

Understanding Stretch-Shorten Cycle Ability in Youth

Abstract

Extensive research has investigated stretch-shorten cycle (SSC) performance in adults, however to date, only a few studies have investigated SSC ability in youths. Youths undergoing puberty experience many physiological changes, which include changes to neuromuscular and musculotendinous systems. To understand the possible differences in SSC ability, this review will: 1) briefly discuss maturation (biological vs. chronological), 2) discuss the contribution of the active and passive components to SSC ability and how these components may change with maturation; and, 3) review literature that has quantified SSC ability across maturation via comparison of countermovement and squat jump performance.

KEY WORDS: stretch shorten cycle, youth, maturation, SSC potentiation, countermovement jump, squat jump

INTRODUCTION

In human locomotion such as running, hopping and jumping, muscle contraction is typified by a combination of eccentric-lengthening followed immediately by a concentric-shortening contraction thus termed a stretch-shorten cycle (SSC). It should be noted that the stretching of a muscle is only considered an eccentric action if the muscle is active during the stretch (1,2). According to Komi and Gollhofer (3) an effective SSC requires three fundamental conditions: 1) a well-timed pre-activation of the muscle(s) before the eccentric phase; 2) an eccentric action phase which must be short and fast; and, 3) an immediate transition or short delay between the eccentric and concentric phase. The improvements in performance by the use of SSC muscle actions are well documented in the literature. One of the most utilized methods to demonstrate the SSC augmentation is by comparing two different types of vertical jumps (no arm swing). A vertical jump that is preceded by a countermovement (i.e. a countermovement jump - CMJ) to a vertical jump without a countermovement (i.e. a squat jump - SJ). In most studies using this approach, the CMJ has led to better vertical jump performance than the SJ by between 18% to 30% in adults (4,5). While the enhancements from the potentiating effects of the SSC are certain, the underlying mechanisms responsible for this potentiation have been a source of debate for many years. These different viewpoints were summarized in an article and subsequent discussions by van Ingen Schenau, Bobbert and De Haan (6,7). Four possible explanations for the SSC enhancement were presented. First, it was proposed that SSC enhancement is due to the storage and utilization of elastic energy in the muscle, particularly the series elastic component (SEC). Second, the countermovement simply provided time for the muscles to build up to a maximum active state before the commencement of the concentric contraction. Third, it was

theorized that alteration of the properties of the contractile machinery occurred during the pre-stretch of the active muscle, which subsequently enhanced the concentric contraction. The contributions of the spinal reflexes were proposed as the fourth possible explanation for SSC potentiation. Spinal reflexes that are triggered by the pre-stretch of a muscle during a countermovement help to increase muscle activation during the concentric phase (8). The reader is directed to the discussion and subsequent commentary by van Ingen Schenau, Bobbert and De Haan (7) for a full treatise of these explanations of SSC potentiation.

A good understanding of SSC in youth will help coaches develop better plyometric programs for children as part of a long term development approach. To do so, an understanding of growth and maturation is first required before proceeding to the active and passive components of SSC, how the components possibly change with maturation and the subsequent effects on SSC ability.

GROWTH AND MATURATION

Irrespective of the underlying mechanisms, SSC potentiation is undeniable and a great deal of research has investigated CMJ and SJ performance in adults. However, there has been less literature that has investigated these jumps in pre-adolescent and adolescent youths. The biological maturity of youths does not necessarily coincide with their chronological ages and can differ by several years (9–11). Youths undergoing puberty experience many physiological changes, which include changes to their musculotendinous and neuromuscular systems (12). The physiological changes during these periods of maturity are likely to contribute to the age associated variations in jumping performances between children of different age groups, maturity level and gender (12–14).

Spurts in growth and performances are likely to occur during adolescence (12). Adolescence is generally viewed as occurring between the ages of 12 to 18 years where great physical and mental development occurs such as puberty. There is a large amount of change occurring during these years and great variability in rate of growth among individuals. Therefore it is important to note the biological age of an individual rather than the chronological age. Biological age as opposed to chronological age is determined by the youth's rate of development and maturational process. This maturational process can be further divided into three significant phases, pre-pubescence, pubescence or post-pubescence with each phase having unique characteristics.

Prepubescents are usually chronologically above 8 years of age but have not yet reached the pubescent stages yet. This maturation phase is the build-up phase prior to the puberty phase and is marked by accelerated growth and the appearance of secondary sex characteristics, but they are not fully capable of sexual reproduction (12,15).

