± 14.5	192.8 ± 21.9	174.3 ± 14.5	182.2 ± 28.7	202.3 ± 25.7	194.6 ± 30.3
Absolute leg stiffness (kN)	12.4 ± 2.4	14.5 ± 2.1	20.3 ± 3.2	24.4 ± 7.5	21.4 ± 5.4	24.5 ± 4.6
Relative leg stiffness ($kN \cdot kg^{-1} \cdot m^{-1}$)	29.2 ± 5.4	29.8 ± 5.6	38.0 ± 4.7	41.8 ± 10.2	31.3 ± 8.4	35.3 ± 8.8

PHV, Peak height velocity, PHV; BMI, Body mass index; SJ, Squat jump; CMJ, Countermovement jump; 5max, 5 maximal hops; 20submax, 20 submaximal hops; GCT, Ground contact time; RSI, Reactive strength index

Table 6.3 P values and effect sizes (ES) using Cohen's with 95% confidence interval (95% CI) between consecutive maturity offset subgroups, based on years from peak height velocity (YPHV)

	Maturity offset subgroups (YPHV)				
	-2.5 vs. -1.5	**-1.5 vs. -0.5**	**-0.5 vs. 0.5**	**0.5 vs 1.5**	**1.5 vs. 2.5**
Age (years)	**<.001[a]** **1.63 (0.86 to 2.39)**	**<.001[a]** **3.18 (2.42 to 3.95)**	**.001[a]** **2.29 (1.54 to 3.03)**	**<.001[a]** **2.54 (1.86 to 3.23)**	**<.001[a]** **1.65 (1.15 to 2.14)**
Maturity offset (Years from PHV)	1.0 2.33 (1.56 to 3.09)	1.0 7.13 (6.37 to 7.90)	1.0 0.58 (-0.17 to 1.32)	.839 4.24 (3.56 to 4.93)	**.003[b]** **2.49 (1.99 to 2.98)**
Height (cm)	**<.001[a]** **2.16 (1.40 to 2.92)**	**.011[c]** **1.35 (0.67 to 2.03)**	**<.001[a]** **1.10 (0.81 to 2.30)**	**.035[c]** **1.14 (0.45 to 1.82)**	**.040[c]** **0.72 (0.23 to 1.22)**
Body mass (kg)	**.018[c]** **1.70 (0.94 to 2.47)**	1.0 0.69 (-0.07 to 1.46)	.170 1.10 (0.35 to 1.84)	**.005[b]** **1.39 (0.71 to 2.08)**	.095 0.60 (0.10 to 1.09)
Body mass index ($kg \cdot m^{-2}$)	.921 0.90 (0.14 to 1.67)	1.0 0.07 (-0.69 to 0.83)	1.0 0.37 (-0.38 to 1.11)	.324 0.85 (0.16 to 1.53)	1.0 0.24 (-0.25 to 0.73)
Leg length (m)	.001 1.77 (1.01 to 2.53)	.919 0.65 (-0.11 to 1.42)	.135 0.87 (0.13 to 1.62)	1.0 0.39 (-0.29 to 1.08)	.713 0.50 (0.01 to 0.99)
SJ height (cm)	1.0 0.19 (-0.58 to 0.95)	1.0 0.32 (-0.45 to 1.08)	1.0 0.07 (-0.68 to 0.81)	1.0 0.20 (-0.49 to 0.88)	1.0 0.29 (-0.20 to 0.78)
CMJ height (cm)	1.0 0.28 (-0.48 to 1.04)	1.0 0.38 (-0.39 to 1.14)	1.0 0.24 (-0.51 to 0.98)	1.0 0.24 (-0.44 to 0.93)	1.0 0.36 (-0.13 to 0.85)
5max jump height (cm)	1.0 0.27 (0.49 to 1.03)	1.0 0.78 (0.02 to 1.54)	1.0 0.30 (-0.44 to 1.05)	1.0 0.36 (-0.32 to 1.05)	1.0 0.28 (-0.21 to 0.77)
5max GCT (ms)	1.0 0.26 (0.50 to 1.03)	1.0 0.06 (-0.70 to 0.82)	.769 0.72 (-0.02 to 1.47)	1.0 0.21 (-0.47 to 0.90)	1.0 0.35 (-0.15 to 0.84)

5max RSI (ms/mm)	1.0 0.10 (-0.66 to 0.86)	1.0 0.55 (-0.21 to 1.31)	1.0 0.54 (-0.21 to 1.28)	1.0 0.24 (-0.44 to 0.92)	1.0 0.08 (-0.41 to 0.57)
20submax flight time (ms)	1.0 0.24 (-0.52 to 1.00)	.213 1.22 (0.46 to 1.98)	1.0 0.69 (-0.06 to 1.43)	.054 0.98 (0.30 to 1.66)	1.0 0.34 (-0.15 to 0.83)
20submax GCT (ms)	1.0 0.57 (-0.19 to 1.33)	.384 1.04 (0.27 to 1.80)	1.0 0.36 (-0.38 to 1.11)	.240 0.75 (0.07 to 1.44)	1.0 0.27 (-0.22 to 0.76)
Absolute leg stiffness (kN)	1.0 0.93 (0.17 to 1.70)	**.014[c]** **2.05 (1.29 to 2.82)**	.239 0.76 (0.01 to 1.50)	.819 0.49 (-0.19 to 1.17)	.112 0.60 (-0.08 to 1.28)
Relative leg stiffness ($kN \cdot kg^{-1} \cdot m^{-1}$)	1.0 0.12 (-0.64 to 0.89)	.082 1.61 (0.85 to 2.37)	1.0 0.51 (-0.24 to 1.25)	**.002[b]** **1.16 (0.48 to 1.84)**	.567 0.47 (-0.03 to 0.96)

PHV, Peak height velocity; SJ, Squat jump; CMJ, Countermovement jump; 5max, 5 maximal hops, 20submax, 20 submaximal hops; GCT, Ground contact time; RSI, Reactive strength index

[a] $P < .001$ difference between consecutive YPHV subgroup **(Bold)**

[b] $P < .01$ difference between consecutive YPHV subgroup **(Bold)**

[c] $P < .05$ difference between consecutive YPHV subgroup **(Bold)**

6.4 Discussion

To the best of the author's knowledge, this is the first study examining both slow and fast SSC function in physically active girls during maturation. The main findings are that the post-PHV maturity status group consistently outperformed the pre-PHV subgroup, that RSI did not differ between any subgroup and that the mid-PHV subgroup generated greater relative stiffness than both the pre- and post-PHV subgroups. Additionally, the -0.5 and the 0.5 YPHV maturity offset subgroups recorded greater leg stiffness and greater relative leg stiffness, respectively, compared to the -1.5 and 1.5 YPHV maturity offset subgroups. A lack of differences in SJ, CMJ and 5max jump height, 5max GCT, and RSI in YPHV maturity offset subgroups suggests that active schoolgirls aged 7-17 years do not demonstrate periods of accelerated adaptation in SSC development in the same manner previously reported in boys (Lloyd et al., 2011b). In contrast to Lloyd et al., 2011b), who found that boys increased RSI but not leg stiffness during mid-PHV (Lloyd et al., 2011b), the mid-PHV demonstrated leg stiffness and relative leg stiffness development, but not RSI values, suggesting accelerated periods of fast SSC development in maturing girls is task dependent.

SJ and CMJ height

In the present study, CMJ height was superior to SJ height, and CMJ and SJ values were higher than hopping height, which concurs with previous data found in boys aged 7-18 years (Lloyd et al., 2009). The ~14% greater SJ and CMJ height achieved by the post-PHV subgroup compared to the pre-PHV subgroup is consistent with literature in the vertical jump height performance of girls aged 9-18 years (Malina et al., 2004b; Emmonds et al., 2018a; Emmonds et al., 2018b). Greater jump height in the post-PHV maturity status groups compared to the pre-PHV maturity status group may be due to several positive neuromuscular adaptations due to growth and maturity, such as greater muscle cross-sectional area (CSA), greater tendon CSA and tendon stiffness, increased fascicle length and pennation angle, enhanced musculotendinous unit recruitment, a greater number of Type II muscle fibres, reduced agonist-antagonist co-contraction, and Golgi tendon organs desensitisation, resulting in better SSC recruitment, and hence, greater maximal force and impulse, and a faster RFD required to jump higher (Radnor et al., 2018).

Interestingly, SJ and CMJ jump height was not significantly higher in the mid-PHV subgroup compared to the pre-PHV subgroup, nor in the post-PHV subgroup compared to the mid-PHV subgroup. This may suggest that the timing and combination of the changes that occur as part of SSC development during growth and maturation is important (Radnor et al., 2018). Similar SJ and CMJ heights in the pre- and mid-PHV maturity groups may suggest the mid-PHV subgroup experienced a lack of motor coordination development necessary to effectively orientate, stabilise and transmit force via their lower limbs (Meyers et al., 2015).

Although empirical evidence remains somewhat limited, it has been argued that reductions in neuromuscular control during the adolescent growth spurt, and the accompanying accelerated changes in body size and proportions (Bisi and Stagni, 2016) may result in a decline in motor and functional performances, defined by some authors as 'adolescent awkwardness' (Baxter-Jones et al., 2002; Quatman-Yates et al., 2012; Williams et al., 2021). During this period, adolescents may experience neurological, multisensory and information processing changes resulting in less efficient postural control compared to adults (Viel et al., 2009). For example, adolescent girls tend to exhibit decreased knee stability during and after puberty, with a concomitant increase in joint torque loads, which is pertinent, given that female athletes participating in cutting and landing sports such as soccer, demonstrate a 400-600% greater incidence of ACL injury when compared with their male counterparts (Arendt and Dick, 1995; Hewett et al., 1999). As adolescent awkwardness is a recognised part of maturation and is accounted for in the talent identification process (Cumming et al., 2017), strength and conditioning practitioners working with girls may wish to introduce a stage-based training progression model to monitor and address potential regressions in technical competency (Cumming et al., 2017). Given that leg power and vertical jump performance are considered as critical elements for successful athletic performance in youth female sports such as netball (Thomas et al., 2017b), basketball (Fort-Vanmeerhaeghe et al., 2016), volleyball (Pawlik et al., 2022), and soccer (Emmonds et al., 2018b), developing technical competency of girls to jump higher is desirable and impactful.

In the current study, RSI values did not increase during maturation. This finding disagrees with previous evidence in girls aged 9-20 years, where RSI consistently increased throughout maturity (Laffaye et al., 2016; Lehnert et al., 2022b; Jeras et al., 2019). Regardless of maturity status, all groups performed the 5max test with GCTs <250 ms indicative of the fast SSC (Flanagan and Comyns, 2008; Lloyd et al., 2009). Interestingly, the pre-PHV maturity subgroup generated significantly faster GCTs, but significantly lower jump heights compared to the post-PHV subgroup, supporting the notion that faster GCTs coupled with lower jump heights can be offset by greater jump height and slower GCTs (Flanagan and Comyns, 2008).

