Understanding Stretch Shorten Cycle Capability in Adolescence Across the Different Maturational Stages.

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ATTESTATION OF AUTHORSHIP

I hereby declare that this submission is my own work and that, to the best of my knowledge and belief, it contains no material previously published or written by another person nor material which to a substantial extent has been submitted for the award of any other degree or diploma of a university or other institution of higher learning, except where due acknowledgement is made.

This thesis fulfills the Auckland University of Technology Master of Sport and Exercise guidelines by constructively critiquing previous literature pertinent to the stretch shorten cycle in youth. This thesis provides a broad experimental application to this growing body of knowledge.

Sofyan Sahrom
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PUBLICATIONS AND PRESENTATIONS

The publications listed below are a result of the research conducted in partial fulfillment of the Master's degree in Exercise and Sports

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The student was the primary contributor (90%) of the research in this thesis and the subsequent analysis and interpretation of the research results. The student was also the main contributor (90%) to the writing of research ethics applications, progress report and papers, as well as being the sole presenter of the research results at conferences. All co-authors have approved the inclusion of the joint work in this thesis.

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Date:

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ABSTRACT

Stretch-shorten cycle (SSC) capability is fundamental to many sporting activities. To date, there have been numerous studies on the SSC potentiation in adults, however, there are very few studies of SSC potentiation in youths. For youths, the biological maturity may not necessarily coincide with the chronological age. Biological maturity for youths can be classified as either in the pre-puberty, puberty or post-puberty maturation stage. The limited literature to-date has shown that youths at different biological maturity stages have different muscle characteristics and development. This study aims to investigate SSC potentiation at the different biological maturity stages. Such a study will provide evidence as to a possible window of trainability for the development of SSC. Using a force plate, this study measured and compared the countermovement jump and squat jump capability of a total of 209 youths (male, *=101*, females, *=108*) aged between 11 to 17 years of age, from the Singapore Sports School. These youth were categorized into the three maturational groups. When compared, gender differences were observed and these differences increased with maturity. Differences in SJ performance across the maturational groups were different as compared to CMJ performance, where no significant maturational differences were observed. It was observed that there was a significant difference in the eccentric utilization ratio for peak force across the maturational stages for both genders. However differences for jump height were not significant. It would seem that concentric force/power capabilities (i.e. SJ performance) are more likely to be influenced by maturation than eccentric force and power. Furthermore it appears that the eccentric capability and thus SSC augmentation is optimal around pubescence and diminishes to some extent with maturity. These changes are most likely best explained by growth related factors (i.e. increase in bone length and loss of tissue extensibility around PHV) as well as maturational factors (i.e. changes in tissue compliance/stiffness). Given these findings it would seem that pre-pubescent athletes would react favorably to plyometric type training given their eccentric force power capability and proposed compliance of their tissues. This study concluded with recommendations for youth coaches to consider. Since vertical stiffness was found to increase with age, a good stretching routine is recommended during this sensitive growth period. Coaches might want to also consider focusing on eccentric training that focuses on full range of motion, correct alignment and stability.

CHAPTER 1: INTRODUCTION

1.0 Brief Background

The comparison of squat jump (SJ) to the countermovement jump (CMJ) provides an indication of the stretch-shorten cycle (SSC) potentiation of the individual (Komi & Bosco, 1978; McGuigan & Doyle, 2006; Walshe, Wilson, & Murphy, 1996; Young, 1995). SSC refers to muscle action where there is an initial active pre-stretch of the muscle or lengthening contraction (eccentric phase) which is then followed immediately by a concentric muscle contraction (Komi & Nicol, 2000; Komi, 1984; Norman & Komi, 1979). This type of muscle action is believed to be responsible for the superior jump performance observed in CMJ compared to SJ (Bobbert, Gerritsen, Litjens, & Van Soest, 1996).

While a great deal of research investigating SSC and both SJ and CMJ performance in adults has been done, there is not much literature investigating these two jumps in pre-adolescent and adolescent youths or SSC in youths. Unlike adults, the biological maturity of youths does not necessarily coincide with their chronological ages and can differ by several years (Armstrong & Welsman, 2002; Bar-Or, 1996; Malina, 2001). This variance is even more magnified when considering the fact that youths are still developing and undergoing different maturational developments at different times. These different developing maturational stages bring with them changes that add to the variances jump performance and possibly also SSC potentiation.

2.0 Purpose of Research

Differences other than the muscle size and amount of muscle fibres exist between youths and adults. Based on Hill's model (1938) of muscle function on the SSC, these differences between youths and adults also suggest a reduced SSC potentiation in youths. By measuring the SSC potentiation in children across the different maturational stages, we are able to investigate whether differences exist and among which age and maturational groups which can also suggest optimal window periods for trainability of the SSC.

3.0 Research Questions

The main research question of this thesis is whether there is a difference in the SSC potentiation in youths as compared to adults. If differences do exist, what exactly are the observable differences?

- If there is a difference between the different maturational stages, where is the difference (jump difference) the greatest?
- Is there a difference in the development of the SSC potentiation and jump variables between genders?
- Is there a difference in the other jump variables between CMJ and SJ across the different maturational stages?

4.0 Definition of Youths

For the purposes of this study, youths are defined as all individuals chronologically under the age of eighteen; and include adolescents, preadolescents and children. Adolescents are defined as youths that are at the onset of puberty, have developed secondary sex characteristics and have reached maturity (Malina, Bouchard, & Bar-Or, 2004). They are chronologically between 13 years of age to 18 years of age for males and 12 years of age for females. Preadolescents are youths between the ages of 8 to 13 for males and 8 to 12 for females (Malina, Bouchard, et al., 2004; Malina, 2001). All youths under the age of 8 are simply defined as children.

When the terms adolescent, preadolescent and children are used in this study they are referring to chronological age of youths, while pre-puberty, pubertal or peri-pubertal and post-puberty refer to estimated biological age.

5.0 Significance of Study

The advantages that SSC offers have lead many coaches to incorporate training drills that aim to develop the SSC potentiation for both adults and youth athletes. However, unlike speed, reaction, motor control development and even strength where suggested window periods of trainability exist as part of a long term development (LTD) of a youth athlete, there have not been many guidelines on developing the SSC potentiation or the optimal window for the trainability of it.

Any difference observed in this study of the SSC potentiation of the youths across different maturation stages, and, gender would provide more insight into the development of the SSC potentiation of youths such as possible window periods. The information gathered might serve as a good guideline that can assist in the planning and design of training programs for youths at the different maturational stages as part of a holistic and LTD.

1.0 Introduction

The biological maturity of youth does not necessarily coincide with their chronological age and can differ by several years. Therefore variability in SSC ability across different age groups are likely to exist. The results reported in the research to-date are, in some cases, conflicting. This chapter will begin with the topic of growth and maturation of youths especially the different maturational stages. To understand the possible difference in SSC ability between youth and adults, the mechanical and electrophysiological basis of SSC potentiation will be reviewed before proceeding to review the jumping performance of youths.

2.0 Growth and Maturation of Youths

Growth refers to the progressions in the size and shape of the body, its organs and circulatory systems until adulthood is reached (Malina, 2001; Tanner, 1962). It follows a definite sequence during puberty which starts from the outside in although the exact timing and rate of this sequence differs from person to person. Maturation refers to the process whereby humans progress from childhood to adulthood. The timing and tempo of this process varies from individual to individual (Malina, Eisenmann, Cumming, Ribeiro, & Aroso, 2004; Malina, 2001). Timing describes how chronological age relates to biological age, while tempo refers to the rate of how quickly children pass through their growth spurts to attain sexual and somatic maturity (Malina, 2001). The exact definition of maturation will vary depending on the biological system used, for example, skeletal versus sexual maturity. Nevertheless, the more commonly used maturity indicators used in studies are reasonably well related and attempt to measure the biological age of the individual. For this literature review, the definition and discussion of growth is limited to the physical stature and weight, while maturation focuses on the biological age of the individual.

2.1 Maturation Stages

Spurts in growth and performances are likely to occur during adolescence (Malina, 2001). 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 tempo 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. An example of this can be seen in Figure 1.