Pubescents are defined as children that are at the onset of puberty, have developed secondary sex characteristics and have reached maturity (12,15,16). Also known as adolescents, they are usually chronologically between 13 to 17 years of age for males and 12 to 16 years of age for females. One of the most recognized events signifying children in this maturation stage would be the increase in stature or adolescent growth spurt. During this adolescent growth spurt, the standing height (increase in) velocity increases and peaks, commonly known as peak height velocity (PHV). PHV values ranges from 5.4cm to 11.2cm per year for females and 5.8cm to 13.1cm per year for males (17). Practitioners can take note of this height increase and

utilize regular height monitoring as a practical method for gauging biological age. There are of course other methods of height monitoring which are shown in Table 1.

Postpubescents are usually chronologically above 17 to 18 years of age for males, and 16 to 17 years of age for females. The skeletal growth slows and the physiologic functions of the sexual organs are fully established (12,15). Ideally, children should be classified and trained according to their biological maturity or developmental stages. For this review the term youth shall referred to individuals below the age of 18 years of age. Other terms such as adolescents, pre, post and pubescents refer to individuals as described above.

Table 1: Classical Methods of Measuring Growth and Biological Maturation

Method	Description
Hand-wrist Radiography	<p>Measure skeletal age by studying the number of bone ossifications present (18–20) .</p> <p>Considerations:</p> <ol style="list-style-type: none"> 1) Hand wrist is only a small component of the skeletal system and may not always be representative (21) 2) Hand wrist radiographs provide a general idea of the amount of growth but not the direction (21).
Cervical Radiography	<p>Lateral cephalographic radiography is used to study the change in morphological characteristics in the cervical vertebrae (22,23). Shown to be equally as sound and effective as hand-wrist radiography and do not require further additional radiography (24,25).</p>

Secondary sexual characteristics	Traditionally has been used as the benchmark standard (16). Involves physical examination of the the sexual characteristics of the individual using the Tanner Scale or Sexual Maturation rating (SMR) (15).
	<p>Considerations:</p> <ol style="list-style-type: none"> 1) Based on Caucasian boys and girls and may not be standardized or suitable for other population 2) Secondary sex indicators are only limited to the pubertal phase of development. 3) Invasive and may not be culturally suitable (26). 4) Reduced reliability for self-examination (27)
Age at Menarche	Menarche refers to the first menstrual period. Age at menarche is the event at which it occurs (12).
	<p>Considerations:</p> <ol style="list-style-type: none"> 1) Girls only 2) Menarche is a late event in the pubertal process and is not appropriate if greater and finer detail of maturation tracking across the puberty span is desired 3) Reliability of self report of age at menarche. The longer the waiting period between examination the less likely one is capable of remembering when the first menstruation was (12).
Height measures	Tracks monthly increase in stature or standing height. Looks for the rate of and PHV (28).
	<p>Considerations:</p> <ol style="list-style-type: none"> 1) Accuracy of growth charts is based on population studies from different parts of the world. Growth charts must be specific to the populations especially in situations such as developing and developed countries 2) Difficult to find growth charts. Growth charts are derived from longitudinal studies which means they are expensive and might not exist for some populations (28).

MEASURING STRETCH SHORTEN CYCLE POTENTIATION

Due to the ease of measuring vertical jumps, different methodological approaches have been developed to measure SSC enhancement using the vertical jump by comparing the CMJ to the SJ (5). Because the CMJ utilizes a countermovement while the SJ does not, in theory the difference between the two types of vertical jumps can be attributed to augmentation associated with the countermovement i.e. SSC augmentation. Table 2 details four common field-based methods of quantifying SSC augmentation that are easy to use.

Table 2: Different methods of measuring SSC augmentation

Methods	Formula	Units
1) Direct Comparison ⁺	CMJ height – SJ height	cm
2) Pre-stretch Augmentation (PSA) ⁺⁺	$[(\text{CMJ} - \text{SJ})/\text{SJ}] \times 100$	%
3) Eccentric Utilization Ratio (EUR) *	$\text{CMJ} \div \text{SJ}$	value
4) Velocity of Vertical take-off (v_{TO}) ^{**}	$\Delta v_{\text{TO}} (\text{CMJ}) - \Delta v_{\text{TO}} (\text{SJ})$	%

*Adapted from Harrison & Gaffney (2001)**; McGuigan et al., (2006)*; Walshe & Wilson, (1997)⁺⁺; Young, (1995)⁺ (29–31)*