Greater 5max jump height in the post-PHV subgroup compared to the pre-PHV subgroup indicates that the more mature group were able to generate greater force production, possibly due to an increase in lean muscle mass and greater power associated with adolescence and development of the SSC (Beunen and Malina, 1988; Radnor et al., 2018). Contrary to previous hopping studies, which found the post-PHV boys and men rebound faster than pre-PHV boys (Lloyd et al., 2012a; Oliver and Smith, 2010), faster GCTs in the pre-PHV subgroup of the current study compared to the post-PHV subgroup may imply this subgroup performed maximal hopping with a greater level of pre-activation (feed-forward) and stretch reflex activation than the post-PHV subgroup, resulting in greater reutilisation of elastic energy (Henchoz et al., 2006; Komi and Gollhofer, 1997), However, as EMG was not used to measure muscle activity, differences in pre-activation and stretch reflex excitation between the maturity groups is hypothetical and requires further research.

As RSI is an indication athletic ability and the risk of ACL injury in (Lehnert et al., 2020), strength and conditioning practitioners working with girls may wish to implement an intervention such as plyometric training (PT), which aims to increase jump height whilst minimising GCT (Potach and Chu, 2016). Introducing PT to reduce GCTs is of particular importance to the 2.5 YPHV maturity offset subgroup of the current study, who recorded RSI contact times more representative of intermediate SSC (~250 ms) rather than fast SSC (Lloyd et al., 2011c).

Although there was no meaningful difference between the leg stiffness of the mid- and post-PHV subgroups, when compared to the pre-PHV subgroup, the mid- and post-PHV subgroups demonstrated significant 67% and 77% increases in absolute leg stiffness, respectively. Leg stiffness is governed in part by pre-activation and short-latency stretch reflexes (Hobara et al., 2007), with up to 97% of the variance in leg stiffness explained by the contribution of pre-activation and the stretch-reflex response of lower limb extensor muscles (Oliver and Smith, 2010). Typically, leg stiffness increases with faster GCTs (McMahon et al., 2012), which is heavily influenced by pre-activation and the stretch reflex (Oliver and Smith, 2010; Lloyd et al., 2012a). During human hopping, leg stiffness primarily depends on ankle stiffness (Farley and Morgenroth, 1999), which suggests that to increase leg stiffness, strength and conditioning practitioners should create trainng programmes that heavily focus on ankle stiffness (e.g., pogo hopping during plyometrics). Given the significant 10% difference in 20submax GCT between the mid- and post-PHV subgroups, it is possible the mid-PHV subgroup demonstrated greater pre-activation and stretch reflex activation of the ankles during the 20submax test than the post-PHV subgroup.

In the current study, the pre-PHV subgroup recorded greater 20submax flight times than both the mid- and post- PHV subgroups, while also recording similar 20submax GCTs compared to the post-PHV subgroup. Based on this finding, it is reasonable to assume the pre- and post-PHV subgroups demonstrated similar levels of pre-activation and stretch-reflex contributions to generate similar GCTs, though the more mature subgroup may have done so to the detriment of flight time (jump height). It is possible the greater body mass in the mid-PHV and post-PHV subgroups compared to the pre-PHV subgroup (35.9% and 81.6%, respectively) may have had a greater impact on absolute leg stiffness than the greater flight times and faster GCTs, as demonstrated by the pre-PHV subgroup. This agrees with several authors, who suggested that higher body mass results in greater absolute leg stiffness (Korff et al., 2009; Lloyd et al., 2012a; Lloyd et al., 2011b; Oliver and Smith, 2010; Kubo et al., 2001).

When comparing consecutive maturity offset subgroups, the -0.5 YPHV subgroup demonstrated a significant increase (40%) in absolute leg stiffness compared to the -1.5 YPHV subgroup. One possible reason for this finding might be that -0.5 group were closer to their spurt in power experienced during adolescence, which is initiated approximately -1.5 YPHV but peaks 0.5-1.0 years post-PHV (Beunen and Malina, 1988). Increasing power (force x velocity) may have increased the rebound capabilities and hoping speed of the -0.5 group, and hence their leg stiffness (Oliver and Smith, 2010; Lloyd et al., 2012a; Lloyd et al., 2009; McMahon et al., 2012).

Despite the mid- and post-PHV maturity status subgroups demonstrating greater absolute leg stiffness compared to the pre-PHV subgroup, when normalised for body mass and leg length, the mid-PHV subgroup demonstrated greater relative stiffness compared to both the pre- and post-PHV subgroup (34.7% and 17.2%, respectively). This finding coincides with Lehnert et al. (2020), who reported that post-PHV girls decreased relative stiffness by 16% as maturity increased from 1.7 to 2.7 YPHV. Similarly, De Ste Croix (2017) reported that girls aged 12.1 and 13.8 years demonstrated greater relative leg stiffness than older girls aged 15.8 years (22.4 and 27.2%, respectively), lending credence to the theory that increases in power and its derivatives (force and velocity) may have occurred more readily during mid-PHV than post-PHV (Beunen and Malina, 1988). Indeed, when comparing offset subgroups of the current study, the +0.5 YPHV subgroup demonstrated a 36.7% increase in relative leg stiffness compared to the +1.5 YPHV subgroup. Greater relative leg stiffness mid-PHV subgroup may also be associated with a temporary reduction in motor coordination in the post-PHV subgroup (Kemper et al., 2015).

It is also possible greater relative stiffness in the mid-PHV compared to the post-PHV is linked to an increase in body fat linked with post-PHV girls. Specifically, Laffaye et al. (2016) found that girls aged 17-18 years reduced leg stiffness due to a 25% increase in fat mass that was not experienced by younger girls. Although fat mass was not directly measured in the current study, the current study found that the BMI of the post-PHV maturity status group was 25.9 and 15.5% greater than the pre- and mid-PHV subgroups, respectively. This increase in BMI may mean the post-PHV girls increased fat mass, which is common in girls aged 15-16 years (Tonnessen et al., 2015; Malina et al., 2004b). As fat plays no positive role in power production (Emmonds et al., 2018a) and reduces strength-to-weight ratio (Moran et al., 2018a), a possible increase amount of fat associated in post-PHV girls may have compromised the SSC capabilities of this cohort (Tonnessen et al., 2015; De Ste Croix et al., 2017). However, the notion that the post-PHV increased in fat mass is speculative and warrants further investigation.

The post-PHV subgroup may have also demonstrated less relative leg stiffness due to a lack of knee stability, a plateau in neuromuscular strength (Meyers et al., 2015), and reduced motor coordination associated with post-PHV female athletes (Standing et al., 2019; Quatman-Yates et al., 2012; Philippaerts et al., 2006). As knee stability and leg extensor strength was not recorded, these theories are speculative, and so future studies should aim to investigate these suggestions further by testing the strength/stability of maturing girls. Relative leg stiffness is important in many sporting actions and can help to identify those at increased risk of ACL injuries (De Ste Croix et al., 2017; Lehnert et al., 2020; Butler et al., 2003). Consequently, strength and conditioning practitioners should emphasise development of relative leg stiffness in youth female athletes, particularly due to the increases participation of girls in sports such as soccer (Football Association, 2024).

The lack of significant performance differences between consecutive offset subgroups in the SJ, CMJ, and RSI makes identification of critical periods of accelerated adaptation in slow and one characteristic of fast SSC development non-existent. Nonetheless, testing the slow and fast SSC function of active girls may provide normative data and an insight into the expected SSC development of maturing girls in a youth-based setting. It should be noted that SSC performance is governed by efficient interaction between both muscular and neural systems (Radnor et al., 2018).

Effective neuromuscular regulation of the SSC during growth and maturation is affected by the development of several anatomical, structural and neural mechanisms (Radnor et al., 2018), and any SSC differences between PHV subgroups could been due to the development of several factors during maturation (Radnor et al., 2018). For example, greater fascicle development during maturity improves the ability to produce force at higher shortening speeds, due to a greater number of in-series sarcomeres (Cronin and Radnor, 2020). In addition, the SSC during maturation is influenced by the development of muscle size and pennation angle, tendon size, tendon stiffness, pre-activation and reflex control (Radnor et al., 2018). Developing RFD during maturation in girls may also enhance their ability to cope with eccentric loads, leading to 'stiffer' jump landings, less yield, and generate faster GTCs (Cronin and Radnor, 2020; Ford et al., 2010). Developing a greater pennation angle, muscle volume and muscle length during maturation may result in a greater passive resistance and, therefore, greater stiffness during SSC actions (Earp et al., 2010; Secomb et al., 2015). This may suggest that girls should perform an effective resistance training programme to increase pennation angle and muscle volume beyond adaptations due to grow and maturation.

6.5 Practical Applications

Periods of accelerated adaptation have been suggested to reflect a time when children are most sensitive to a training stimulus (Bayli and Hamilton 2004; Viru et al., 1999). Lloyd et al. (2011b) reported that boys demonstrated accelerated development in slow (SJ and CMJ height) and fast (RSI and leg stiffness) SSC function -3 to +3 years from PHV. The results of this chapter suggest that strength and conditioning practitioners should not expect the same SSC developmental changes in girls that has been observed in boys during periods of maturation (Lloyd et al. 2012a). Greater jump height and leg stiffness in post-PHV group compared to the pre-PHV group, but no differences between consecutive maturity groups in jump height and GTC implies that growth and maturation alone do not influence the characteristics of slow and fast SSC function (e.g., impulse and GCT). The greater relative leg stiffness and lower GCTs in the mid-PHV girls during the 20submax test implies this group demonstrated greater pre-activation prior to ground contact to perform faster rebounds during repeated hopping (Lloyd et al., 2012a). Future research may wish to test this theory by using EMG to directly measure muscle activation during hopping of pre- and post-PHV girls (Lloyd et al., 2012a; Oliver and Smith, 2010).

Given that during growth and maturation girls experience 'windows of opportunity' to improve several aspects of athletic ability such as power, speed and strength (Balyi and Hamilton, 2004; Lloyd and Oliver, 2012), it is reasonable to suggest that all groups in this chapter should perform an effective training programme such as resistance and/or plyometric training (PT) to increase SSC function and enhance neuro-musculoskeletal development (Lloyd et al.,2012b; Dallas et al., 2020; Markovic & Mikulic, 2010). For example, in the mid-PHV girls, who demonstrated greater relative leg stiffness, introducing strength and hypertrophic training could complement PT. Doing so may help maintain this degree of leg stiffness whilst also improving neuromuscular characteristics associated with the onset of PHV (Beunen and Malina, 2008) to mitigate injury risk. It should be acknowledged that the current chapter involved non-elite schoolgirls. Therefore, future research may wish to examine the effects of grow and maturation on SSC function in elite youth female athletes, as doing so would allow strength and conditioning practitioners working with this population create a more complete SSC function profile of their athletes.