Figure 1. An illustration of growth variations that co-exist in children. All three boys are chronologically 13 years of age, however in terms of biological age, they are very different with the tallest boy who is already in his late puberty.

Pubescents are defined as children that are at the onset of puberty, have developed secondary sex characteristics and have reached maturity (Malina, 2001; Tanner, 1962). Also known as adolescents, they are usually chronologically between 13 years of age to 17 years of age for males and 12 years of age to 16 years of age for females. One of the most recognised event signifying children in this maturation stage would be the increase in stature or adolescent growth spurt. During this adolescent growth spurt, the height (increase in) velocity increases and peaks and is commonly known as peak height velocity (PHV). PHV values ranges from 5.4 cm to 11.2 cm per year for females and 5.8cm to 13.1cm per year for males (Neinstein & Kaufman, 2002).

Pre-pubescents 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 (Malina, Bouchard, et al., 2004). Post-pubescents 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 (Malina, Bouchard, et al., 2004). Ideally, children should be classified and trained according to their biological maturity or developmental stages.

Therefore for this literature 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 shall be referring to individuals as described above.

3.0 <u>Stretch Shorten Cycle</u>

In most human locomotion, such as running, hopping and jumping, muscle contraction is usually typified by a combination of eccentric-lengthening followed immediately by a concentric-shorten 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 (Komi, 1983; 2000). According to Komi and Gollhofer (1997) an effective SSC will require 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 also described as a countermovement; 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 utilised methods to demonstrate the SSC augmentation is by comparing a vertical jump that is preceded by a countermovement (i.e. a countermovement jump - CMJ) to a jump without a countermovement (i.e. a squat jump - SJ). In most studies using this approach, the CMJ has led to better jump performance than the SJ by between 18% to 30% in adults (Bobbert, Gerritsen, Litjens, & Van Soest, 1996; Komi & Bosco, 1978). While the enhancements from the potentiating effects of the SSC are certain, the underlying mechanisms responsible for this potentiation have been the source of debate for many years. These different viewpoints were summarized in an article and subsequent discussions by (van Ingen Schenau, Bobbert, & De Haan, 1997a; van Ingen Schenau, Bobbert, & de Haan, 1997b). Four possible explanations for the SSC were presented. First, it was proposed that SSC enhancements were due to the storage and utilization of elastic energy stored 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, was contractile history; it was theorized that alteration of the properties of the contractile machinery occurred during the prestretch of the active muscle, which subsequently enhanced the concentric contraction. The contributions of the spinal reflexes offer the fourth possible explanation for SSC potentiation. Spinal reflexes that are triggered by the prestretch of a muscle during a countermovement help to increase the muscle stimulation during the concentric phase (Dietz, Schmidtbleicher, & Noth, 1979). The prestretch also allows a longer latency response which is also believed to increase the muscle stimulation (Jones & Watt, 1971). The subsequent discussion and commentary by van Ingen Schenau et al., (1997b) suggested that while these explanations are valid and possible mechanisms for the enhancement, there is still a lack of consensus on the exact mechanisms for it. Therefore it would be very difficult to provide a clear explanation of SSC potentiation and is likely to continue as a source of research and debate especially considering its importance in sporting movement.

3.1 Measuring Stretch Shorten Cycle

Irrespective of the underlying mechanisms, SSC potentiation is undeniable and different approaches have been developed to measure SSC enhancement by comparing the CMJ to the SJ (Komi & Bosco, 1978). One of the most utilized methods to demonstrate the SSC augmentation or potentiation is by comparing the jump difference of the CMJ to the SJ during a vertical jump. The difference in jump performance has been shown to differ by between 18% to 30% in adults in favour of the CMJ (Bobbert, Gerritsen, Litjens, & Van Soest, 1996; Komi & Bosco, 1978).

Because the CMJ utilizes a countermovement while the SJ does not, in theory the difference between the two jumps is the use of a SSC augmentation. Therefore various test methods of measuring SSC potentiation has attempted to measure the jump difference and in turn quantify it. These field based tests are designed to be practical and suitable for monitoring training. Perhaps the simplest of these methods is the reactive strength method (RS) which is essentially comparing the difference (cm) between the CMJ and the SJ. Table 1 below highlights some of the common methods of measuring SSC augmentation during jumps.

Table 1: Different methods of measuring utilisation of elastic energy during jumps.

Methods	**Formula**	**Units**
1) Direct Comparison	CMJ height – SJ height	cm
2) Reactive Strength Index (RSI)	Jump Height / Time	cm
3) Prestretch Augmentation (PSA)	[(CMJ - SJ)/SJ] x 100	%
4) Eccentric Utilization Ratio (EUR)	CMJ ÷ SJ	value

Note: Adapted from Harrison & Moroney, (2007); Komi & Bosco, (1978); McGuigan et al., (2006); Walshe & Wilson, (1997); Young, (1995)

3.1.1 Direct Comparison

In (1978), Komi & Bosco attempted to measure SSC enhancement by measuring the jump height between three different jumps, the SJ, the CMJ and Drop Jump (DJ) at various height (cm). In this study, the investigators measured jump height (cm) based on the rise of the individual's body's center of gravity (COG) and found that the CMJ produced better jumps (13-21%) as compared to SJ. This direct comparison between jumps is probably one of the earliest and simplest methods to measure SSC enhancement. The simplicity of this method probably also allows comparison between studies. The result does not give a perspective on how much the "increase" in performance was due to a pre-stretch.

3.1.2 Reactive Strength Index

Reactive Strength Index (RSI) was developed as part of the Strength Qualities Assessment Test (SQAT) used at the Australian Institute of Sport (Young, 1995). It was developed to differentiate the different strength qualities of track and field athletes and be more sensitive to the nature of the event (sprints vs. jumps). The

RSI unlike the other methods utilizes the DJ instead, thus the RSI attempts to observe the athlete's ability to withstand and use the stretch loads from a drop jump. Young, (1995) defined reactive strength as the ability to quickly change from an eccentric to a concentric contraction. The RSI is calculated by dividing the height of the jump from a DJ and dividing it by the time in contact prior to the takeoff (jump)(mm/ms).The test can be conducted at different drop heights so as to increase stretch loads on the leg extensors. Therefore if the RSI increases or maintains as the drop height increases, it can be assumed that the athlete has sound ability for his reactive strength.

3.1.3 Prestretch Augmentation

The Prestretch Augmentation (PSA) method was first designed by Walshe, Wilson, and Murphy, (1996) to estimate the increase in performance derived from a pre-stretch based on the difference in jump height. Jump height was measured using a sliding marker placed on the shaft of a Plyometric Power System (PPS) (Plyopower Technologies, Lismore, Australia). Prestretch augmentation was expressed as a percentage increase in performance over the squat jump. It was found to have a negative correlation with stiffness ($r = -0.50$, $p > 0.05$). Using percentage is a user friendly way to describe how much "increase" in performance resulted from the pre-stretch.

3.1.4 Eccentric Utilisation Ratio

Another method of quantifying SSC augmentation is using the eccentric utilisation ratio (EUR). It is essentially the ratio of the CMJ in relation to the SJ (McGuigan et al., 2006). In normal circumstances, this ratio should exceed one. Since it is just a ratio, the EUR method can be used with either jump height or elevation (measured in centimeters) and peak power measured using the force plate. Similar to the pre-stretch augmentation method, it is a user-friendly way to describe the "increase" in performance due to a pre-stretch. No gender specific difference was observed and this ratio has been found to be a useful indicator of SSC performance between various sports. It is sensitive to changes in the type of training that the athlete is going through especially across seasons. Another advantage of the EUR is that it results in very little fatigue and insignificant impact on the athlete training program since only one performance of each jump is required.