ACTIVE AND PASSIVE COMPONENTS AND SSC PERFORMANCE

A.V. Hill in his original experiment on the thermodynamics of muscle contraction in 1938 (32) described a two-component model of muscle that consisted of a contractile component (CC) and a purely elastic element which lies in series with the CC and known as the series elastic component (SEC). Over the years, the model was extended into a three-component model (33,34) where another elastic component known as the parallel elastic component (PEC) was added. The addition of the third component was introduced to help explain the passive force of an inactive fiber. The

model attempts to describe characteristics rather than direct reference to any individual structures. Therefore each component can be comprised of many different muscle structures that possess those characteristics. The contractile component of the model refers to the moving or contracting components or structures of muscles (i.e. the muscle fibers- actin and myosin filaments) that provide the active force during contraction of the muscle. The SEC refers to the structures of the muscle, which lies in series or in line with the muscle fibers such as cross-bridges, structural proteins and tendons. The PEC is non-contractile in nature and lies parallel to the muscle fibers. A relaxed passive muscle exerts the force that it contributes when it is stretched beyond its resting length. Muscle connective tissues such as the perimysium, epimysium and endomysium are examples of the PEC.

During human locomotion such as walking, running or jumping, the three components interact to produce efficient motion. For example, in the initial eccentric phase of a CMJ the CC is active, the SEC and PEC are being lengthened and as a result elastic energy is stored. In the ensuing concentric contraction, the stored elastic energy is utilized in conjunction with the contractile forces being produced in the CC. The magnitude of the energy returned is proportional to the applied force and induced deformation with reported energy returns of between 65 to 85% in human tendons (35,36). The contribution of the SEC and PEC are minimized if the squat position is held for approximately four seconds prior to the concentric phase (37). The assistance of elastic energy is likely to exist even for the SJ, however when starting from a static squat most of the elastic energy is dissipated as heat energy and therefore the forces associated with the ensuing concentric contraction are primarily attributed to the CC. These factors that occur in most cases during the SJ (extended duration) are thought to be one of the main reasons why SJ is inferior to CMJ performance i.e. minimal

contribution of SEC and PEC. Figure 1 highlights the difference in force profile between a CMJ and SJ.

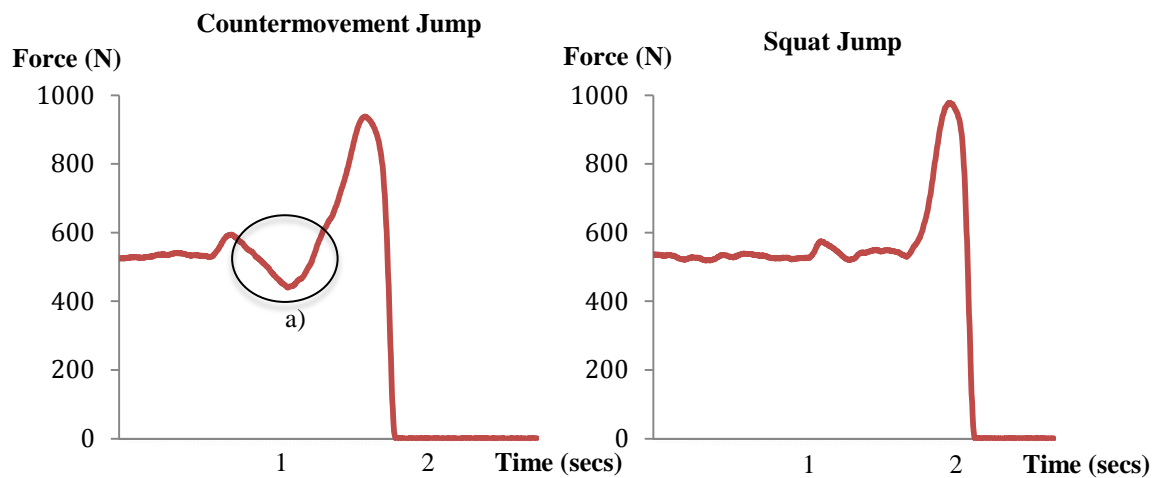


Figure 1: A typical force (ground reaction) profile taken from a force plate during both countermovement and squat jump. The first figure represents a countermovement jump while the second one represents a squat jump. The circled point a) represents the counter-movement (where the child squats and move downwards) prior to the jump. A valid SJ should not have any counter-movement prior to the jump. This is especially important when comparing CMJ and SJ.