6.6 Conclusion

Several anatomical, structural and neural factors that develop during maturity influence SSC function. The findings of this study suggest that performance variables differ greatly between pre- and post-PHV, but with ambiguity for some comparisons between mid- and pre- and post-PHV girls (e.g., leg stiffness). One interesting finding is that RSI did not increase between PHV subgroups, which suggests that greater jump height in the post-PHV girls is offset by greater contact times, and that more mature girls may perform hopping with greater triple flexion due to knee instability and knee valgus. Also, in accordance with previous studies, relative leg stiffness was greater in the mid-PHV subgroup than both the more and less mature girls. Due to a lack of significant differences in the performance of SJ, CMJ, and RSI (and the derivatives of jump height and GCT) in girls when accounting for maturity offset intervals, it appears schoolgirls aged 7-17 years do not demonstrate periods of accelerated adaptations in SSC development in the same manner as boys. This finding was unexpected, given that the jump height, RSI and leg stiffness has been shown to develop, albeit in a non-linear fashion in other previous studies (Laffaye et al., 2016).

Chapter 7

Effect of in-season plyometric training and biological maturation on slow and fast stretch-shortening cycle development in youth female soccer players

7.1 Introduction

Soccer is an intermittent sport where sprinting and jumping contribute to more than 50% of all goals scored (Faude et al., 2012). Strength, power and their derivatives (e.g., acceleration, sprinting speed, and jump height) are important determinants in soccer (Hoff and Helgerud, 2004). Collecting data on sprint and jumping performance of youth female soccer players (aged 9 – 15 years) would allow strength and conditioning practitioners to make informed decisions about the "athleticism" and to inform future training programme design (Emmonds et al., 2018b). In recent years, participation of girls in soccer has increased exponentially, with over 1 million girls aged 5-15 years now regularly playing soccer in England (Football Association, 2024).

Unfortunately, soccer poses the highest risk of anterior cruciate ligament (ACL) injuries in adolescent girls compared to any other sport (Childers et al., 2025; Joseph et al., 2013). Youth female players are also more likely to suffer ACL injuries than youth male players during soccer (Childers et al., 2025; Bram et al., 2021; Joseph et al., 2013), due to several anatomical, hormonal and biomechanical sex-differences that occur during maturation (Mancino et al., 2024; Childers et al., 2025). As such, mitigating the risk of ACL injury is of great importance to strength and conditioning practitioners when working with youth female soccer players.

Plyometric training (PT) is a popular, sports-specific, effective, time-saving, and easy to administer training strategy for improving the sprinting and jumping ability of youth soccer players (Asadi et al., 2018). Crucially, PT has also shown to reducing serious knee injuries in girls (Chimera et al., 2004; Hewett et al., 1996). Lower-body plyometric exercises such as jumping, hopping and bounding are characterised by cyclic or spontaneous rapid eccentric contractions (deceleration or absorption of force) to a concentric phasing (acceleration or propulsion of force) (Markovic and Mikulic, 2010); both of which are determined by effective use of the SSC. The SSC causes storage of elastic energy during the initial stretch, which contributes to a potentiation of force during the subsequent shortening of the muscle (Komi, 2003). The effectiveness of PT has been demonstrated in children aged 10-17 years, who have improved power and strength (Thomas et al., 2009); sprinting speed (Beato et al., 2018; Michailidis et al., 2013; Kotzamanidis, 2006); change of direction speed (Meylan and Malatesta, 2009; Saez de Villarreal et al., 2015); rebound jump height (Lloyd et al., 2012b; Moran et al., 2018a); vertical jump performance (Moran et al., 2018a; Slimani et al., 2017); the rate of force development (RFD) (Matavulj et al., 2001); the reactive strength index (RSI) and leg stiffness (Lloyd et al., 2012b; Dallas et al., 2020) following PT; all of which are effective physical performance traits within soccer (Ramirez-Campillo et al., 2015b; Ramirez-Campillo et al., 2015a; Ramirez-Campillo et al., 2019; Loturco et al., 2015a).

PT itself is an umbrella term describing SSC activities, which can be further broken down to GCT) of slow (>250 ms) and fast (<250 ms) SSC actions (Taylor et al., 2022). Typically, jumping is used to assess both slow and fast SSC profiles due to the cheap and reliable methods employed (Asadi et al., 2018). Commonly, countermovement jumps (CMJ) determine slow

SSC, while drop jumps, repeated hopping and sprinting determines fast SSC (Lloyd et al., 2011c; Flanagan and Comyns, 2008; Taylor et al., 2022; Komi and Nicol, 2011). Such SSC tasks help derive variables such as GCT, RFD, power and concentric force (Emmonds et al., 2018a; Emmonds et al., 2018b; Lloyd et al., 2009; Lloyd et al., 2011c). Repeated hopping also measures RSI and leg stiffness (Lloyd et al., 2009), which is important considering these measures are positively correlated to sprinting speed (Chelly and Denis, 2001), jump height (Arampatzis et al., 2001b), hopping height (Hobara et al., 2008; Farley and Morgenroth, 1999), running economy (Dalleau et al., 1998; Kerdok et al., 2002) and a reduction in ACL injury (Lehnert et al, 2020). Given the prevalence of ACL injuries in youth female soccer (Childers et al., 2025), it would be pertinent for such measures conducted within female soccer players. However, to date there is a dearth of data for this population within the literature.

The potential lack of PT related data within the literature on youth female soccer players maybe due to the added complexity of female maturation. A key mechanical function of the SSC is the absorption and retention of energy to the musculotendinous unit (MTU) during the eccentric phase, which then transfers to elastic energy during the concentric phase (Turner and Jeffreys, 2010; Komi and Bosco, 1978). While a stiffer MTU is desirable during most SSC tasks (McMahon, 2017), a key hormone involved in MTU of female athletes is oestrogen (Chidi-Ogbolu and Baar, 2018), with the potential of high oestrogen levels decreasing power and athletic ability and making women more prone for catastrophic knee ligament injury (Chidi-Ogbolu and Baar, 2018). With females generally having more compliant tendons due to higher oestrogen levels (Chidi-Ogbolu and Baar, 2018), their SSC function is at a disadvantage to males (Padua et al., 2005; Granata et al., 2002a); which is likely further amplified during different stages of maturation (Malina et al., 2004a; Laffaye et al., 2016).

Although children demonstrate periods of ‘accelerated adaptation’ in SSC function, much of this evidence is based on boys (Moran et al., 2017a; Moran et al., 2018b; Moran et al., 2017c; Lloyd et al., 2011b), as too is the the evidence that PT can amplify SSC development (Ramirez-Campillo et al., 2018b). While PT has been shown to increase the SSC development of girls, the influence of maturation on training is sparse and contradictory (Davies et al., 2019; Romero et al., 2019; Moran et al., 2018a; Ramirez-Campillo et al., 2023; Slimani et al., 2017). This might in part due to methodological differences between training prescription and/or stratification according to age and maturity demonstrated in the above-mentioned studies. The literature also shows that boys may experience ‘synergistic adaptation’ which refers to the symbiotic relationship between specific adaptations of an imposed training stimulus and the concomitant growth and maturity-related adaptations (Lloyd et al., 2015). While a previous meta-analysis by Moran et al., (2018) suggests that the phenomenon of synergist adaptation may exist in girls, a limitation of this study is that it did not report maturity status but rather chronological age, which does not reflect the timing and tempo of growth and maturation (Malina et al., 2004b; Lloyd et al., 2014a).

Undertaking PT once per week appears to have a positive impact (Cohen’s d $\geq$ 1.34) on several SSC actions such as kicking distance, leg power, jump height, and speed of youth female soccer players aged 13 (Rubley et al., 2011) and 18 years (Ozbar et al., 2014). Following 4 - weeks PT, leg stiffness and RSI was also shown to improve in boys aged 12.3 and 15.3 years

(Lloyd et al., 2012b), while RSI was shown to improve in female rhythmic gymnastics aged 8.4 years and leg stiffness improved in female taekwondo athletes aged 13.9 years (Dallas et al., 2020) Given the observed accelerated adaptation of SSC during maturation in boys, but differences in maturity between females of different biological ages, it is pertinent to observe the effect of PT across a spectrum of maturation status in youth females. It would also be interesting to observe at which stage of maturation, if any, girls experience synergist adaptation, which may influence how and when PT is introduced in youth female training programmes. To the author's knowledge, there are no studies that have examined the effectiveness of low frequency PT in the development of several slow (CMJ) and fast SSC (RSI, leg stiffness and sprinting) tasks in youth female soccer players, with consideration given to maturity. Thus, the aim of this study was to determine CMJ, RSI, leg stiffness and sprinting metrics in female soccer players, and observe the effect of a low frequency 8-week PT training programme on these individuals.

7.2 Method

7.2.1 Study design

This was a 16-week cross over design which involved an 8-week "control" period (soccer-only training) and an 8-week "intervention" period (soccer combined with PT). Soccer sessions were ~60 mins duration and were conducted once per week. The same duration and frequency of soccer was completed in the intervention period with 10-20 min PT once per week replacing the standard warm up of the 60 mins soccer training, in addition to their normal physical education lessons (twice per week; 60 minutes per session) throughout the entire chapter. All tests were completed during the in-season of the regular soccer calendar, with test 1 (T1) performed in week 0, test (T2) performed in week 8, and test 3 (T3) completed in Week 16, with the control period being between T1 and T2, whilst the intervention being between T2 and T3.

7.2.2 Participants

Detailed descriptions of participant recruitment and assessment of anthropometric, maturation, and SSC variables are detailed in Chapter 3. In this chapter, 45 youth female recreational soccer players (Table 6.1) from three English squads within the same soccer club (U16s; n = 15, U12s; n = 15, U10s; n = 15) volunteered to take part in this study. The Ethics Committee of Manchester Metropolitan University (Manchester, UK) granted approval for this research. All procedures complied with the last Declaration of Helsinki (World Medical Association, 2013).

Table 7.1. Mean ± standard deviation (SD) of participants based on years from peak height velocity (PHV).

	Pre-PHV (n = 15)	**Mid-PHV (n = 15)**	**Post-PHV (n = 15)**
Variable	**Mean ± SD**	**Mean ± SD**	**Mean ± SD**
Age (yrs.)	9.6 ± 0.4	11.8 ± 0.5	15.0 ± 1.1
Maturity Offset (yrs.)	-2.1 ± 0.4	-0.2 ± 0.5	2.3 ± 0.8
Height (m)	1.40 ± 0.05	1.53 ± 0.04	1.64 ± 0.06
Body mass (kg)	31.9 ± 4.4	41.8 ± 5.7	57.3 ± 10.9
Body mass index ($kg·m^2$)	16.2 ± 1.5	17.7 ± 2.5	21.3 ± 3.1
Leg length (m)	0.68 ± 0.03	0.75 ± 0.03	0.80 ± 0.05
Soccer training (yrs.)	2.4 ± 1.5	3.3 ± 2.0	5.8 ± 3.0

7.2.3 Testing

All SSC dependent variables are detailed in Chapter 3. Testing was performed in week 0 (T1), Week 8 (T2), and Week 16 (T3), with T1 and T2 serving as pre- and post-testing for soccer-only training (8 weeks), and T2 and T3 measuring all dependent variables prior to and following soccer training supplemented with 8-week PT. Following 2 familiarisation sessions, jump height (cm) was measured during a countermovement jump (CMJ). RSI and its determinants of jump height (mm) and GCT (ms) were measured during 5 maximal (5max) hopping, while leg stiffness and its determinants of flight time (ms) and GCT (ms) were measured during 20 submaximal (20submax) hopping. Relative leg stiffness and 20 m sprint time were also calculated.