Most adult athletes will have an EUR of at least one (McGuigan et al., 2006). A high EUR will mean that the ability or SSC augmentation of the athlete is high. Due to its simplicity and flexibility, the EUR has been proposed as a test for SSC augmentation in various sports and during different phases of training. McGuigan et al., (2006) observed that when compared across five different team sports, [Australian rules football (1.10 ± 0.08), field hockey (1.02 ± 0.13), rugby (union) (1.13 ± 0.14), softball (1.03 ± 0.09) and soccer (1.14 ± 0.15)], athletes from the sports of Australian rules football, rugby and soccer had greater EUR (jump height) values when compared to the other two whose EUR was just slightly above one. The same comparisons were also found when using peak power. These are expected when comparing the nature and likely greater reliance of stretch shorten activities of the three sports (Australian rules football, rugby and soccer) as compared to the other two sports (field hockey and softball) suggesting its suitability to measure differences in training states (McGuigan et al., 2006).

3.2 Measuring Stretch Shorten Cycle in Children

There has been a great deal of research that has investigated CMJ and SJ performance in adults. However, there has been less literature that has investigated these jumps and the EUR in pre-adolescent and adolescent youths. Unlike adults, the biological maturity of youths does not necessarily coincide with their chronological ages and can differ by several years (Armstrong, &Welsman, 2002; Malina, 2001). Youths undergoing puberty experience many physiological changes, which include changes to their muscular and neuromuscular systems (Malina, 2001). The physiological changes during these periods of maturity are likely to be contributing to the age associated variations in jumping performances between children of different age groups, maturity level and gender (Malina, 2001; Temfemo, Hugues, Chardon, Mandengue, & Ahmaidi, 2009).

Currently there have not been many studies that that have observed specifically the SSC potentiation ability in youths and at different stages of puberty. A few studies, especially recent ones, have attempted to look at the SSC capabilities of children (boys) at different chronological ages and have suggested the possible existence of the windows of trainability (Harrison & Gaffney, 2001; Lloyd, Oliver, Hughes, & Williams, 2011). Lloyd et al. (2011) observed an increased adaptation to jumping performance during the ages of 10 to 11 and 12 to 13 which coincided with an increase in reactive strength also at the specific age of 10 to 11 and 12 to 13. Since reactive strength is defined as the ability to change quickly from an eccentric to a concentric contraction, it does suggest that there is an increase in SSC (slow) potential during these two chronological age periods. Since the biological maturity of youth does not necessarily coincide with chronological age especially during the ages of 10 to 13 for boys (Armstrong & Welsman, 2002; Bar-Or, 1996; Malina, 2001), it would be of benefit to compare SSC augmentation also with maturation as it might provide a deeper insight into windows of trainability for plyometric activity. With this in mind, this chapter will first look at the mechanical and electrophysiological basis of SSC potentiation in particular the storage of elastic energy and reflex potentiation, then discuss the applicability and the developments of these determinants to youth and finally discuss the relationship to jumping performance.

4.0 Development of tension/force in the muscle - Hill's model of muscle function

A.V. Hill in his original experiment on the thermodynamics of muscle contraction in 1938, 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 as shown in Figure 2 (Edman, Elzinga, & Noble, 1982; Forcinito, 1997) 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 made up or formed by 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 fibres- 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. The force that it contributes is exerted by a relaxed passive muscle when it is stretched beyond its resting length. Muscle connective tissues such as the perimysium, epimysium and endomysium are examples of the PEC.

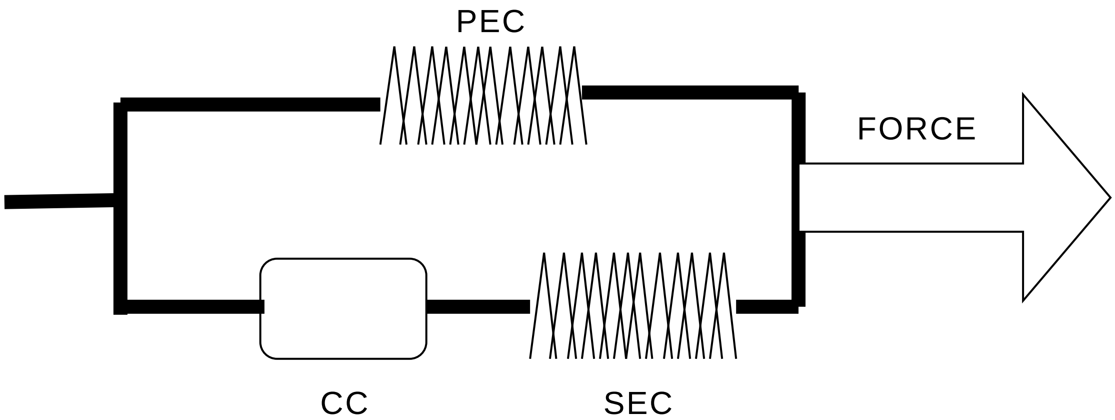

Figure 2: Three component model of muscle contraction and tension, the contractile component (CC), series elastic component (SEC) and the parallel elastic component (PEC) Taken from Edman et al., (1982); Forcinito, (1997); Hill, (1938).

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 elastic energy is utilised in conjunction with the contractile forces being produced in the CC. The magnitude of the energy released is proportional to the applied forced and induced deformation. The contribution of the SEC and PEC are especially minimized if the squat position is held for approximately four seconds prior to the concentric phase (Wilson & Flanagan, 2008). 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 which occur in most cases during the SJ (extended duration) is thought to be one of the main reasons why SJ is inferior to CMJ performance i.e. minimal contribution of SEC and PEC.

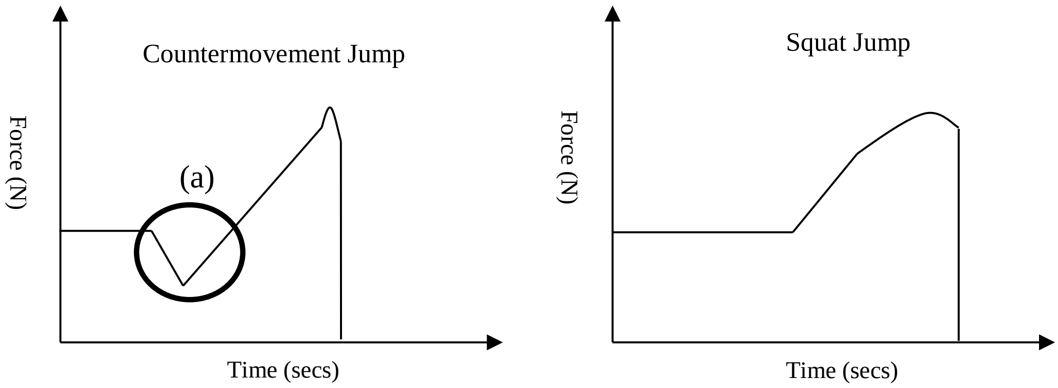

Figure 3: A typical force profile taken from a force plate during both countermovement and squat jump. The first figure represents a countermovement jump while the second one represents a squat jump. The circle (a) represents the counter-movement (where the child squats and move downwards) prior to the jump.

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 (Kubo, Kanehisa, & Fukunaga, 2001). 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 (Turner & Jeffreys, 2010).

5.0 Determinants of SSC Augmentation

5.1 Contribution of Elastic Energy and Components

Stored elastic energy (SEE) is generally accepted as one of the major mechanisms of augmentation in the SSC (Cavagna, Saibene, & Margaria, 1965). SEE is generally believed to be a valid amplifier of power with a prestretch (Jacobs, Bobbert, & van Ingen Schenau, 1996; 1993). While the exact role of SEE during SSC is debated in the literature, there is no study that denies its place in force potentiation during SSC. Based on literature there are two possible different roles of the SEE.

SEE contributes to force production through the release of energy during recoil that has been stored when it was resisting the deformation (Kubo, Kawakami,

& Fukunaga, 1999; Lichtwark & Wilson, 2005). It is hypothesized that the magnitude of storage and subsequent release of elastic energy is equivalent to the amount of deformation that the muscle or tendon undergoes, more particularly the tendon during the eccentric phase. Elastic energy is believed to be stored in all three components of the muscle model though at different levels (Biewener & Roberts, 2000). The SEE that is released during the concentric phase is added to the force production and therefore contributes to the superior jump performance of the CMJ. This theory is supported by numerous researchers who performed studies with jumping (Bosco et al, 1987; Fini, Ikegaw & Komi, 2001; Kubo, Kawanaki & Fukunaga, 1999; Lichtwark & Wilson, 2007), sprinting and distance running (Bobbert, et al. 1996).