Each of the components contributes to total force production during the SSC. However, it has also been observed that the mechanical properties of the SEC and the PEC were not related to each other (38). Among the three components, it is likely that the main contributors of the propulsive force during the SSC lie more with the SEC and the CC due to these components response to deformation and ability to store potential energy. The magnitude of the PEC contribution is currently debatable (39). Nonetheless the following sections discuss how the contributions of the active (CC) and passive (SEC and PEC) components change with maturation and the subsequent effects on SSC ability.

CONTRIBUTIONS OF THE CONTRACTILE COMPONENT AND CHANGES WITH MATURATION

Other than changes in muscle mass and fibre type proportions, the exact changes that occur in the contractile properties of muscle during puberty are relatively unknown as there have been few studies that have investigated these changes.

Activation ability of a muscle refers to the individuals' ability to successfully recruit and activate the motor unit during a movement. When more motor units are able to be activated for a movement, the muscle is able to generate a higher amount of force. It has been consistently shown that youths have a lower voluntary muscle contraction ability or MVC than adults (40–42). Furthermore the magnitude of twitch tension (TT) and maximum voluntary contraction (MVC) are two of the main changes that have been found to increase with age and maturity in children (41,43–45).

Comparisons of the extensor hallucis brevis muscle in male subjects aged between 3 to 22 years of age clearly demonstrated that maximal isometric twitch tensions increased gradually as the individual matured (44). This improvement while gradual at first undergoes a significant marked increase during puberty.

Differences in the maturity and development of the muscle groups can be observed as early as six years of age. Belanger and McComas (46) conducted a study to determine the extent of the changes of contractile properties of the ankle muscle during childhood (6 to 13 years old, $n=10$) and adolescence (15 to 18 years old, $n=8$). A strong and positive relationship was observed in children between age and MVC torque values for both ankle dorsiflexion ($r=0.78$) and plantar flexion ($r=0.76$). The same relationship was also observed for twitch torque and age for both children ($r=0.81$) and adolescent ($r=0.81$). The mean values were approximately double the

values for the adolescent (148.9 N.m) as compared to the younger children (78.3 Nm). However, no significant correlations were found between age and contraction time. The authors concluded that these differences were likely due to the fibre type proportions between the dorsiflexion and plantar flexor muscles (47) and possibly other variables such as active state and myosin light chain phosphorylation(48).

The results of the study by Belanger and McComas (46) further support the concept of age related differences for the contractile components which is also observed for motor unit activation although it was partial. The younger the child, the less voluntary activation the individual has (41,45). Davies et al.(41) observed that there was a relationship in voluntary muscle ability and age ($r = 0.93$). The study also reported that younger children (preadolescent) take a longer time to reach peak tension as opposed to older children (adolescent) and adults when electrically stimulated. Blimkie et al. (45) compared the degree of motor unit activation during voluntary contraction in a group of males between the ages of 10 to 16 years of age. No significant difference in elbow flexor percentage of motor unit activation among the age groups (89.4% versus 89.9%) was found. However, there was a significant difference for the knee extensors (77.7% versus 95.3%). While these findings are conflicting (lower body only) as compared to the other studies, it seems that age-associated variance exists.

When compared to adults, motor unit activation or neurological adaptations are likely to be one of the primary adaptations to strength training adaptations in prepubescents (45,49–51). Ozmun, Mikesky and Surburg (49) used electromyography (EMG) to measure strength training induced changes in prepubescent boys and girls after 8 weeks of strength training. The authors observed significant increases in both maximal isokinetic strength (27.8%) and a corresponding increase in integrated EMG

(IEMG) amplitude of 16.8% with no corresponding significant increase in muscle size suggesting the youths in the study experience a neurological adaptation as opposed to hypertrophy. Ramsay et al. (51) and Blimkie et al. (45) investigated the contribution of changes in motor unit activation to training induced strength increases in prepubescent boys. In both studies, there was a corresponding increase in motor unit activation with strength change, although in terms of percentage increase, motor unit activation was not proportionate and much less than the increase in strength. While many factors (eg, hypertrophy) can contribute to strength training adaptations, in prep-pubescent, motor unit activation are likely to be the primary factor for strength training adaptations.