All jumping and hopping tests were carried out using the Optojump Next optical measurement system (Microgate, Bolzano, Italy), while sprint time was measured using Brower Speed Trap II times gates (Brower Timing Systems, Utah, USA). CMJ height and RSI was measured three times, with the best values used for further analysis. A single test of 20submax measured leg stiffness, while the quickest time following two 20 m sprints were used for further analysis (Lloyd et al., 2009; Loturco et al., 2013). To minimise the effect of fatigue and allow the phosphagen energy system to fully resynthesize (Harris et al., 1976), 4 minutes rest between each sprint was permitted (Koral et al., 2018; Meyers et al., 2015). The CMJ and each hopping trial had an intra-set rest of 90 s (Meylan and Malatesta, 2009) and an interset rest of 2 minutes (Ramirez-Campillo et al., 2014).

7.2.4 Statistical analysis

Data is presented as mean ±standard deviation (SD). A 3 (Time) x 3 (Groups) analysis of variance (ANOVA) was used as an omnibus test to observe PT effect over time (T1-3) and groups (pre- mid- and post-PHV). Where sphericity was not met, significance was assessed using Greenhouse-Geisser. Normality and homogeneity of variance between groups was tested using the Shapiro-Wilk and Levene's test. If significant within- or between-group effects were observed, pairwise comparisons were conducted using the Bonferroni post-hoc analysis. If normal distribution assumptions were not met following ANOVA; Wilcoxon and Mann-Whitney-U tests were used for within- and between-group comparisons, respectively, both with a Bonferroni correction of $\alpha = 0.05/2$ used for the Wilcoxon test and a Bonferroni correction of $\alpha = 0.05/3$ used for the Mann-Whitney-U test. Effect size (ES) was determined using the modified Cohen's d scale, with ≤ 0.2 classified as trivial, 0.2-0.6 small, 0.6-1.2 moderate, 1.2-2.0 large, 2.0-4.0 very large, and ≥ 4.0 extremely large (Hopkins, 2002). Level of significance was set at $P < 0.05$ (Moeskops et al., 2018). The SPSS version 28 (IBM Corporation, New York, USA) was used for further analysis.

7.2.5 Plyometric training

A full description and rational of the PT intervention is detailed in Chapter 3. The PT group followed once per week PT programme for 8 weeks using vertical and horizontal drills to improve force production in both planes (Ramirez-Campillo et al., 2015b). The duration of plyometric exercises in each session was approximately 10-20 mins, dependent by the planned intensity and volume of the session. 7-days rest was provided between each training session (Rubley et al., 2011; Ozbar et al., 2014; Bouguezzi et al., 2020). The intensity of the programme was increased in accordance with previous plyometric training guidelines aimed at children and adolescents (Lloyd et al., 2011a). Training volume was determined by the number of foot contacts made during each session (Jarvis et al., 2016), starting with 80 contacts in the first session, increasing to 190 contacts in the penultimate session and 60 contacts in the final session. A contact was identified each time the lower extremities perform one attempt of each plyometric exercise.

Plyometric drills lasted approximately 5-10 s, and 90 s rest was allowed after each set (Meylan and Malatesta, 2009). As per testing, 2 minutes of recovery was permitted when moving from one drill to another (Ramirez-Campillo et al., 2014). The following exercises were included in the intervention programme training (Table 7.2). During the PT programme, exercises were randomised (Hernandez et al., 2018). This method was deemed appropriate to elicit variation and encourage competition, fun and motivation in the athletes (Flangan and Comyns, 2008), which is especially important among youth athletes (Hernandez et al., 2018).

Table 7.2. 8-week (once per week) progressive plyometric training programme

	Week 1	Week 2	Week 3	Week 4	Week 5	Week 6	Week 7	Week 8
Submaximal bilateral hopping	2 x 20	2 x 10	2 x 10	3 x 10	2 x 20	3 x 20	3 x 20	2 x 20
Maximal bilateral hopping	5 x 6	2 x 10	2 x 10	2 x 10	2 x 10	2 x 10	3 x 10	2 x 5
Countermovement jumps	10*	2 x 10	2 x 10	2 x 10	2 x 10	2 x 10	2 x 10	1 x 10
Unilateral vertical hopping		2 x 10	2 x 10	2 x 10	2 x 10	2 x 10	2 x 10	
Bilateral horizontal hops		2 x 10	2 x 10	2 x 10	2 x 10	2 x 10	2 x 10	
Unilateral horizontal hops			2 x 10	2 x 10	2 x 10	2 x 10	2 x 10	
Bounding					2 x 10	2 x 10	2 x 10	
Sprinting	20 m x 2	10-m x 3	15-m x 2	20 m x 2	30-m x 2	50-m x 2	50-m x 3	20 m x 2
Total foot contacts per leg *	80	100	120	130	160	180	190	60

* Total excludes sprints

7.3 Results

Countermovement Jump Height

There was a significant time (P < .001) and group (P < .001) effect, but no group*time interaction (P = .767) for relative CMJ jump height. Prior to PT, there was no difference in CMJ height between post- and mid-PHV (P = .902; Table 6.3), but pre-PHV had a smaller CMJ height than both mid- (P < .001; Table 6.3) and post-PHV (P < .001; Table 6.3) at all time points. There was no change in CMJ height during the football only period (T1 to T2, P = .288; Table 6.3), but CMJ height did increase following the PT intervention (P < .001; Table 6.3). Pre- mid- and post-PHV did not improve in CMJ height from T1 to T2 (P = 1.00, P = .142 and P = 1.00, respectively; Table 6.3), but all improved from T2 to T3 (P < .001, Table 6.3). ES between T1-T2 were 0.01 - 0.09 and between 0.75 and 1.78 following PT (Table 6.3).

5max Jump Height

There was a significant effect for time (P < .001) and group (P < .001), but there was no group*time interaction (P = .251) for 5max hop height. Prior to PT, the post and mid-PHV were similar in 5max hop height (P = .111; Table 6.3), The post-PHV also demonstrated greater jump height than the pre-PHV group at all time points (P ≤ .001; Table 6.3), while the mid-PHV group only recorded a greater jump height than the pre-PHV at T3 (P = .005; Table 6.3). 5max hop height increased from T1 to T2 (P = .003; Table 6.3) and increased further again during the PT intervention (T2 to T3, P < .001; Table 6.3). Pre- mid- and post-PHV did not improve in 5max hop height from T1 to T2 (P = .577, P = .111 and P = .157, respectively; Table 6.3), with the mid- and post- PHV improving from T2 to T3 (P < .001 and P = .018 respectively;

Table 3). Pre-PHV did not increase 5max hop height following PT (P = .281; Table 6.3). ES between T1-T2 were between 0.18 - 0.19 and between 0.24 and 0.48 following PT (Table 6.3).

5max Ground Contact Time

There was a significant effect for time (P < .001) and a group*time interaction (P = .013) for GCT, but no group effect (P = .094; Table 6.3) for 5max GCT. At T1, the mid-PHV group demonstrated a significantly greater GCT than the pre-PHV group (P < .018; Table 6.3), with no other significant differences between any other groups at any time point. There was no difference in 5max GCT during the football period (T1 to T2, P = .091; Table 6.3), but this decreased significantly during the PT intervention (T2 to T3, P < 0.001; Table 6.3). Pre- and post-PHV did not improve in 5max GCT from T1 to T2 (P = .970 and P = .433, respectively; Table 6.3), whereas the mid-PHV did (P = .048; Table 6.3). The pre-, mid-, and post-PHV improved from T2 to T3 (P = .004, P < .001, and P = .002, respectively; Table 6.3). ES between T1-T2 were 0.19 - 0.30 and between 0.70 and 1.01 following PT (Table 6.3).

5max RSI

There was a significant effect for time (P < .001) and group (P = .026) as well as a significant group*time interaction (P < 0.001) for 5max RSI. Post- 5max RSI was greater than pre-PHV at T2 and T3 (P ≤ .021; Table 6.3), as was the mid-PHV group at T3 (P = .045; Table 6.3). 5max RSI increased from T1 to T2 (P = .001; Table 6.3) and increased further again during the PT intervention (T2 to T3, P < .001; Table 6.3). Mid- and post-PHV improved in 5max RSI from T1 to T2 (P = .025 and P = .013, respectively; Table 6.3), whereas the pre-PHV did not (P = 1.00;

Table 6.3). The mid- and post-PHV improved 5max RSI from T2 to T3 (P < .001 and P = .002, respectively; Table 6.3), but pre-PHV did not (P = .33, Table 6.3). ES between T1-T2 were 0.04 - 0.26 and between 0.33 and 0.75 following PT (Table 6.3).

20submax GCT

There was a significant effect for time (P < .001) and a group*time interaction (P = .027) for 20submax GCT, but no group effect (P = .166). There was no significant difference in 20submax stiffness GCT between any group at any time point (P ≥ .173; Table 6.3), nor was there any difference between T1 and T2 (P = .278; Table 6.3), but the PT intervention reduced 20submax stiffness GCT (T2 to T3, P < .001; Table 6.3). Pre- mid- and post-PHV improved in 20submax GCT from T1 to T2 (P = .025 and P = .013, respectively; Table 6.3), whereas the pre-PHV did not (P = 1.00; Table 6.3). The mid- and post-PHV improved 20submax GCT from T2 to T3 (P < .001 and P = .002, respectively; Table 6.3), whereas pre-PHV did not (P = .333; Table 6.3). Pre- mid- and post-PHV did not improve 20submax GCT from T1 to T2 (P = .466, P = .061 and P = 1.00, respectively; Table 6.3), with all improving from T2 to T3 (P < 0.001; Table 6.3). ES between T1-T2 were 0.14 – 0.18 and between 0.97 and 1.29 following PT (Table 6.3).

20submax Flight Time

There was a no effect for time (P = .337), group (P = .227) or group*time interaction (P = .0.892) for 20submax flight time. Pre-, mid-, and post-PHV did not improve in 20submax flight time during T1 and T2 (P ≥ .486; Table 6.3), nor during T2 and T3 (P ≥ .616; Table 6.3). ES between T1-T2 were 0.09 - 0.23 and between 0.00 and 0.23 following PT (Table 6.3).

20submax Leg Stiffness

There was a significant effect for time ($P < .001$), group ($P < .001$) and a group*time interaction ($P = .027$) for 20submax leg stiffness. Prior to PT, there was no difference in 20submax leg stiffness between pre- and mid-PHV ($P = 1.00$; Table 6.3), but post-PHV had a greater leg stiffness than both pre- ($P < .001$; Table 6.3) and mid-PHV ($P < .001$; Table 6.3). There was no change in 20submax leg stiffness in any group during the football only period (T1 to T2, $P = .419$; Table 6.3), but leg stiffness increased in all groups following the PT intervention ($P < .001$; Table 6.3). Pre- mid- and post-PHV did not improve in leg stiffness from T1 to T2 ($P = 1.00$, $P = .140$, and $P = 1.00$, respectively; Table 6.3), with all improving from T2 to T3 ($P < .001$; Table 6.3). ES between T1-T2 were 0.02 - 0.15 and between 0.85 and 1.11 following PT (Table 6.3).