There are researchers who do not believe that SEE is the reason for the superior jump performance except possibly during maximal effort (Lichtwark & Wilson, 2005). It has been suggested instead that increased efficiency through the reduction in metabolic cost of movement is the likely cause of the superior jump performance (Bobbert, Gerritsen, Litjens, & Van Soest, 1996; Lichtwark & Wilson, 2005). According to these researchers, this efficiency is due to the inverse relationship between the release of SEE and the force production in the CC. This theory is supported by other researchers who have suggested that the fibres of the CC contract at speeds that are different from those at the muscle tendon unit, which means that some fibres are deactivated in the presence of SEE and therefore are not used during contraction (Lichtwark & Wilson, 2007). However, none of these studies deny the existence of SEE and its place in SSC.

Tendons have been constantly described as the key component of the SEC due to the high level of viscoelasticity and muscle stiffness (Keitaro Kubo et al., 2007; Lichtwark & Wilson, 2007). It is very likely that tendon recoil contributes to both energy conservation and power production due to its response to load (G. A. Lichtwark & Wilson, 2007). The efficiency of tendon at SEE is considered high where it is estimated that at least 85% of the stored energy can be returned (Bennett, Ker, Imery, & Alexander, 1986; Pollock & Shadwick, 1994). Recent *in vivo* studies have even suggested that the efficiency can possibly be higher, between a range of 65 to 90% (Lichtwark & Wilson, 2005; Maganaris & Paul, 2000). Tendon elasticity and its response to load can be best described as “strain-rate dependent” or the rate at which the tendon is being stretched or loaded. Tendons will be much stiffer, stronger and absorb much more energy when it is quickly stretched as opposed to it being stretched slowly. Explosive sudden movements such as jumping, bounding, push-off and sudden sprints are movements that are likely to benefit from this characteristic of the tendon complex.

It has also been observed that elite athletes are significantly more able to store elastic energy in their tendons as compared to untrained subjects due to a higher stiffness level (Arampatzis, Karamanidis, Morey-Klapsing, De Monte, & Stafilidis, 2007; Hobara et al., 2008; Häkkinen, Alén, & Komi, 1984). This partly explains the goal of athletic training which is to develop the transfer of energy through these structures. Tendons being living tissues adapt to training and undergo remodelling and increase stiffness as a result. However, the exact effects of exercise on the tendon, especially in terms of the structural and chemical parameters are still not well understood. Literature suggests that increases in the tendon stiffness in adults is not likely due to the increase in tendon hypertrophy or collagen concentration alone and is pointing more towards mechanical parameters (Buchanan, 2002; Buchanan & Marsh, 2001; Kjaer, 2007; Woo et al., 1981).

Tendons strain-rate dependent response can be attributed to its primary make-up of 30% densely packed collagen and 2% elastin, which are embedded in an extracellular matrix. The collagen is made up of mainly Type I collagen (97 to 98%) and form fibrils. The fibrils in turn are packed in parallel to form fascicles, which are also packed in parallel to form the tendon fiber (Raspanti, Ottani, & Ruggeri, 1990). It is this parallel arrangement, which is usually along the muscle’s line of action and the cross-link between them that makes the tendon stronger than muscle and allows it to transmit forces effectively (Elliot, 1965; Raspanti et al., 1990). The fibres in the centre are also thicker while those on the ends are thinner and more helical. Tendons ability to detect and respond to load is believed to be due to the calcium (Ca^{2+}) signalling (influx, efflux and diffusion) and intercellular communication through gap junctions (McNeilly, Banes, Benjamin, & Ralphs, 1996; Wall & Banes, 2005).

Dermatan sulfate and chondroitin sulfate are two other components of tendon that are likely to play different roles in the tendon’s ability to withstand deformation. Dermatan sulfate is believed to form associations between the fibrils therefore strengthening it. It is the associations and inter fibrillar bridges created that are believed to contribute to the parallel arrangement of fibrils (Zhang et al., 2005). Chondroitin sulfate is believed to occupy space between the fibrils and keeps them separated. This separation is believed to also help the fibrils withstand deformation (Aro et al., 2008).

Series elastic storage of energy is not only limited to the tendon. The aponeurosis, a sheet of connective tissue has also been suggested as another possible storage site for mechanical energy (Azizi, Halenda, & Roberts, 2009; Roberts, Marsh, Weyand, & Taylor, 1997). Aponeuroses are also made up of collagen and histologically similar to tendons. Just like tendons they are also arranged in line with the muscle line of action (Azizi et al., 2009; Scott & Loeb, 1995). Many consider the aponeuroses as an extension of the tendon and they were originally believed to be loaded similarly (Brown, Scott, & Loeb, 1996). Other authors disagree however and suggest that the aponeuroses can be loaded biaxially, both longitudinally (parallel) and transverse (perpendicular) (Roberts et al., 1997; Scott & Loeb, 1995). Recent studies on *in situ* aponeuroses have found it to function as an efficient spring in both directions (Azizi et al., 2009; Azizi & Roberts, 2009; Scott & Loeb, 1995). It is likely that the aponeuroses is another key site for SEE in many movements especially more so for proximal musculature that contains lesser or shorter identifiable tendons.

Outside of the tendon the biggest contributor to SEE is believed to be from a fascinating and huge protein found within skeletal muscle, aptly named titin, which was first discovered in 1997 by Maruyama. A seminal study performed by Magid and Law in (1985) demonstrated convincingly that the origin of passive muscle tension was within the myofibrils themselves. This is extremely significant because before the study, most had assumed that the extracellular connective tissue such as the perimysium, epimysium, and endomysium caused the majority of its passive properties. However, Magid & Law, (1985) found that the source for passive force bearing within the muscle was within the normal myofibrillar structure not extracellular, as had previously been supposed and supported by later studies (Horowits, 1992; Tskhovrebova & Trinick, 2002). Titin appears to provide a connection between the thick filaments and the Z band, which keeps the myofilaments aligned and contributes to the banding structure of skeletal muscle.

Because the titin connection provides a continuous link along the sarcomere, it contributes significantly to the passive tension of muscle.

Besides its contribution to passive tension, titin also functions as molecular springs thereby providing the relaxed myofibrils with elasticity (Labeit & Kolmerer B, 1995; Maruyama, 1997). Labeit and Kolmerer (1995) described the domain architecture of titin, which helped explained titin elasticity. A segment of titin, which is confined to the I-band, is made up of two regions, the PEVK region and the Ig domains. The expressions of the regions are dependent on the muscle type (skeletal vs. cardiac). N2-A isoforms are found for skeletal muscle sarcomeres while cardiac cells co-express N2-B isoforms and N2-BA isoforms variants. The PEVK region is rich in proline, glutamate, valine and lysine. During quick length change of muscle, the PEVK domain has been found to interact with the thin filament, which leads to a viscous force component at the very least in cardiac muscles. This is especially so during increased stretch rate, where *in situ* (skeletal muscle) the PEVK region has been found to be the main contributor to titin extensibility. This contribution has been suggested to be due to the “enthalpic” component of elasticity in the PEVK region during electrostatic and hydrophobic interactions. This elasticity in turn contributes to the extensibility of myofibrils at higher stretch lengths. The Ig-domain are serially linked immunoglobulin-like modules that assemble into seven stranded beta-barrels and behave as entropic springs. This behaviour of the Ig-domain is likely to be the main contributor of passive force development of the myofibrils during sarcomere extensions. Besides its contribution to a passive mechanical action, titin is also believed to play an active role during contraction (Labeit & Kolmerer B, 1995). It has been suggested that titin could stiffen upon activation before the sarcomere starts to increase in stiffness (Wang, McCarter, Wright, Beverly, & Ramirez-Mitchell, 1991). It has been observed that during contraction when the intracellular Ca^{2+} increases, it appears to bind to titin and increase titin’s contractile force. Therefore it is possible that Ca^{2+} affects titin stiffness.