While some contractile properties gradually increase with age, it has also been suggested that other contractile properties of muscle may have already matured by early childhood (44,51). McComas et al. (44) observed that the twitch contraction times of the younger children (2 to 16 years of age, $n=19$) were already within adult range. The same observation was also observed for the ratio of muscle strength to muscle cross-sectional area, which is used to indicate maturity of the contractile properties. For some muscle groups such as the knee flexors, the ratio remains relatively consistent throughout the different maturational groups. For other muscle groups (e.g. the elbow flexors), the ratio increases as the individual ages through their adolescent years (44). Although the study population was small ($n=19$), the authors did observe a noticeable increase which while inconclusive, does add support to the suggestion of early maturation of the contractile properties. This increase suggests that the growth of contractile force increases at a much greater rate than the increase in muscle mass or the ability to develop voluntary maximum force during adolescent growth.

Stretch reflex potentiation has been observed to be related to age or maturity level (52–54). Grosset, Mora, Lambertz and Perot (54) attempted to observe the development of reflex excitability in prepubescent children. They believed that while the central mechanism that controls stretch reflex in children are mature by the time they reach prepubescence, the mechanically induced reflex only increases with the age of the child. Lin et al. (53) in their study observed that reflex twitch time also improved as an individual matures before it slowly deteriorates again as one grows older. It has been suggested that this increase is due to the maturation of the sensorimotor pathways (53). Other possible contributors to the development of the stretch reflex could possibly be improved spindle sensitivity and/or increased gamma drive (γ) of the muscle spindles (54). Grosset et al. (54) who observed changes in stretch reflex and muscle stiffness in children, also suggested that elastic properties of muscle (and in relation to muscle stiffness) which decreased as the individual matured, was likely one of the major contributors to the development of the stretch reflex due to the correlation between the changes in reflex amplitude and active muscle stiffness. Changes in passive muscle stiffness with maturation are explored in detail in the next section.

CONTRIBUTION OF THE ELASTIC COMPONENT AND CHANGES WITH MATURATION

Due to the importance of the SEE and muscle stiffness in the SSC, it is important to investigate this phenomenon in youth. Previous studies on both human and animal cadavers have shown that there are changes in the elastic properties across ages (38,55–59). Differences in mechanical stiffness between maturational groups can differ from 84% to as much as 334% (56,57). Elliot in 1965 observed that the tensile

strength of the male human tendon for infants was 30MPa and 100MPa in adults, a difference of about 334% (57). This difference in tendon stiffness (patella) reduces as the child matures and by the age of 8 to 9 years has reduced to 94% between men and boys and 84% between women and girls (56). The same pattern was also observed for the Young's modulus with a difference of 99% between men and boys and 66% between women and girls. Young's modulus describes the ratio of stress to strain and refers to the soft tissues ability to withstand changes in length during lengthwise tension. The investigators concluded that an increase in mechanical stiffness between human children and adults are due to the change in stiffness of the tendon microstructures.

Kubo et al. (59) investigated tendon compliance of three different age groups. Significant differences in muscle compliance were found among younger boys, older boys and adult men (Table 2). The tendon structures of the younger children were reported to have the highest compliance, while adults the highest stiffness. Significantly higher tendon stretch was also noted for the younger boys with muscle forces above 0.35 MPa of Fm per muscle cross-sectional area than the other two groups. There was no significant difference when comparing the tendon stretch between the older boys and the adults. Stiffness was defined by Kubo et al (59) in his study as the relationship between the estimated muscle force and tendon elongation during the ascending phase of a leg extension. This observation regarding muscle/tendon compliance in youth is supported by the other studies some of which has been highlighted in Table 3 (53,54,59–62)

Table 3: Stiffness across different age groups

Study	Age Group/Type of Stiffness	Youths	Adult
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Kubo, Keitaro Kanehisa, Kawakami, Fukunaga & Fukanaga, (59)	Age Group	Younger Boys 10.8±0.9 years (n=9),					Older Boys 14.8±0.3 years (n=9)			24.7±1.6 years, (n=14)
	Tendon Compliance (mm/N)	4.1 ± 0.9·10 ⁻² mm/N					2.9 ± 0.1·10 ⁻² mm/N			1.8 ± 0.3·10 ⁻² mm/N
Grosset, Mora, Lambertz and Perot (54)*	Age Group	7 year (n=10)	8 year (n=9)	9 year (n=8)	10 year (n=11)	11 year (n=8).				Adults (n=9)
	Musculo- articular stiffness of the ankle - Passive (Nm/rad)	24±2	25±3	28±2	32±3	36.5±2				74.5±2.5
	Musculo- articular stiffness of the ankle - Active (Nm/rad/%)	17±8	19±5	28±6	29±7	37±4				57±5
Lloyd, Oliver, Hughes, & William (61)	Age Group	7 year (n=10)	8 year (n=9)	9 year (n=8)	10 year (n=11)	11 year (n=8)	12 year (n=8)	13 year (n=8)		
	Mean Relative Stiffness (BM/LL)	56.5	60.3	63.2	64.6	60.8	56.75	59.3		
Lloyd, Oliver, Hughes, Williams, & Hughes (62)	Age Group	9 year (n=8)			12 year (n=8)		15 year (n=8)			
	Absolute leg stiffness (kNm ⁻¹)	17.65 ± 3.22			23.5± 6.02		28.8± 7.45			
	Relative leg stiffness	37.73 8.28			39.03 ± 5.16		40.02 ± 6.91			