20max Relative Leg Stiffness

There was a significant effect for time ($P < .001$) and group ($P = .035$), but no group*time interaction ($P = .251$) for relative 20submax leg stiffness. Prior to PT, there was no difference in relative 20submax leg stiffness between pre- and mid-PHV ($P = .733$; Table 6.3), but post-PHV had a greater relative leg stiffness than the pre-PHV at T2 and T3 ($P \leq .035$; Table 6.3). There was no change in relative 20submax leg stiffness in any group during the football only period (T1 to T2, $P = .536$; Table 6.3), but relative leg stiffness increased in all groups following the PT intervention ($P < .001$; Table 6.3). Pre- mid- and post-PHV did not improve in relative leg stiffness from T1 to T2 ($P = .510$, $P = .242$ and $P = 1.00$, respectively; Table 6.3), with all improving from T2 to T3 ($P < .001$; Table 6.3). ES between T1-T2 were 0.06 - 0.17 and between 0.94 and 1.49 following PT (Table 6.3).

20 m Sprint Time

There was a significant effect for time (P < .001) and group (P < .001) but no group*time interaction (P = .796) for 20m sprint time. Pre-PHV were slower than the mid- and post-PHV groups at all time points (P ≤ .039 and P < .001, respectively) at each time point, with post- also being quicker than mid-PHV at each time point (P ≤ .007; Table 6.3). There was no change in 20m sprint time during the football only intervention (T1 to T2, P = .123; Table 6.3), but participants got quicker following the PT intervention (T2 to T3, P < .001; Table 6.3). Pre- mid- and post-PHV did not improve sprint time from T1 to T2 (P = 1.00, P = 1.00 and P = .571, respectively; Table 6.3), with all improving from T2 to T3 (P ≤ .024, Table 6.3). ES between T1-T2 were 0.04 - 0.18 and between 0.29 and 0.78 following PT (Table 6.3).

Table 7.3. Mean ± SD for all dependent variables for each maturity group per test, p-values between-group differences, % change difference prior to soccer training (T1 – Week 0), following soccer training (T2 – Week 8), and before PT (T2 – Week 8) and following PT (T3 – Week 16), p-values within-group, and effect size (ES) using Cohen's d (95% CI) for T1-T2, and T2-T3 changes

Variable	**Test 1 Week 0**	**Test 2 Week 8**	**Test 3 Week 16**	**Δ% T1 - T2**	**T1 - T2**	**Δ% T2 - T3**	**T2 - T3**
	Mean ± SD	Mean ± SD	Mean ± SD	%	ES (95% CI)	%	ES (95% CI)
CMJ (cm)							
Pre-PHV	18.2 ± 2.1	18.2 ± 2.1	21.9 ± 2.1	0.2	0.01 (-0.74 – 0.76)	**20.3**[j]	1.78 (1.03 – 2.53)
Mid-PHV	**25.0 ± 5.3**[b]	**25.5 ± 5.0**[b]	**29.1 ± 4.6**[b]	1.8	0.09 (-0.66 – 0.84)	**14.1**[j]	0.75 (0.01 – 1.50)
Post-PHV	**25.5 ± 4.0**[g]	**25.5 ± 4.1**[g]	**29.1 ± 4.2**[g]	-0.3	0.02 (-0.73 – 0.76)	**14.4**[j]	0.90 (0.15 – 1.64)
5max jump height (cm)							
Pre-PHV	16.9 ± 3.2	17.4 ± 2.7	18.3 ± 3.8	3.3	0.19 (-0.56 – 0.93)	4.6	0.24 (-50 – 0.99)
Mid-PHV	20.1 ± 5.0	21.0 ± 5.0	**23.5 ± 5.4**[c]	4.5	0.18 (-0.57 – 0.93)	**12.1**[j]	0.48 (-0.26 – 1.23)
Post-PHV	**22.9 ± 4.5**[g]	**23.7 ± 4.3**[g]	**25.2 ± 3.4**[g]	3.6	0.19 (-0.56 – 0.93)	6.2	0.37 (-0.38 – 1.12)
5max GCT (ms)							
Pre-PHV	226.5 ± 32.6	232.3 ± 29.7	206.9 ± 42.3	2.6	0.19 (-0.56 – 0.94)	**-11.0**[i]	0.70 (-0.05 – 1.44)
Mid-PHV	**271.1 ± 57.9**[a]	256.3 ± 49.3	215.5 ± 29.0	-5.4	0.27 (-0.47 – 1.02)	**-15.9**[j]	1.01 (0.26 – 1.76)
Post-PHV	239.5 ± 30.2	230.8 ± 27.9	208.2 ± 25.0	-3.7	0.30 (-0.45 – 1.05)	**-9.8**[h]	0.85 (0.11 – 1.60)
RSI (mm/ms)							
Pre-PHV	0.76 ± 0.16	0.77 ± 0.16	0.85 ± 0.32	0.9	0.04 (-0.70 – 0.79)	10.7	0.33 (-0.42 – 1.07)
Mid-PHV	0.80 ± 0.38	0.87 ± 0.35	**1.16 ± 0.44**[a]	**7.7**[h]	0.17 (-0.58 – 0.92)	**34.5**[j]	0.75 (0.00 – 1.50)
Post-PHV	0.98 ± 0.27	**1.04 ± 0.25**[e]	**1.23 ± 0.24**[e]	**6.9**[h]	0.26 (-0.49 – 1.01)	**17.7**[j]	0.75 (0.01 – 1.50)
20submax GCT (ms)							
Pre-PHV	220.5 ± 28.6	225.7 ± 28.1	194.3 ± 19.8	2.4	0.18 (-0.56 – 0.93)	**-13.9**[j]	1.29 (0.54 – 2.04)
Mid-PHV	242.2 ± 49.7	233.7 ± 44.9	197.0 ± 29.0	-3.5	0.18 (-0.57 – 0.93)	**-15.7**[j]	0.97 (0.22 – 1.72)
Post-PHV	213.5 ± 25.5	210.1 ± 21.5	187.0 ± 20.1	-1.6	0.14 (-0.60 – 0.89)	**-11.0**[j]	1.11 (0.36 – 1.86)
20submax flight time (ms)							
Pre-PHV	282.8 ± 46.2	293.1 ± 69.6	293.4 ± 64.63	3.7	0.18 (-0.57 – 0.92)	0.1	0.00 (-0.74 – 0.75)
Mid-PHV	324.7 ± 73.2	332.1 ± 87.6	327.3 ± 61.7	2.3	0.09 (-0.66 – 0.84)	-1.4	0.06 (-0.69 – 0.81)
Post-PHV	317.1 ± 70.4	335.9 ± 89.6	316.6 ± 80.4	5.9	0.23 (-0.52 – 0.98)	-5.8	0.23 (-0.52 – 0.98)
Absolute leg stiffness (kN)							
Pre-PHV	10.17 ± 2.40	9.89 ± 2.42	12.65 ± 2.55	-2.8	0.12 (-0.63 – 0.87)	**27.1**[j]	1.11 (0.36 – 1.86)

Mid-PHV	11.64 ± 4.17	12.26 ± 3.84	16.04 ± 4.13	**5.3**[g]	0.15 (-0.59 – 0.90)	**30.9**[j]	0.95 (0.20 – 1.70)
Post-PHV	**18.89 ± 4.79**[dg]	**18.98 ± 4.70**[dg]	**23.63 ± 6.10**[dg]	0.5	0.02 (-0.73 – 0.77)	**24.5**[j]	0.85 (0.11 – 1.60)
Relative leg stiffness (kN·kg^{-1}·m^{-1})							
Pre-PHV	22.42 ± 4.67	21.66 ± 4.14	27.61 ± 3.84	-3.4	0.17 (-0.57 – 0.92)	**27.5**[j]	1.49 (0.72 – 2.24)
Mid-PHV	21.65 ± 8.00	22.67 ± 7.22	29.54 ± 7.33	4.8	0.14 (-0.61 – 0.88)	**30.3**[j]	0.94 (0.20 – 1.69)
Post-PHV	26.79 ± 6.10	**27.15 ± 5.33**[e]	**33.56 ± 6.74**[e]	1.3	0.06 (-0.69 – 0.81)	**23.6**[j]	1.06 (0.31 – 1.80)
20 m sprint time (s)							
Pre-PHV	3.67 ± 0.17	3.66 ± 0.15	3.56 ± 0.11	-0.6	0.13 (-0.62 – 0.88)	**-2.8**[h]	0.78 (0.03 – 1.53)
Mid-PHV	**3.46 ± 0.34**[a]	**3.45 ± 0.30**[a]	**3.36 ± 0.31**[a]	-0.3	0.04 (-0.71 – 0.78)	**-2.5**[j]	0.29 (-0.46 – 1.03)
Post-PHV	**3.17 ± 0.18**[cg]	**3.14 ± 0.18**dg	**3.08 ± 0.17**[cg]	-1.0	0.18 (-0.57 – 0.93)	**-2.0**[j]	0.37 (-0.38 – 1.11)

T1, pre-soccer-only training1; T2, post-soccer-only training and pre-PT, T3, post soccer and plyometric training; CMJ, countermovement jump; 5max, 5 maximal hops; 20submax, 20 submaximal hops; RSI, reactive strength index; GCT, ground contact time

[a] P ≤ .05 between Pre- and Mid-PHV groups **(Bold)**
[b] P ≤ .001 between Pre- and Mid-PHV groups **(Bold)**
[c] P ≤ .01 between Mid- and Post-PHV groups **(Bold)**
[d] P ≤ .001 between Mid- and Post-PHV groups **(Bold)**
[e] P ≤ .05 between Pre- and Post-PHV groups **(Bold)**
[f] P ≤ .01 between Pre- and Post-PHV groups **(Bold)**
[g] P ≤ .001 between Pre- and Post-PHV groups **(Bold)**
[h] P ≤ .05 within-group changes **(Bold)**
[i] P ≤ .01 within-group changes **(Bold)**
[j] P ≤ .001 within-group changes **(Bold)**

7.4 Discussion

To the authors' knowledge, this was the first study to examine the effect of low frequency PT on the slow- and fast-SSC in youth female soccer players, with consideration given to maturity. The results show that a low frequency 8-week PT programme improved all key performance variables measured, other than repeated jumping flight time, compared to football training alone, regardless of maturation status. This finding concurs with one meta-analysis that reported that pre- and post-PHV athletes responded equally well in jump height and sprinting following PT (Ramirez-Campillo et al., 2023). Importantly, the current chapter demonstrated that low frequency PT could induce improvements in both slow- and fast-SSC related variables above what would be expected by growth and maturity alone, suggesting that the current cohort experienced synergistic adaptation. Further, we have identified that some key performance variables differ based on maturation status alone.