Muscles are also able to store energy over short distances where cross-bridge cycling does not occur. This energy is stored in the SECs within the muscle, which includes the cross-bridges and the actin and myosin filaments. Studies show that muscle fibres can be stretched by about 3 to 5% depending on the fibre arrangement before cross-bridge cycling occurs (Flitney & Hirst, 1978). Just like all viscoelastic tissues, it will be stiff when it is stretched more rapidly. However, the general belief is that muscle is not as efficient with the return of energy as compared to tendon. A study on activated rabbit muscle found that only 60% of the energy was returned (Best, McElhaney, Garrett Jr, & Myers, 1994). The remaining energy was likely to be converted to heat and dissipated. Therefore while it is acknowledged that the muscles CC stores some elastic energy, it does not seem to play a major role in SEE.

5.2 Contributions of the Contractile Components

It is likely that the exact contribution of the CC to SSC augmentation is dependent on the movement and more specifically the movement strategy. During a large movement the length change can occur in the CC and/or the SEC. In movements where there is very little tension or resistance in the eccentric phase, the length change occurs in the CC itself with very little crossbridge interdigitation - e.g. large amplitude movements. In muscles where there is a great amount of active tension or resistance in the eccentric phase, the length change tends to take place in the SEC structures and tissues, this in turns loads the tendonous structures and increases the storage of elastic energy. For example, it has been proposed that for rapid small amplitude movements, the CC stays relatively isometric. A relaxed and semi-lengthened CC will be very compliant i.e. passive stiffness. The muscle is significantly stiffer when the CC is activated i.e. active stiffness (Zatsiorsky & Kraemer, 2006). The greater the contraction of the CC, the greater the muscle stiffness will be. Therefore movements with a much greater range of motion and contraction will benefit from this aspect of CC contribution. It has been theorized that with training, muscle stiffness can far exceed the stiffness of tendons (Kyröläinen, Komi, & Kim, 1991; McBride, McCaulley, & Cormie, 2008; Potteiger et al., 1999; Rimmer & Sleivert, 2000; Schmidtbleicher, Gollhofer, & Frick, 1988; Spurrs, Murphy, & Watsford, 2003)

With motor unit activation, the muscle on the whole begins to develop tension and subsequently contracts (if it is allowed). Contraction or shortening of the fibres occurs when one or both ends are not fixed and allow the muscle to shorten. When the ends are fixed or during movements where the muscles are activated but cannot shorten, an isometric contraction occurs (Gordon, Huxley, & Julian, 1966a; ter Keurs, Iwazumi, & Pollack, 1978). It has been observed that in such situations, some of the sarcomeres, of the muscle shorten, which further stretches other sarcomeres and stretching elastic elements of the muscles increasing the tension measured at the tendon (Gordon, Huxley, & Julian, 1966b). The greater the contractile force that the muscle can generate, the more that it will resist lengthening and thus have a higher stiffness. Therefore in many SSC movements, the muscles will be activated isometrically to remain highly stiff, the changes in length is likely to be in the tendinous structures. The subsequent recoil of the tendon will provide the greatest shortening of the muscle tendon unit during the fast propulsive phase of the SSC movement.

The prestretch of active muscles during SSC movements is believed to lead to an alteration of the properties of the CC. A greater alteration occurs with an increased speed of stretch (Bobbert, et al, 1996). The alteration is due to the cross-bridges of the active muscles that become “stuck” after the lengthening. These “stuck” cross-bridges take more time to release contributing to force production when followed by an isometric or concentric action (Lee, Joumaa, & Herzog, 2007). This is supported by studies, which have also shown that the force production of a muscle fibre that has “tensed” can be further improved by a prestretch (Edman, Elzinga, & Noble, 1982; 1978). Force production by tetanised single muscle fibres have also found to be augmented by a prestretch. In both examples, the enhancements were found to be linked to the speed of prestretch where an increase in speed would lead to an increase in enhancement. This enhancement however, will decrease when the duration between the prestretch and the following muscle contraction increases and the muscle probably reverts to its original state (Kubo et al., 2000; Edman, Elzinga, & Noble, 1982; 1978)

Contribution from the stretch reflex is another possible mechanism that explains the SSC enhancement even though the exact contributions of the stretch reflex directly to SSC and at which phase of the SSC is still unclear and debated (van Ingen Schenau et al., 1997a). In 1979, Dietz, Schmidtbleicher and Noth, observed high stretch reflex activity after a stretch of an active muscle. The stretch reflex refers to the muscles response to lengthening, as muscle spindles residing within the muscles are sensitive to the length changes in the muscle tendon complex. If the stretch in a muscle is rapid and of small amplitude, such as short range SSC movement, the same muscles are activated via alpha motor neurons to contract forcefully as observed in increased concentric work output, with an increased in stretching and pre-activation (Dietz, Noth, & Schmidtbleicher, 1981; Dietz et al., 1979).

Nicol and Komi in 1998, studied the contribution of the stretch reflex to the force enhancement at the athlete tendon (ATF) during passive dorsiflexion stretches (*in vivo*). During a slow single stretch there was a linear ATF increase but no EMG response was detected. However, for faster single stretch and multiple stretch, clear increases in ATF was observed 13 to 15 ms after the EMG response which indicated the stretch reflex response (Nicol & Komi, 1998). Consistent with this observation, greater force was also observed from movements with greater stretch loads (Komi & Gollhofer, 1997).

The stretch reflex is likely to be influenced by the level of training as it has been observed to be higher in trained subjects as compared to untrained subjects (Casabona, Polizzi, & Perciavalle, 1990; Komi & Gollhofer, 1997; Voigt, Chelli, & Frigo, 1998). Casabona et al. (1990) compared the stretch reflex (using the H-reflex technique) of the soleus and lateral gastrocnemius muscle between three groups, sprinters, volleyball athletes and untrained subjects. It was observed that there was a significant difference in response between the trained (sprinters and volleyball athletes) as compared to the untrained. There was however, no significant difference in reflex activity between the sprinters and volleyball athletes.

One of the main concerns and criticisms regarding the exact contributions of the stretch reflex revolves around the fact that the resultant mechanical response might be too slow to actually contribute to muscle stiffness or force (van Ingen Schenau et al., 1997b). The fastest stretch reflex component (short latency component) would require a minimum period of 130ms between stretch onset and the rise of force (van Ingen Schenau et al., 1997b). The length of this time period would rule out its contribution to fast SSC movements such as running and hopping. Although slow running has been observed to benefit from stretch reflex (Cronin, Carty, & Barrett, 2011). Based on this logic, only slower SSC movements such as the CMJ would benefit from the stretch reflex. There are studies however, oppositional to this logic. Nicol and Komi (1998) observed a much shorter mechanical response time of about 55ms, which included the time required for force to be transmitted to the elastic components in the Achilles tendon of an adult female during an induced dorsiflexion. They also observed that there was only a 13 to 15ms delay between the stretch reflex onset and force rise. Ishikawa and Komi (2007) reported that the stretch reflex (short latency) contributed to moderate to slow speed running movements of less than 6.5m/s but not fast or higher speed running (6.5m/s and above). Both these studies support the earlier suggestion by Jones and Watt (1971) who had already suggested that the stretch reflex response (longer latency) can be activated after a delay of only 50 to 120ms. They believed that this was sufficient time to influence the concentric phase of human hopping, although they agreed that it is probably too slow to influence movements such as fast hopping. Therefore in summary, the evidence suggests that the mechanical response of the stretch reflex does not contribute to fast SSC movements but more slower or moderate speed SSC movements. The latency of the stretch reflex component is unlikely to contribute to a quick enough effect for the faster SSC movements.

Indirectly, stretch reflex activation is believed to contribute to stiffness (Dyhre-Poulsen, Simonsen, & Voigt, 1991; Hoffer & Andreassen, 1981; Komi & Gollhofer, 1997; Komi, 2000). Hoffman reflex (H-reflex) has been observed to react or modulate accordingly to the motor task. H-reflex in the soleus muscle was low (suppressed) during landing and increase during hopping (Dyhre-Poulsen et al., 1991). At the same time, muscle stiffness was observed to be lower during landing (acting like a shock absorber) and higher during hopping (acting like a spring). H-reflex measure, is often used as an indicator of the excitability of the central component of the stretch reflex. H-reflex and stretch reflex are not the same since H-reflex bypass the muscle spindle. However there are likely to be parallel changes between both during reflex excitation.