*Note: * numbers are approximate from graph.*

Two main reasons have been suggested to explain the increase in tendon stiffness. The first is due to the increase in tendon mass and therefore the anatomical cross-sectional area and tendon length. One of the contributors to increase in tendon size and cross-sectional area is probably the increase in the collagen fibril diameter itself as the individual matures (63,64). This combined with other normal growth changes such as increases in muscle size and mass leads to an increase in the loading on the tendon itself. This combination of growth and loading in turn leads to an

increase in tendon stiffness during maturation (55,56). Other than pure increase in overall mass, other changes have also been noted such as micro structural changes in the tendon (63–68), increases in the fibril density or packing and increases in the cross-linking within the collagen (65,67).

The second reason for increasing stiffness has been attributed to the reduction of collagen crimping, which is another micro structural change of the tendon that contributes to increased stiffness. Collagen fibres are packed in parallel, however they are not straight but wavy (63,69). The crimp is a structural characteristic that refers to the “waviness” of the fibril, which contributes to the nonlinear stress strain relationships. A nonlinear stress strain means that the stiffness of the soft tissues changes with deformation increasing the effect, as opposed to a linear relationship where the stiffness remains constant. As the collagen fibrils becomes “uncrimped”, tendon stiffness increases contributing to the overall stiffness of the tendon. Studies on both humans and animals have shown that there is a reduction in collagen crimping with increased age from youth to adult (70,71).

Aponeuroses are broad flat membranes that are histologically similar to tendons but lack the same level of blood supply and nerves. While tendons connect muscle to bone, aponeuroses connect muscles to the part that moves, be it bone or other muscles. Aponeuroses undergo a similar progressive development from childhood to adulthood (59,72) and are likely to have an effect on the storage of elastic energy. The aponeuroses for those under the age of 16 were found to be slender, shorter and lower volume (72,73). The length of the aponeuroses appeared to increase with age (59). Adults above the age of 40 were consistently found to have much thicker aponeuroses (72). However, the aponeuroses for an elderly group (60 years of age and older) were still particularly well developed and strong. This

observation supports the concept of function over age for the aponeuroses similar to muscles.

In summary, children have more compliant tissues, which stiffen as the individual matures. This is likely to play a role in the SSC ability of youths, the extent of its effect however is unknown. The extent of its trainability is also difficult to assess and differentiate be it due to maturation or training. It should be noted that even research into adult stiffness/compliance and the effect on force production is conflicting. For example, a compliant tissue will store more energy and perform more work if contraction time allows this to occur, whereas when contraction durations are brief as in the case of foot strike when sprinting a stiffer musculotendinous unit that is capable of higher rates of force development is desirable (74–76). It is likely that there is an optimal range of stiffness/compliance that is best for specific tasks, however, more research is needed in this area for both adults and youth. Practitioners might want to take this into consideration when attempting to target and train stiffness in youths.

JUMPING PERFORMANCE OF CHILDREN

The magnitude of potentiation that results from the pre-stretch augmentation cited in the previous literature was from research using mainly adults. Youths, specifically adolescents and preadolescents who have yet to reach full maturity in terms of the development of muscle, tendon and/or reflexes may not have the same level of potentiation. This section explores this theme in more detail.