The marked improvement by all maturity groups in CMJ, leg stiffness, relative leg stiffness and sprint speed indicates that youth female soccer players can effectively improve the slow- and fast-SSC, when PT is integrated into their regular soccer training. These findings agree with much of the research, which shows that PT is an effect modality of training to improve explosivity, such as CMJ (Moran et al., 2018a; Hewett et al., 1996; Ozbar et al., 2014), RSI (Davies et al., 2019) and leg stiffness (Lloyd et al., 2012b; McMahon et al., 2012), of athletes involved with invasion sports, such as soccer.

It has been stated that SSC is governed by neural regulation (Radnor et al., 2018), and that pre-PHV athletes may respond more favourably to the high neural demands of PT (Lloyd et al., 2015), due in part to central nervous system maturation and neuroplasticity (Myer et al., 2013). This chapter further confirms that younger female muscle tissue is pliable and adaptable to different frequencies, loads and stresses across a maturity spectrum. This chapter though, only measured the external biomechanical changes, not structural differences in tissue, such as muscular-tendon compliance. That aside, the variables measured in this chapter certainly infer that youth female soccer players improve tendon stiffness (through absolute and relative leg stiffness) and RSI, which are both observed as key injury indicators in female sport (Lehnert et al., 2020), particularly surrounding ACL injury during soccer (Childers et al., 2025). There is confidence, therefore, that by including even low frequency PT alongside soccer training, youth female soccer players will improve not only key performance indicators but also help prevent serious long-term injury through the improvement of said variables.

Myer et al., (2005) stated that female athletes may especially benefit from multicomponent neuromuscular training such as PT because they often demonstrate lower baseline levels of explosive strength compared with male athletes. Markovic (2007) also stated that there is a positive transfer of PT on vertical jump height, with RSI and leg stiffness also improving in children following 4-weeks PT (Lloyd et al., 2012b; Dallas et al., 2020). In agreement, the current chapter has shown that both slow- and fast-SSC are adaptable in youth female soccer players, while completing both components within an 8-week training programme. This concurs with other studies involving youth female soccer players (Rubley et al., 2011; Ozbar et al., 2014; Sanchez et al., 2022). Though these studies only conducted slow and/or fast SSC programmes in a bid to increase jump height, kicking distance and 20 m sprinting, meaning that none of the above-mentioned studies aimed to increase RSI and leg stiffness, whereas the current chapter did. This is important, given that developing the RSI and leg stiffness improves athletic ability and can lower the risk of ACL injury population susceptible to such injuries (Lehnert et al., 2020). A major critique of some studies involving youth female athletes is that they have not compared the SSC function in all stages of maturity status within female populations (Davies et al., 2019; Moran et al., 2018a; Romeo et al., 2019). By splitting groups into pre-, mid- and post-PHV, this chapter was able to somewhat eliminate maturity effects of individual participants, such as hormonal (Landen et al., 2023; Hewett, 2000) and training age (Jeras et al., 2019) differences, and present the external biomechanical changes following an 8-week PT programme.

There was a general trend that more mature participants outperformed their lesser mature counterparts, and this chapter consistently observed that post-PHV were more physically dominant than pre-PHV in all performance variables (Table 6.3). The improved performance in the post-PHV group was not a surprise, as with and without maturation-related disruptions to motor coordination (e.g., greater knee-valgus and 'adolescent awkwardness'), performance increases align with others (Davies et al., 2019; Quatman-Yates et al., 2012; Barber-Westin et al., 2006). Greater RSI in the mid- and post-PHV groups in the current chapter compared to the pre-PHV group might be linked to the more mature groups having ~19 kg greater body mass to the pre-PHV group. Girls typically gain ~3.5 kg of muscles mass annually during PHV and the difference in combined mid- and post-PHV age to pre-PHV accounts for ~14 kg of estimated muscle mass. Certainly, the likely additional estimated muscle mass would contribute to greater concentric force and more effective eccentric forces, hence the greater CMJ, RSI and sprint speeds observed in the more mature groups compared to lesser mature groups. However, this study did not measure body composition in any form, and so the link, while theoretically sound, requires further investigation.

Previous studies have shown the hopping RSI can increase by 35% and 53.5% in female gymnasts aged 8.44 and 10.8 years following 4-week or 6-week PT, respectively (Dallas et al., 2020; Ng et al., 2023). The significant improvements in RSI of the mid- and post-PHV groups following PT in the present study may indicate these groups effectively used muscle elasticity and neuromuscular control of working muscles (Flanagan and Comyns, 2008; Jarvis et al., 2021) and increased their tolerance to eccentric loading of the MTU during maximal hopping to overcome high impact forces (Ng et al., 2023). This could have been elicited from neural mechanical adaptations such as increased motor unit recruitment (Dallas et al., 2020), to overcome the high-impact forces experienced during the PT (Ng et al., 2023), resulting in improved excitability of the neural receptors due to the increased desensitisation of the Golgi tendon organ (GTO) (Chimera et al., 2004; Davies et al., 2015; Turner and Jeffreys, 2010), and the quciker RFD and greater stretch-reflex contribution follow PT (Davies et al., 2015; Matavulj et al., 2001). Heightened excitibility and a less sensitive GTO may have facilitited more spontaneous neuromsulcar coordination, which is characterised by the nervous system generating faster muscle-firing patterns, leading to neural efficency (Ng et al., 2023).

It is generally accepted that RSI is an important measure of SSC and rebound capability of youth athletes related to athletic ability (Flanagan and Comyns, 2008; Jarvis et al., 2021; Ramirez-Campillo et al., 2018b) and injury prevention (Toumi et al., 2006; Raschner et al., 2012). Finding that RSI did not increase in the pre-PHV group, therefore, may suggest that younger girls may need greater training volume, duration and/or frequency to improve RSI.

Leg stiffness describes the ability to attenuate an applied force during deformation of the leg, where an optimal amount of leg stiffness allows a large force to be attenuated over a shorter range of motion (McMahon and Cheng, 1990). The training intervention led to a significant increase in absolute leg stiffness.

It has been stated that leg stiffness increases due to lower GCT, greater flight time, higher body mass, or a combination of one or more of these factors (McMahon et al., 2012; Farley et al., 1991; Korff et al., 2009). Moreover, leg stiffness is governed in part by pre-activation and short-latency stretch reflexes (Hobara et al., 2007), with up to 97% of the variance in leg stiffness explained by the contribution of pre-activation and stretch-reflex response of lower limb extensor muscles (Oliver and Smith, 2010). In the current study, there was no group or time effect for flight time and no group effect for GCT, but GCT decreased for all groups following the PT intervention. It is likely therefore, that the changes in body mass, as described above, increased pre-activation prior to ground contact, and activation of stretch reflex contributed to the changes in leg stiffness in the current cohort.

When normalised to body mass and limb length each group demonstrated significantly greater relative leg stiffness following the PT intervention (Lloyd et al., 2012b); again, post-PHV had greatest relative leg stiffness compared to the other two groups. Similarly, Lloyd et al. (2012b) reported that while older pre-PHV boys aged 12 years and post-PHV boys aged 15 years increased absolute and relative leg stiffness following 4-weeks PT, early pre-PHV boys aged 9 years did not. The finding by Lloyd et al. (2012) agrees with Dallas et al. (2020), who found that while relative leg stiffness increased in post-PHV girls aged 13.9 by 31% ($P = .008$), it remained unchanged in girls aged 8.44 years ($P > .05$). Given the observation in the current chapter, it would be pertinent for maturing females alike to conduct jumping related activities with external weight, to elicit the biomechanical changes of the MTU as, from the current set of results, this appears to be the prominent factor that affects RSI. However, more work is needed to understand how much external weight is required to elicit such a response.

At each time point, sprint time was lower in the post-PHV group compared to the pre- and mid-PHV groups and lower in the mid-PHV compared to the pre-PHV group. This fining concurs with other literature in the sprint time of youth female athletes (Malina et al., 2004) Following PT, sprint time improved in all maturity groups. Interestingly, the pre- and mid-PHV improved more than the post-PHV ($P < .001$, $P = .001$, and $P = .024$, respectively). Sprinting involves both slow (e.g. acceleration phase) and fast-SSC (e.g. brief ground contacts) components, and relies on interaction of several other physiological and physical factors including technique (step velocity, stride length and frequency), leg power, musculotendinous stiffness, leg stiffness, lower body strength, high levels of RFD, vertical force and anaerobic muscle power, and high levels of horizontal force to increase forward propulsion (Suchomel et al., 2016; Lockie et al., 2015; Washif and Kok, 2021; Meylan et al., 2014b, Provot et al., 2024).

In the current chapter, improvements of CMJ (a surrogate of concentric strength and slow-SSC), RSI (a measure of eccentric force absorption, transfer of energy and fast-SSC), leg stiffness (a measure hysteresis, or energy dissipation) and GCT (a measure of impulse) following PT and all are identifiable within sprinting mechanics (Meylan et al., 2014a; Schmidtbleicher, 1992; Washif and Kok, 2021; Carr et al., 2015; Lockie et al., 2015). Thus, improvements in this variable are somewhat unsurprising in the current group.

Increased slow and fast SSC function following PT could be due to multiple positive neuromusculoskeletal adaptations, including: increased neural drive to the agonist muscles; increases in explosive muscle strength (contractile RFD and impulse); changes in the muscle activation strategies (i.e. improved intermuscular coordination); changes in the mechanical characteristics of the muscle-tendon complex of plantar flexors; changes in muscle size and/or architecture; and changes in single-fibre mechanics (Markovic and Mikulic, 2010; Asadi et al., 2017; Aagaard et al., 2002; Lloyd et al., 2011a; Kubo et al., 2021; Grgic et al., 2021). Increased neural drive to the agonist muscles may be due to a desensitisation of the GTO (Davies et al., 2015), thereby reducing the co-contraction of the agonist and antagonist muscles that dampen force production (Frost et al., 2002).

It is reasonable to suggest that improvements to muscle activation strategies, MTU complex, and muscle size increased due to the high neural and muscular demands of PT (Markovic and Mikulic, 2010). PT may also improve the eccentric strength of the thigh muscles, a prevalent component during the deceleration phase of impulsive movements (Sheppard and Young, 2006), which may involve a rapid switch from eccentric to concentric muscle action in the leg extensor muscles. As mentioned though, this study did not measure changes to *in vivo* biomechanical or muscular-tendinous properties, so these suggestions are valid, but speculative. Certainly, these results are useful for any coach or physical preparation coach to incorporate PT into their regimens to help create positive outcomes in the short linear sprints essential to defending, attacking, and scoring in soccer (Faude et al., 2012).

7.5 Practical Applications

Given the prevalence of sprinting and jumping in goal scoring situations in soccer (Faude et al., 2012), strength and conditioning practitioners should focus on testing and developing these skills in female soccer players (Turner et al., 2013a; Turner et al., 2013b). The findings of the current chapter lend credence to the existence of synergistic adaptation in youth female soccer players, regardless of maturational status (Ramirez-Campillo et al., 2023). The improvements found in slow and fast SSC following once-a-week PT has practical implications for strength and conditioning practitioners working with girls, giving them the confidence that supplementing soccer practice sessions with PT will have positive result on the SSC function, regardless of biological maturity. However, as the current data was obtained from recreational female soccer players. This means that the results may not be generalisable to other populations, such as elite youth female soccer players, due to elite soccer players being exposed to PT earlier in their playing 'careers', and as such have a lower capacity for improvement compared to recreational players. Future research, therefore, may wish to examine the effects of PT and maturation on the SSC function in elite youth female soccer players, as doing so would allow strength and conditioning practitioners working with this population to design an effective PT programme aimed at increasing several positive adaptations applicable to soccer (e.g., jump height and linear sprinting).