The increase stiffness due to the stretch reflex has also been observed to contribute to increased force primarily through the short-latency stretch reflex (Cordo & Rymer, 1982; Hoffer & Andreassen, 1981; Komi & Gollhofer, 1997; Voigt, Dyhre-Poulsen, & Simonsen, 1998). The stretch reflex response is believed to be a result of the increased muscle spindle afferent discharge. This is supported by the observation that a muscle which had its reflexes intact was more resistant to stretch than those that did not, even given when muscle force prior to stretch was identical (Hoffer & Andreassen, 1981). The increased resistance to stretch or stiffness was not correlated with the amplitude of the early EMG peak. This no-correlation suggests and supports the theory that the reflex mechanism is a non-activation dependent contributor to the overall stiffness and force application in SSC activity.

A countermovement allows the muscle to shorten more slowly allowing a pre-load effect and resulting in a higher overall muscle force. When the muscles begin the countermovement, the muscles are activated so as to allow the body to resist the resultant downward momentum, which occurs prior to the concentric phase (Walshe, Wilson, & Ettema, 1998). This allows the muscle force to increase during the eccentric and isometric phases when the movement is still relatively slow and before the speed increases during the concentric phase. This is effectively a pre-loading effect and allows the muscle to begin the movement with a higher muscle force as opposed to a concentric only movement. Due to force-velocity relationship, the muscle ability to develop force in a concentric only movement is reduced the moment the contraction speed (of the contraction) increases. Therefore the pre-load that the countermovement offers results in a higher overall force.

6.0 Applicability of the Model in Youths

6.1 Contributions of the Elastic Components in Youth

Due to the importance of the SEE and muscle stiffness in the SSC, it is important to investigate these phenomenon in youth. Previous studies on both human and animal cadavers have shown that there are changes in the elastic properties across ages (Danielsen & Andreassen, 1988; Elliot, 1965; Kubo, Kanehisa, & Fukunaga, 2001; O'Brien, Reeves, Baltzopoulos, Jones, & Maganaris, 2010). Differences in mechanical stiffness between maturational groups can differ from 84% to as much as 334% (Elliot, 1965; O'Brien et al., 2010). Elliot (1965) observed that the tensile strength of the human tendon for infants was 30MPa and 100MPa in adults a difference of about 334%. This difference in tendon stiffness (patella) reduces as the child matures and by the age of 8 to 9 years, this difference has reduced to 94% between men and boys and 84% between women and girls (O'Brien et al., 2010). 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. The investigators concluded that increase in mechanical stiffness between children and adults are due to the change in Young's modulus of the tendon and believed that this change is due to changes in the tendon microstructures.

Kubo et al. (2001) investigated muscle compliance and stiffness in the tendons of three different age groups (Table 2). Significant differences in muscle compliance were found among younger boys (10.8±0.9 years), older boys (14.8±0.3 years) and adult men (24.7±1.6 years, *n=14*). The tendon structures of the younger children were reported to have the highest muscle compliance ($4.1 \pm 0.9 \cdot 10^{-2}$mm/N), while adults the highest muscle stiffness ($1.8 \pm 0.3 \cdot 10^{-2}$mm/N). Significantly higher tendon stretch was also noted for the younger boys with muscle forces above 0.35 MPa of muscle stress (which is estimated to be between 16 to 22% than adults) 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 (2001) in his study as the relationship between the estimated muscle force and tendon elongation during the ascending phase of a leg extension. While the sample size is small, it is possibly the first known study to show growth changes *in vivo* in three different human populations and concurred with previous findings from animal studies.

This observation on the muscle compliance is supported by the other studies (Grosset et al., 2007; Lin, Brown, & Walsh, 1997; Wang, Lin, & Huang, 2004). Earlier in 1997, Lin, Brown and Walsh noted that the muscle compliance (º/Nm) in relation to a tendon tap decreases as an individual ages when comparing youths (3.9 years to 13.6 years, *n=22*) and adults (19 years to 70 years *n=9*). Grosset et al., (2007) tracked the changes in both passive and active musclo-articular stiffness of the ankle in prepubescent children (7 to 10 years of age) and compared them with adults (n=9) (Table 2). A total of 46 children were then divided into five groups based on their respective chronological ages. Passive musculo-articular stiffness was defined as the intercept point (IP) between the age of the prepubescent children and the linear musculo-articular stiffness - torque relationship. Active musculo-articular stiffness was expressed as musculo-articular stiffness index ($SI_{MA\text{-}EMG}$). In both passive and active stiffness, the musculo-articular stiffness increased with age and with adults exhibiting doubles or triple the stiffness values of the children (Table 2).

The correlation between stiffness and the age of the children was 0.96 for passive musculo-articular stiffness and 0.97 for active musculo-articular stiffness (Grosset et al., 2007). These differences could possibly suggest the differences in the SSC potentiation for youths and suggest that Hill's model (1938) may differ slightly for youths.

Table 2: Stiffness across different ages

Study	Age Group/Type of Stiffness	Youths							Adult
Kubo, Kanehisa, Kawakami, Fukunaga, & Fukanaga, (2001)	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)*			$4.1 \pm 0.9 \cdot 10^{-2}$mm/N			$2.9 \pm 01.1 \cdot 10^{-2}$mm/N		($1.8 \pm 0.3 \cdot 10^{-2}$mm/N)
Grosset, Mora, Lambertz, & Perot, (2007)	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)
	Musclo-articular stiffness of the ankle - Passive *(Nm/rad)*	24±2	25±3	28±2	32±3	36.5±2			74.5±2.5
	Musclo-articular stiffness of the ankle - Active *($SI_{MA\text{-}EMG}$)*	17±8	19±5	28±6	29±7	37±4			57±5
Lloyd, Oliver, Hughes, & Williams, (2011)	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 M G, Williams, & Hughes, (2012)	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: Adapted from Grosset et al., (2007); Kubo, Kanehisa, Kawakami, et al., (2001); Lloyd et al., (2012; 2011)

Lloyd et al, (2009; 2011) has measured vertical leg stiffness of children in two different studies (Table 2). In both these studies, higher mean leg stiffness was observed in the older boys as compared to the younger boys during sub-maximal hopping at 2.5 Hz on the contact mat. In the first study, Lloyd et al., (2009) tested the reliability of using a contact mat to effectively measure SSC and vertical leg stiffness during sub-maximal and maximal hopping by comparing the results from a contact mat to a force plate. They observed that the contact mat tends to overestimate vertical leg stiffness, however they concluded that the contact mat was a valid tool with moderate reliability for measuring SSC for sub-maximal hopping ($r=0.92–0.95$; TEE=6.5–7.5%) but not maximal hopping ($r=0.59$; TEE=41.9%). For other variables it was deemed as reliable for measuring SJ height (CV=8.64%), and reactive strength index (CV= 13.98%). There have been a few other studies that support the use of the contact mat for monitoring jump performance (Garcia-Lopez et al., 2005; Leard et al., 2007). Nevertheless there are limitations to using a contact mat which is essentially a timing device which measures mainly contact and flight time only. Other values are simply calculated from these two values using Newtonian laws and therefore are not direct measures especially for values such as force etc. These limitations should be factored in when interpreting results from a contact mat.

During that study it was also observed that the first group consisting of young boys aged between 13 to 14 years of age were measured on a contact mat while the second group consisted of both boys and girls between the ages of 16 to 17 were measured on a force plate. In both groups and on both pieces of equipment, relatively low muscle stiffness was observed in the younger group as shown in Table 3. The younger group (13.5±0.5 years old) consisted of all boys while the older age group (16.5±0.5 years old) was a mixed gender group consisting of 12 males and 8 females. For the older age group, the authors only provided mean vertical leg stiffness values for the group as a whole and did not provide values for male and females. Based on the literature that females at that age group are likely to have lower values (Quatman, Ford, Myer, & Hewett, 2006; Richter, Jekauc, Woll, & Schwameder, 2010), it is possible that the actual values for the males in the older age group to be much higher and thus a greater difference. Future studies in this area should need to take into account gender differences. While the study did not directly compare the stiffness between the two different age groups, it can be observed that the older age group showed slightly better vertical leg stiffness than the younger age group during both sub-maximal hopping (Table 3). Therefore the values observed here while interesting cannot be taken as conclusive, especially considering that they were extrapolated from a contact mat. However these observations are similar and support the later study by Lloyd et al., (2011).