A number of studies have attempted to compare the jumping performance of children to adults (60,77,78). Wang et al. (77) compared the CMJ performance of prepubescent children (6 ± 0.41 years) to adults (18 ± 0.50 years). The authors found

significant differences in the range of motion for the jump, particularly the depth of the crouch during the countermovement, and a more backward projection (in reference to the line of centre of gravity) during take-off for the prepubescent children. These differences were due to limited range of movement (ROM) during the crouch and what the authors termed as immature joint functions at the knee before take-off (77). Limited ROM in the ankle and knee of the children during the take-off has been observed (44) and is likely indicative of low ability to perform the jump, possibly due to a lack of experience in performing the jump or possibly a physical limitation (less likely). Immature joint function refers to different firing patterns in the children as compared to the adults. To descend into the crouch, children utilised mainly concentric contractions of the joint flexors compared to adults who utilised both concentric contractions in the joint flexors and eccentric contractions in the joint extensors. Such differences were attributed to probable lack of form in jumping strategy due to experience and immature joint function. It is also possible that the lack of coordination could reflect a motor system that is unable to exploit the SSC at the current stage of maturation. Therefore any future studies with children should include a strict familiarisation jump session before the study or prior jump experience to help tackle the lack of form in jumping strategy.

Harrison and Gaffney (78) conducted a study to observe the effects of age and gender on SSC performance. The vertical jump performance of prepubescent children (n=20) consisting of 12 girls (6 ± 0.4 years) and 8 boys (6 ± 0.2 years) were compared to adults (n=22) consisting of 12 females (21 ± 1 years) and 10 males (23 ± 3 years). The SSC potentiation was calculated by comparing the differences between the CMJ and SJ collected from a force plate. The variable used to compare the difference was the ratio of velocity at take-off (ΔV_{TO}) derived from the resultant ground reaction force

on the force plate. The children had a percentage difference in Δv_{TO} of $10.5 \pm 19.7\%$, which was higher than the adult group which had Δv_{TO} of $6.3 \pm 5.6\%$. However, it should be noted that there was great variability in the Δv_{TO} of children and that there was a noticeable difference in scores between boys ($14.5 \pm 24.9\%$) and girls ($7.8 \pm 15.1\%$). It was believed that one of the primary reasons for this difference was due to the poor execution and performance of the SJ, rather than SSC augmented improvement in the CMJ (78).

The researchers proposed three reasons in support of their conclusion. First, a lower or reduction in variability is an indication of motor development, learning and maturity, therefore a greater variation as observed in the children suggested a less developed or mature motor pattern. This variability was again observed in the high Δv_{TO} scores of the SJ for the children. The variability suggested non-optimal performance of the SJ, which was consistent with what was observed by Bobbert et al.(4). The second observation reported was that when comparing the CMJ to the SJ, the children generated a significantly greater relative peak power and force for the CMJ (Table 4). Children also generated significantly lower peak power ($28 \pm 3 \text{ W.kg}^{-1}$) in the SJ when compared to adults ($48 \pm 7 \text{ W.kg}^{-1}$) with similar results for peak force (Table 4). These results suggest lower motor development or mastery of the SJ as compared to the CMJ. The third reason was that significant variations were observed in relative peak force in the SJ for children as compared to adults, which again suggests reduced motor control or mastery of the SJ as compared to the CMJ and that it is possibly age-dependent. In both situations, poor execution of the SJ would increase the ratio of Δv_{TO} between CMJ and SJ.

Table 4: CMJ and SJ variables between Children and Adults

	Countermovement Jump			Squat Jump		
	Peak Force (N.kg ⁻¹)	Peak Power (W.kg ⁻¹)	v _{TO}	Peak Force (N.kg ⁻¹)	Peak Power (W.kg ⁻¹)	v _{TO}
Children	24±4	30±5	1.49±0.21	20.5±1.5	28±3	1.37±0.21
Adult	23±3	53±7	2.43±0.27	23±1.5	48±7	2.29±0.25

Note: The results are approximate from graph and adapted from study. V_{TO} = velocity at take-off

Adapted and derived from Harrison & Gaffney (78)

The variability in jumping performances observed by Harrison and Gaffney which is suggestive of motor control issues related to maturity, has been observed in many other studies on jumping in youth (77,79–83). The variability could also possibly suggest an inability to exploit SSC. However from a coaching standpoint it is likely that motor control or a lack of skill is one of the main cause of variability. Practitioners might want to focus on coaching good jumping and landing technique first (84,85). This would at least eliminate or minimise the variability due to motor control issues and minimise injury risk associated with jumping and landing (86–89). Future research measuring SSC enhancement (SJ vs. CMJ) in youth populations needs to take into account these issues and ensure that the youth subjects are proficient in both methods of jumping.