This chapter was the first study to examine leg stiffness values of youth female soccer players prior to and following PT. Possible causative factors for the beneficial adaptations following PT are likely multifaceted and include greater neural drive to the agonist muscles; increased tendon stiffness; greater neural contribution during the short latency stretch reflex period; increased muscle cross-sectional area; increased RFD; desensitisation of the GTO; and an overall improvement in inter- and intra-muscular coordination (Markovic and Mikulic, 2010; Davies et al., 2015; Radnor et al., 2017). From a practical perspective, the current study has revealed the potential benefits of low frequency plyometric intervention programmes in augmenting youth SSC function.

7.6 Conclusion

This chapter aimed to aim to develop the slow and fast SSC capabilities of maturing young female soccer players using low frequency horizontal and vertical PT. The data showed that 8-week of low frequency horizontal and vertical PT significantly improved CMJ height, RSI, leg stiffness, relative leg stiffness, and sprint time beyond that of 8-week soccer-only training. During PT, several neuromusculoskeletal adaptions could have occurred to increase slow and fast SSC function (Markovic and Mikulic, 2010). Further work is needed, however, to fully understand the effectiveness of PT in youth female soccer players, and whether there is a minimal dose response to such training for youth females, and whether dose response changes dependent on age and maturation.

Chapter 8

Discussion

8.1 Overview

It is widely acknowledged (and outlined in Chapter 3) that female athletes are underrepresented in sport and exercise science physiology research (Costello et al., 2014). This is particularly true when examining the literature using plyometric training (PT) to increase athletic ability, especially during maturation (Moran et al., 2018a; Ramirez-Campillo et al., 2018b; Ramirez-Campillo et al., 2023). PT was used in this thesis as it utilises the power and muscle force enhancing capabilities of the stretch-shortening cycle (SSC), which is a mechanism that includes the eccentric and concentric muscle actions used in sporting movements such as sprinting and jumping (Markovic and Mikulic, 2010). Despite the widespread application of PT in male soccer, only ~10% of 242 studies have included girls aged <18 years (Ramirez-Campillo et al., 2018b), and just 3 of 90 PT studies in soccer have involved youth female players (Ramirez-Campillo et al., 2022).

Owing to the anatomical, physiological, and hormonal differences between boys and girls during maturation (Malina et al., 2004b), girls may respond differently to PT than boys (Davies et al., 2019). Therefore, the aim of the present thesis was to provide more knowledge as to the effects of PT in girls throughout maturation, as doing so could allow practitioners to optimally design and appropriately introduce PT in this population.

Based on the author's knowledge, chapters 4-7 are the first to examine the slow (>250 ms) and fast (<250 ms) SSC based on squat jump (SJ), countermovement jump (CMJ) height, reactive strength index (RSI), and leg stiffness in active schoolgirls and CMJ, RSI, leg stiffness, and linear sprinting in female soccer players using several levels of maturity based on peak height velocity (PHV). The results of this thesis demonstrates that post-PHV girls consistently outperform pre-PHV girls, that mid-peak height velocity (PHV) active schoolgirls demonstrated 'accelerated adaptation' in absolute and relative leg stiffness, and that regardless of maturational status, female soccer players demonstrate 'synergist adaptation' in CMJ height (slow SSC), and RSI, leg stiffness, relative leg stiffness, and 20 m sprinting (fast SSC) following 8-week low frequency (once per week) PT. This thesis, therefore, extends the understanding of the development of SSC function in girls during maturation and following PT.

Study 1 (Chapter 4)

Traditionally, SSC function has been measured using a static laboratory-based force platform (Glatthorn et al., 2011; Healy et al., 2016; Balsalobre-Fernandez et al., 2015). However, the high cost (£20,000) and inaccessibility of this equipment makes it unsuitable for youth-based organisations where budget is often a constraining factor. Study 1 tested the inter-device agreement between two more cost effective, portable devices; the Optojump Next (£3,000) and the MyJump 2 smartphone app (£10) during a squat jump, CMJ, drop jump (DJ), 5 maximal (5max) hops, and 20 submaximal (20submax) hops in 34 post-PHV youth female soccer players (Emmonds et al., 2018b). Study 1 also examined the test-retest reliability of the same devices using the same tests in 24 of the original 34 post-PHV participants. The novel aspect of this study was that it was the first time the reliability of leg stiffness has been measured using the MyJump 2 app (Haynes et al., 2018). The data presented in chapter 4 found a high degree of agreement between the devices and moderate-to-high reliability in all metrics. Additionally, biological maturity was estimated using a somatic test with a potential error of 5-months (Mirwald et al., 2002).

The data in chapter 4 demonstrated that strength and conditioning practitioners could test the slow and fast SSC of post-PHV youth female soccer players reliability using the cost-effective app. However, systematic bias between the devices showed that the Optojump Next and MyJump 2 app were not interchangeable and, therefore, strength and conditioning practitioners should be consistent with the device they use to test the progress of their athletes (Glatthorn et al., 2011). It was also noted in Chapter 3 that the app was not time-efficient and lacked the simultaneous feedback offered by the Optojump Next system. Additionally, RSI and leg stiffness could only be measured using the app during a DJ, whereas the Optojump Next offered the flexibility to test RSI and leg stiffness using the reliable and valid hopping protocol used in multiple paediatric studies (Lloyd et al., 2009; Lloyd et al., 2012b; Dallas et al., 2020; Lehnert et al., 2020). Therefore, the Optojump Next system was used for the remainder of this thesis.

Study 2 (Chapter 5)

It is generally accepted that rebound actions such as a DJ and continuous hopping measure the fast SSC (Flanagan and Comyns, 2008; Lloyd et al., 2009; Jeras et al., 2019). However, several studies have reported that DJ and hopping are not always performed with GCTs associated with the fast SSC (Bassa et al., 2012; Ruffieux et al., 2020; Pedley et al., 2020; Dallas et al., 2020). To the author's knowledge, the data presented in chapter 5 was the first to compare the RSI and leg stiffness values and their determinants of jump height, flight time and GCT following a DJ and hopping in adolescent female soccer players. In this study 34 post-PHV youth female soccer players performed several DJ, and 5max and 20submax hopping trials using the Optojump Next system.

The data in chapter 5 revealed that based on GCTS, a DJ measured slow-to-intermediate (255 ms) SSC function, whereas both hopping protocols measured the fast SSC (206 ms), which concurs with findings found in boys aged 7-17 years (Lloyd et al., 2011c). As fast GCTs are essential to leg stiffness (McMahon et al., 2012; Lloyd et al., 2011c), it was unsurprising that both hopping protocols elicited greater leg stiffness than the DJ. In contrast, the DJ generated greater jump heights, slower GCTs, but greater RSI, demonstrating that slower GCTs can be offset by greater jump heights to increase RSI (Flanagan and Comyns, 2008).

These results may suggest that hopping was more reliant on supra-spinal feed forward input and short latency stretch reflexes to regulate greater levels of leg stiffness (Lloyd et al., 2012a), whereas greater jump heights in the DJ suggest participants performed a CMJ-DJ with greater triple flexion and slower GCTs rather than a bounce-DJ more indicative of the fast SSC (Pedley et al., 2017; Struzik et al., 2016). Although a DJ could have been used to measure RSI, it was felt that due to the risk of injury in girls associated with the DJ (Barber-Westin et al., 2006), and the requirement to measure RSI and leg stiffness using the mechanisms associated with the fast SSC (elastic energy and activation of the stretch reflex) (Komi and Gollhofer, 1997), subsequent studies should use the 5max to measure RSI and the 20submax test to measure leg stiffness, which concurs with several previous studies involving children (Lloyd et al., 2009; Lehnert et al., 2020; Dallas et al., 2020; Lloyd et al., 2012b).

Study 3 (Chapter 6).

To the author's knowledge, this was the first study to examine the potential of accelerated adaptation in slow (SJ and CMJ and fast (RSI and leg stiffness) SSC function in active schoolgirls aged 7-17 years. Chapter 6 included 130 girls recruited from a single school in England, who were categorised according to maturity offset (pre-, mid-, and post-PHV), and years from PHV (YPHV). Adopting the findings of Chapter 4 and 5, this thesis used the versality of Optojump Next to measure hopping, and the reliability of the 5max and 20submaxing hopping to measure RSI and leg stiffness, respectively, using this device.

The results of chapter 6 indicated that the post-PHV subgroup consistently outperformed the pre-PHV subgroup in all dependent variables, bar 5max GCTs, 20submax flight time, and 20submax GCTs. Additionally, RSI did not increase during maturity, while the mid-PHV generated greater relative leg stiffness than the pre- and post-PHV subgroups. The data also identified possible periods of accelerated adaptation in the -0.5 and the 0.5 YPHV subgroups, who recorded greater leg stiffness and greater relative leg stiffness compared to the -1.5 and 1.5 YPHV maturity offset subgroups, respectively.

Although all groups demonstrated fast SSC based on GCTs (≤ 197.6 ms), the findings that only leg stiffness values increased based on YPHV suggested that accelerated adaptation in fast SSC was task dependent. These findings disagree with a study in boys, which observed potential periods of accelerated adaptations in SJ and CMJ height in pre-PHV boys and RSI in pre-, mid-, and post-PHV boys (Lloyd et al., 2011b). This has practical implications, suggesting that strength and conditioning practitioners should not expect the same SSC developmental changes in boys and girls during periods of maturation. Finally, training may increase RSI and leg stiffness over and above changes expected during normal growth and maturation. Therefore, practitioners should consider adding an appropriate form of training to increase the fast SSC function of maturity athletes.

Study 4 (Chapter 7)

Based on the findings in the previous chapter (Chapter 6), it was considered that there may be accelerated periods of adaptation to PT based on the post-PHV subgroup consistently outperforming the pre-PHV subgroup (bar RSI), the mid-PHV outperforming the pre- and post-PHV subgroups in relative leg stiffness and the -0.5 and 0.5 YPHV subgroups outperforming the -1.5 and 1.5 YPHV subgroups in leg stiffness and relative leg stiffness, respectively. This likely reflected altered physiological composition of the muscle-tendon unit. To the author's knowledge, this was the first study to compare the effects of 8-week soccer-only training with 8-week soccer training, supplemented with low frequency (once per week) PT in the development of CMJ height, RSI, leg stiffness, relative leg stiffness, and 20 m sprinting in recreational female soccer players, with consideration given to maturity.