Table 3: Vertical leg stiffness during sub-maximal hopping of two different age groups

Sub-maximal Hopping (Only)	Mean sub-maximal leg stiffness (kN.m^{-1})			
	Younger Group (n=18)			Older Group (n=20)
	Session 1	Session 2	Session 3	
K_{leg} 2.0 Hz	18.80+6.07	18.29+5.41	19.52+5.59	23.8+6.3
K_{leg} 2.5 Hz	26.05+5.55	26.62+5.95	25.55+6.05	29.8+5.7

***Note:** K_{leg} 2.0 Hz and 2.5 = leg stiffness during sub-maximal hopping at 2.0 Hz and 2.5 Hz respectively. Younger Age Group + 13.5±0.5 years, Older Group = 16.5±0.5 years.* Adapted from (Lloyd et al., 2009)

In the second and more recent study (Lloyd et al., 2011), among boys from 7 years of age, to 16+ years of age, vertical leg stiffness (absolute) increased with age. Of note was that the boys at the age of 10-11 and 12-13 years of age had a significantly greater increase or worthwhile change in vertical leg stiffness. However in terms of relative vertical leg stiffness, the vertical leg stiffness seemed to increase from the ages 7 to 11, before declining. This increase was observed again at about 13 years of age, but did not achieve the same levels as the age of 11. It is possible that this decrease in development of relative vertical leg stiffness was due to physical maturation and a rapid increase in body mass. Future studies in this area need to take into account differences such as gender and body mass differences.

It would seem from these and previous results that the stiffness of the muscle-tendon complex develops as the elastic tissues of the individual ages and the muscle mature. 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 cross-sectional area and tendon length and subsequently Young’s modulus. One of the contributors to increase in tendon size and cross-section area is probably due to the increase in the collagen fibril diameter itself as the individual matures (Diamant, Keller, Baer, Litt, & Arridge, 1972; Parry, Barnes, & Craig, 1978). 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 the growth itself and loading in turns leads to an increase in tendon stiffness during maturation (Danielsen & Andreassen, 1988; O'Brien, Reeves, Baltzopoulos, Jones, & Maganaris, 2010). Other than pure increase in overall mass, micro structural changes in the tendon have been noted (Bailey, Paul, & Knott, 1998; Diamant et al., 1972; O'Brien et al., 2010; Parry, Barnes, et al., 1978; Parry, Craig, & Barnes, 1978; Reed & Iozzo, 2003). Studies have noted increases in the fibril density or packing and increases in the cross-linking within the collagen (Bailey et al., 1998; Reed & Iozzo, 2003).

The second reason is due 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 (Diamant et al., 1972; Rigby, 1964). The crimp is a structural characteristic that refers to the "waviness" of the fibril that contributes to the nonlinear stress strain relationships. As the collagen fibrils becomes "uncrimped", its 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 age (Kastelic, Palley, & Baer, 1980; Patterson-Kane, Firth, Goodship, & Parry, 1997).

Aponeuroses, just like the tendon undergoes a similar progressive development from childhood to adulthood (Brunel, El-Haddioui, Bravetti, Zouaoui, & Gaudy, 2003; Kubo, Kanehisa, et al., 2001). The aponeuroses for those under the age of 16 were found to be slender, shorter and had lesser volume. (Brunel et al., 2003; Kubo et al., 2000). The aponeuroses for older boys (14.8±0.3 years old) and adults (24.7±1.6 years of age) were found to be much longer (Kubo, Kanehisa, et al., 2001). Adults above the age of 40 were consistently found to have much more thicker aponeuroses (Brunel et al., 2003). However, the authors did note that aponeuroses for an elderly group (60 years of age and older) was still particularly well developed and strong. This observation supports the concept of function over age for the aponeuroses similar to muscles.

To the knowledge of these authors there is very little research that has investigated the change in titin isoforms with maturation. It is possible that the titin isoforms undergo the same development cycle as any other tissue. Based on studies on the rat myocardium of various ages, it was observed that the development of the titin isoforms for the heart undergoes a similar development cycle and maturational time length as other tissues such as the myosin and troponin I (Warren, Krzesinski, Campbell, Moss, & Greaser, 2004).

In summary, children have more compliant tissues, which stiffens 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. It should be noted that even research into adult stiffness/compliance and the effect on force production is conflicting (Markovic & Mikulic, 2010). 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 (during sprinting) a stiffer musculotendinous unit that is capable of higher rates of force development is desirable (Markovic & Mikulic, 2010). 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 is needed.

6.2 Contributions of the Contractile Components in Youth.

The most common differences in muscle between adults and youth would be morphological in nature. Muscle development in youth is likely and naturally expected to be smaller (in size and number of myofilaments) due to the lack of maturity and development. Other factors such as pennation and muscle architecture would all affect the moment arm which in turn would affect the force and power development for jumping.

There are a few studies that have investigated age or maturity related differences in voluntary activation ability (Belanger & Mccomas, 1989; Davies, White, & Young, 1983; Maughan, Watson, & Weir, 1984; Neu, Rauch, Rittweger, Manz, & Schoenau, 2002). Davies et al (Davies et al., 1983) compared the differences in tetanic tension (TT) and maximal voluntary contraction (MVC) between two groups of children, one group consisted of 11 year olds (*n=26*) while the other consisted of 14 year olds (*n=26*) and young adults (21.5 years old, *n=12*). They found that the 14 year olds were significantly stronger than the 11 year olds in both TT at 10 Hz (579±115 vs. 441±49), 20 Hz (862±200 vs. 616±80) and 50 Hz (1054±265 vs. 765±74) and MVC (1382±412 vs. 877±49). Nevertheless both groups of children were significantly weaker (54 to 111% in for TT and 39 to 120% for MVC) than the adults. They also found differences of about 45% (595 N) in maximal strength (absolute) between the adults and the 14 year old youths and in turn a difference of 58% (492 N) between the 14 year old and the 11 year old youths.The authors believed that the difference is likely to be due to muscle bulk (muscle mass).This maturation specific finding is shared by other studies (Lexell, Sjöström, Nordlund, & Taylor, 1992; Neu et al., 2002). For example, Neu et al. (Neu et al., 2002) when comparing grip strength and muscle CSA noticed a steady increase in forearm strength (maximal isometric grip) from the ages of 6 to adults (subjects parent's up to the ages of 40) with the adults possess twice the strength when compared to the 6 year olds for both boys and girls and appears to be independent of sex hormones. However forearm muscle growth rate is gender specific and influenced by hormonal changes. And once anthropometric measures such as muscle CSA are factored in, the differences in strength disappear or diminish. This study suggests that the increase in maximal isometric grip force during childhood and adolescence has two components. The first is muscle growth, which takes a gender-specific course during puberty, indicating that it is influenced by hormonal changes. The second is an increase in grip force per muscle CSA, which is similar in both genders and thus appears to be independent of sex hormones.

Changes in muscle fibres types could be another possible contributor to the difference in strength the extent however is yet to be determined. While it has been suggested that changes in muscle fibres types exist as the individual matures (Lexell et al., 1992; Sjöström, Lexell, & Downham, 1992; Timson & Dudenhoeffer, 1990; Vogler & Bove, 1985), the changes seems more to be a transformation from Type 1 to Type 2 muscle fibres. A study by Dubowitz (1965) however found otherwise and even suggested that these properties (muscle fibres types or fiber type proportions) are complete by birth or soon after. A closer look at the study by Lexell et al (1992) however reveals that while they found significant transformation from Type 1 to Type 2 fibres (approximately 35 to 50%) as an individual matures from the ages of 5 to 20 years of age. They also found and concluded that increase in mean fibre size in also the main contributor of increase muscle cross-sectional area which is one of the main contributor on increase in muscle force. Overall it is likely that some changes in fibre types proportion does occur especially in response to the individual's local environment and demands as the individual ages however the true extent of the contribution of the changes in muscle fibre types in yet to be determined especially considering the variability in the experiences of the individual and the environment that the individual grows up with.