Most literature comparing CMJ vs. SJ in children has shown the CMJ to be superior, which is to be expected. Observations from recent research (61) has suggested that this might not always be the case, at least for jump height. The jumping performances and SSC ability (CMJ vs. SJ) of children across chronological ages of 7

to 17 years of age were measured. Periods of accelerated adaptation in SSC across the ages of 14 to 16 years of age were observed. However, in that same study it was also observed that children aged 12 to 14 years of age had a better mean SJ jump height (cm) as compared to the CMJ. Children, 15 years of age had the same jump height performance between CMJ and SJ. These children could possibly be post peak height velocity (PHV). While the investigators did not directly address the superiority of the SJ performance as compared to the CMJ, it was suggested that since these ages were post PHV, it could be due to a combination of an increase in maximal isometric strength and concentric strength capability of the subjects as opposed to their SSC ability. Post PHV is a period where it has been observed that there is an increase in strength and muscle mass (90). Since maximal isometric strength regardless of age is believed to be proportional to muscle size (91), it is possible that the greater maximal isometric strength combined with increase concentric ability might explain why the mean SJ jump height performance was better than the CMJ during ages of 12 to 14. It is likely that after the age of 16 years when the children are more mature, they exhibit the expected adult like CMJ vs. SJ jump performance.

SUMMARY AND PRACTICAL APPLICATIONS

Certain neuromuscular and musculotendinous changes do occur with maturation but the influence of these changes on SSC ability of youth is not yet clear. This is because the biological maturity of youth do not necessarily coincide with chronological age and therefore the variability in SSC ability across different populations are likely to exist. No studies have directly investigated SSC augmentation for jumping potentiation across maturation i.e. pre-, at- and post-pubescence. The more compliant tissues evident in children which stiffen as they

mature are likely to play a role in the SSC ability of youths. Thus, measuring SSC potentiation in children and determining if SSC potentiation differs across maturational stages would provide an insight to the optimal windows for trainability of the SSC. Better understanding windows of trainability should enable development of programs for children to optimize their SSC ability as part of long-term development of youth athletes.

Practitioners, looking to assess SSC ability in youth practitioners might want to consider two main factors, the first would be the biological maturity of the youth, second would be the method. Practitioners can use any of the methods highlighted for assessing biological age (Table 1) and SSC ability (Table 2). One of the methods highlighted is the eccentric utilization ratio (EUR) which is essentially the ratio of the CMJ in relation to the SJ, calculated by taking the displacement of the CMJ and dividing it by the displacement of the SJ resulting in a ratio, the EUR. It is expected that adult athletes will have an EUR of at least 1.0 (19) which suggests a poor SSC augmentation ability. A higher EUR would suggest that the athlete possesses a high SSC augmentation ability. The EUR can also be measured using other outputs. If there is access to a force plate or position transducer, outputs such as peak and mean power can be used. The additional advantage of monitoring peak power (EUR) on top of monitoring the SSC augmentation ability will also allow the coach to monitor increases in actual power production with training and as the adolescent matures. This is especially important for monitoring adolescents' who are still growing and are likely to experience changes in mass. Unlike adults, jumping performance in youths is not as stable with great variability and lack of familiarization with the jump itself. For youths, learning effects and the subsequent increased jump efficiency might lead to sudden increase in jump displacement in a very short period of time with or without

the necessary increase in power production capability. These reasons combined could serve as a better monitoring tool of performance to those coaching youths and provides another additional advantage of using EUR peak power.

It is important to note the EUR for children might differ depending on the familiarity with the SJ. One of the consistent observations found in jump studies utilizing youth subjects is the variability in jumping performance, particularly in the SJ owing to motor control issues related to maturity. Without any intervention or specific familiarization, it is likely that children will not exhibit the SJ performances typically observed in adults until they are much more mature leading to a misleading, and usually an inflated value. Therefore, it is recommended that when comparing CMJ and SJ performance in children, a familiarization jump session should be included and research should ideally utilize children with some prior jump experience.

It is suggested that practitioners working with youths looking to develop SSC related ability such as jumping and other plyometric type of training might want to focus on two aspects which combined would likely allow for a better jump performance. The first would be the development of good sound jumping and landing techniques as many of the studies reviewed have highlighted the variability of jumping performance of youth. The development of good technique will minimise the variability and improve the coordination of the jumping pattern (84,85). This might possibly lead to an improvement in the motor pattern to better exploit SSC. A sound muscle strengthening program concurrent or before a serious plyometric program might also lead to an improvement. The improvement in the jumping technique and improvements in muscular strength not only allow for a better jump performance but also minimise the risk of injury to the youth.

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