It was hypothesised that the responsiveness would not differ between pre-, mid-, and post-PHV youth female soccer players, but that soccer plus PT would generate greater training gains than soccer training alone. Chapter 7 found that CMJ height, RSI, leg stiffness, relative leg stiffness, and 20 m sprinting performance did not increase following soccer only training, but that all variables did increase following soccer + PT, except RSI in the pre-PHV group. Improvements in slow and fast SSC function during chapter 7 could be attributed to 'synergistic adaptation' (symbiotic changes due to training and adaptations due to growth and maturity), as well as various neuro-musculoskeletal adaptations found in previous studies including: increased neural drive to the agonist muscles; alterations in muscle size and/or architecture; and changes in single- fibre characteristics (Markovic and Mikulic, 2010). Other possible neural adaptations following PT includes changes to muscle activation strategies (inter-muscular coordination); particularly during the pre-landing phase of the CMJ and hopping; and changes to the stretch reflex excitability (Bishop and Spencer, 2004; Lloyd et al., 2012b; de Villarreal et al., 2010). However, this is speculative and warrants further investigation.

It is also worth noting that while low-frequency PT consistently improved slow and fast SSC function, several variables can be manipulated that may have further increased PT training gains experienced by the current population (Lloyd et al., 2011a; Ramirez-Campillo et al., 2023). In future, strength and conditioning practitioners working with female soccer players during maturation may wish to compare the effect of PT duration, frequency, and exercise selection on CMJ, RSI, leg stiffness, and sprinting performance, as finding the optimal PT programme to improve these variables would undoubtable influence future PT design aimed at this population.

8.2 Overarching outcomes

Considered together, the data from this thesis has identified a reliable method of assessing SSC outcomes for the purposes of field-based testing in a large cohort of adolescent female participants (Chapter 4). These techniques were adopted in subsequent chapters to identify the appropriate technique for fast SSC assessment (Chapters 5) and confirming that PHV stage alters the performance of dynamic tasks to measure SSC outcomes (Chapter 6). Finally, it was identified that PT led to favourable adaptations in SSC outcomes in pre-PHV participants, compared to post-PHV (Chapter 7).

8.3 Limitations

It is important to note that several limitations existed in this thesis. For example, the measurement of slow and fast SSC function in the Optojump Next and MyJump 2 app was not validated to laboratory-based force plates using the post-PHV female soccer players of chapter 4. Therefore, chapter 4 lacked the opportunity to validate these devices and protocols to the gold standard in current population. Additionally, as pre- and mid-PHV girls were not included in the agreement and reliability studies (Chapter 4), it remains unclear if maturational status could have altered the outcomes, given that post-PHV land with greater knee valgus and joint laxity due to fluctuations in oestrogen following the age of menarche can increase the likelihood of ACL injury and diminish the force production required to jump higher (Barber-Westin et al., 2010; Beutler et al., 2009; Barber-Westin et al., 2006; Chidi-Ogbou, 2018).

Although there was an error in these measurements, the % mean difference between the devices was small (range: -2.4 to 1.0%), as too was the difference in test-retest data of both devices (range: -8.1 to 7.7%). Despite this error, there is agreement between these devices and the criterion measure (Gencoglu et al., 2023b; Sharp et al., 2019; Healy et al., 2016; Ruggiero et al., 2016; Glatthorn et al., 2011; Rago et al., 2018), meaning that although the absolute values may be slightly under or overestimated in jump height, flight time, and GCT within the population, the high ICC of the two methods suggests the relative differences between PHV groups would not be altered through the use of the criterion measure. Combined with the point above, this would suggest that the relative improvements in the PT chapter would not be different if the criterion measure was used. The use of field-based assessments to remove barriers for recruitment was essential in a youth-based setting, given that the portable devices used could successfully transported to participants rather than the participants having to travel to a laboratory-based setting, which was unfeasible considering that they trained between 6-7 pm each week.

Each study in this thesis also used an estimate of biological maturation using the Mirwald et al. (2002) method rather than using the more accurate methods such as the Tanner-Whitehouse method, which assesses maturity using left-wrist radiography, the Tanner secondary sexual characteristics method, and the 'gold standard' method of skeletal age (Malina et al., 2004b; Lloyd et al., 2014a). Without access to medically trained professionals to administer and evaluate, it was deemed more appropriate to use the PHV method, particularly as all studies were carried out in the field (Lloyd et al., 2014a).

It has been previously stated that linear growth occurs in tandem with pubertal development (Ebling, 2005). For example, girls approximately aged 11 years demonstrate Tanner stages 1 and 2 of sexual maturation, whereas girls aged 12-18 years demonstrate Tanner stages 3 and 4 of sexual maturation (Faigenbaum et al., 2009a). A more recent study, however, noted that there is substantial variability in the timing of PHV across Tanner stages (Granados et al., 2015). In girls, the Mirwald equation has been reported to be a reliable (R^2 = 0.91; standard error of estimate = 0.50), non-invasive, practical solution for the measure of biological maturity for grouping adolescent athletes, previously termed 'biobanding' (Rogol et al., 2018). It is unlikely that the use of different methods of assessing biological maturity would have altered the outcomes of Chapters 4-7, particularly as elements involved in SSC outcomes from this thesis are inextricably linked with the components of the maturation assessments, regardless of the heterogenous presentation of other methods that calculate maturity (Malina et al., 2004b; Lloyd et al., 2014a).

Due to the sensitive nature of assessing menstrual status in adolescent participants (Lloyd et al., 2014a), the menstrual phase of the participants in each study was not measured. In part, this was because the menstrual cycle does not impact maximum bilateral, triple extension movements and jump height variables used in this thesis (Julian et al., 2017; Romero-Moraleda et al., 2019; Blagrove et al., 2020; Morenas-Aguilar et al., 2023). Although, the completion of age of menarche questionnaires, menstrual cycle diaries and/or blood/saliva testing would have identified the possible impact of menstrual cycle phases, and arguably strengthened the results of thesis, due to the high number of participants, such an approach was deemed unrealistic and too costly (blood testing kits are £20 per sample) and would have created a possible stigmatised barrier to participation reducing the sample pool from which data could be drawn.

Although once per week PT increased slow and fast SSC in all maturity groups in chapter 7, it is possible that designing a different PT program would have generate even higher training gains. Indeed, a meta-analysis by Moran et al. (2018), reported that PT including >2 sessions per week over >8 weeks, lasting more than 30 minutes, elicited the greatest training gains in girls aged 10.8 to 16.9 years. However, this thesis aimed to examine PT alongside soccer-training, which in the current cohort only occurred once per week for 8 weeks, a frequency and duration which other authors have found to have a positive impact on the athletic ability of youth female soccer players (Rubley et al., 2011; Ozbar et al., 2014), albeit not in RSI and leg stiffness development. As with any novel implementation of a training programme, particularly one with potential injury risks in adolescent female athletes (Rubley et al., 2011), it was prudent to adopt once/week training, due to a lack of other data on the effects of PT in female participants of this age group. Despite the potential risk of injury, there were no adverse effects noted, with 0% dropouts during the PT intervention, meaning that future research could build on the 1/week frequency adopted with PT in the present thesis. Ethically, low frequency is essential to establish whether more frequent PT could be adopted.

A further limitation of this thesis is that the research chapters did not include youth male soccer players. Measuring both sexes may have allowed the creation of comparative data between the boys and girls using several measures of slow and fast SSC. Maturity-matched males could have been used as a control group to compare the data found in girls against the plethora of data found previous in boys. Such information may have offered strength and conditioning practitioners working a in youth-based setting data-driven knowledge about the anatomical, physiological, neuromuscular, and hormonal differences between the sexes and how this may alter SSC function during maturation. This offers future scope for such studies in elite and non-elite male and female youth athletes.

8.4 Directions of future recommendations

The research examining SSC development of active girls and youth female soccer players with and without additional PT is extremely sparse, particularly with consideration given to maturity (Moran et al., 2019; Ramirez-Campillo et al., 2018b). While this thesis has enabled a clearer understanding of the slow and fast SSC function of maturity girls with and without PT, there remains several unanswered questions within the current literature. Consequently, there exists greater scope for future research within this domain. This thesis successfully examined the development trends in a range of SSC measures with and without PT, future research may wish to conduct a longitudinal study of the development of SSC function in girls, which would employ continuous or repeated measures, statistical testing and analysis to follow change in individuals over prolonged periods of time (Caruana et al., 2015). Tracking the SSC function of girls from pre-PHV to early adulthood would potentially reduce the sensitivity and variation of an assessment to identify any true associations/differences, which a single 'snapshot' cannot do. Such future research would enable a clearer identification of any potential periods of accelerated adaptation of slow and fast SSC.

Although Study 4 (Chapter 7) demonstrated that low-frequency PT can develop slow and fast SSC, strength and conditioning practitioners working with youth female soccer players may wish to further manipulate several PT variables, such as duration, frequency, volume, intensity, exercise direction (Ramirez-Campillo et al., 2023; Lloyd et al., 2011a) in order to find the most optimal PT programme. For example, future research may wish to examine the potential effects of once-a-week PT vs. twice-a-week PT on RSI and leg stiffness, as it remains unclear as to the effect of training frequencies in youth female soccer players in these SSC measures. Finding the most effective form of PT would undoubtedly influence future training and injury prevention strategies in girls, considering girls often drop out of sport due to time conflicts (18%), boredom (14%), or injury (26%) (Stewart and Taylor, 2000).

The SSC is governed by efficient neural regulation, such as pre-activation and excitement of the stretch reflex, which has been identified and examined in boys and men using electromyography (EMG) analysis (Lloyd et al., 2012a; Oliver and Smith, 2010). Lloyd et al (2012a) suggested that has they age and mature, boys become more reliant on supra-spinal feedforward input and short latency stretch reflexes to regulate greater levels of leg stiffness and RSI when hopping. However, to the best of the author's knowledge, similar studies do not exist in girls nor in female soccer players during maturity. Examining the direct role of feedforward and the stretch reflex in slow and fast SSC would add to the current knowledge, particularly as studies involving youth female athletes during maturation is a developing field.

The literature has also shown that SSC function is influenced by anatomy (e.g., increases in muscle mass, motor unit size, and pennation angles), agonist-antagonist co-contraction, tendon and joint stiffness, neuromuscular efficiency during maturation. (Radnor et al., 2018). Future research may wish to use techniques such as ultrasound to examine the interaction effects of PT structural adaptations in girls, as doing so would enhance our understanding of the exact mechanisms that underpin PT adaptations in this population.

8.5 Conclusion

The current thesis has made a significant contribution to the developmental literature into the slow and fast SSC function of girls and its responsiveness to plyometric training according to recognised periods of biological maturity. This was also the first time that leg stiffness has been tested using the MyJump 2 app, and the first time that leg stiffness has been examined in youth female soccer players during recognised periods of biological maturity. It is important to understand that girls may not develop the SSC in the same many as boys, particularly following puberty. Additionally, acknowledging that youth female soccer players can benefit significantly following low-frequency PT would allow strength and conditioning practitioners to conduct training in a time-efficient manner. Given that plyometric exercises mimic the specific explosive short-duration, high-intensity, vertical and horizontal manoeuvres during a soccer match (Ramirez-Campillo et al., 2015b; Ramirez-Campillo et al., 2015a), is it important that strength and conditioning practitioners working with girls understand that PT can potentially increase the transference effect between PT and on-pitch soccer performance (Ramirez-Campillo et al., 2019; Loturco et al., 2015a).

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