Other than changes in muscle mass, the exact changes that occur in the contractile properties of muscle during puberty is 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 activate and recruit 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 observed that youths have a lower voluntary muscle contraction ability than adults (Asmussen & Heebøll-Nielsen, 1955; Davies et al., 1983). Furthermore, twitch tensions and maximum voluntary contractions are two of the main changes that have been found to increase with age and maturity in children (Blimkie, Ramsay, Sale, MacDougall, & Smith, 1989; Davies et al., 1983; McComas, Sica, & Currie, 1971; McComas, Sica, & Petito, 1973). Comparisons of the extensor hallucus 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 (McComas et al., 1971). This improvement while gradual at first undergoes a significant marked increase during puberty.

Belanger & McComas, (1989) conducted a study to determine the extent of the changes of contractile properties of the ankle muscle during puberty. Strong and positive relationship were observed between age and maximal voluntary contractions (MVC) torques values. The mean values were approximately double the values for the adolescent (aged 15 to 18) as compared to the younger children (aged 6 to 13). However no correlations were found between age and contraction time. Similar relationships were also found between age and plantar flexion twitch torque in the younger children but not during adolescence. The authors concluded that these differences were likely to be due to the fibre type proportions between the dorsiflexion and plantar flexor muscles and possibly other variables such as active state and myosin light chain content (Belanger, McComas, & Elder, 1983; Moore & Stull, 1984).The results of the study by Belanger & Mccomas, (1989) further support the concept of age related differences for the contractile components. These differences in the maturity and development of the muscle groups can be observed as early as six years of age.

Blimkie et al., (1989) observed similar age-dependent differences for motor unit activation although it was partial. He compared the motor unit activation in a group of males between the ages of 10 to 16 years of age. By using, supramaximal electrical stimulation during peak maximal voluntary isometric contractions, he was able to observe the degree of motor unit activation during voluntary contraction. He observed no significant difference in elbow flexor percentage of motor unit activation among the age groups (89.4% versus 89.9%). However, there was a significant difference for the knee extensors (77.7% versus 95.3%). While the findings observed in the Blimkie et al., (1989) study are conflicting (lower body only) as compared to the other studies, it seems that age-associated variance exists. This is similar to the observation by Davies et al., (1983) who observed that there was a relationship in voluntary muscle ability and age. The younger the child, the less voluntary activation the individual has. Davies et al. 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.

Another aspect which suggests a difference in the activation ability of children would be the difference observed in terms of trainability or neuromuscular adaptations in youths. Ozmun, Mikesky, & Surburg, (1994) used electromyography (EMG) to measure strength training induced changes in prepubescent boys and girls after 8 weeks of strength training. He observed significant increases in both maximal strength (isokinetic) by 27.8% and a corresponding increase in integrated EMG (IEMG) amplitude of 16.8%. This is consistent with two earlier studies by Ramsay et al., (1990) and Blimkie et al., (1989) who investigated the contribution of changes in motor unit activation to training induced strength increases in prepubescent boys. In both these studies, there was a corresponding increase in motor unit activation (30%) with strength change (37%) for the elbow flexors. While both these studies did not directly compare their results to adults, the difference observed in the two maturity stages suggest that at some point of development in the pubertal stages, there exists a difference in motor unit activation especially between adults and prepubescent boys. This difference could have a possible effect on the stiffness regulation of the muscle which in turn affects the contribution to the SSC.

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 (McComas et al., 1971; Ramsay et al., 1990). McComas et al., (1971) observed that the twitch contraction times of the younger children (2 to 16 years of age, *n=19*) including the youngest which was three years of age was 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 (McComas et al., 1971). Although the study population was small (*n=19*), the authors did observe a noticeable increase which, although inconclusive, does add support to the suggestion that early maturation of the contractile properties occurs. 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 (Finan & Smith, 2005; Grosset et al., 2007; Lin et al., 1997; Obata, Kawashima, Akai, Nakazawa, & Ohtsuki, 2010). Grosset, Mora, Lambertz and Perot (2007) have attempted to observe the development of reflex excitability in prepubescent children. They observed and believed that while the central mechanisms that control stretch reflex in children are mature by the time they reach pre-pubescence, the mechanically induced reflex only increases with the age of the child. Lin et al. (1997) in their study observed that reflex twitch time also improved as one 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. 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 (Grosset et al., 2007). Grosset et al. (2007) who observed changes in stretch reflex and muscle stiffness in children, also suggested that that elastic properties of muscle (and in relation to muscle stiffness) which increased as the individual matures, was likely to be one of the major contributors to the development of the stretch reflex due to the correlation between the changes in reflex amplitude and muscle stiffness.

7.0 Jumping Performances of Children

The magnitude of potentiation that results from the storage and utilisation of elastic energy cited in the previous literature was from research using 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 as adults due to the differences in muscle between adults and youths (Malina, 2001). This section explores this theme in a little more detail.

A number of studies that have attempted to compare the jumping performance of children to adults (Harrison & Gaffney, 2001; Wang, Lin, Huang, & Chung-Hsien, 2002; Wang et al., 2004). Wang et al. (2002) 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 (except at the hip), and a more backward projection (in reference to the centre of gravity) during take-off for the prepubescent children. These differences are 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 (Wang et al., 2002). A more limited ROM in the hip, knee and ankle during the crouch phase likely meant that the children did not crouch low enough. Limited ROM in the ankle and knee of the children during the take-off is a consistent observation (Wang et al., 2002; Wang et al., 2004).This is likely to be indicative of low ability to perform the jump possibly due to a lack of experience in performing the jump or possibly physical limitation, though this is less likely. Immature joint functions refer to different firing patterns in the children as compared to the adults. During the crouch, children spent more time on concentric contractions in the joint flexors and less time in the extensors eccentric contractions to create downward motion and go into the crouch. The flexor eccentric contractions also appear much earlier which might be counterproductive during the propulsive stage of the jump. Overall the authors concluded that the differences are probably due to a lack of form in jumping strategy due to experience and immature joint function. Therefore any future studies with children will require 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 (2001) conducted a study to observe the effects of age and gender on SSC performance. The vertical jump performance of prepubescent children (n=20) which consisted of 12 girls (6±0.4 years) and 8 boys (6±0.2 years) were compared to adults (n=22) which consisted 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 on the 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 researchers observed that the children were able to utilise SSC to enhance their vertical jump performance. The children had a percentage difference in ΔV_{TO} of 10.5±19.7%, which was higher than the adult group which had ΔV_{TO} of 6.33±5.59%. However, it should be noted that there was great variability in the ΔV_{TO} for children and that there was a noticeable difference in scores between boys (14.5±24.9%) and girls (7.83±15.1%). It was believed that one of the primary reasons for this enhancement was due to the poor execution and performance of the SJ, rather than SSC augmented improvement in the CMJ. The researchers explained that there were three reasons why they came to such a conclusion. First, was the observation that there was significantly greater variability in the ΔV_{TO} in children as compared to adults. This variation existed not only in terms of the coefficient of variability in the V_{TO} itself but also across trials and jump types. 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. (1996). 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±3 $W.kg^{-1}$) in the SJ when compared to adults (48±7 $W.kg^{-1}$) 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 suggested 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. Surprisingly the children were able to generate similar peak forces to adults however it was not the case for peak power for CMJ. Other than poor execution of the CMJ in youth compared to adults, it could suggest an inefficient utilisation of the SSC.

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, adapted from study.* V_{TO} *= velocity at take-off*

Adapted from Harrison and Gaffney, (2001)

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 (Gerodimos et al., 2008; Harrison & Moroney, 2007; Lloyd et al., 2009; Wang et al., 2002). 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. The results from a recent study (Lloyd et al., 2011) however, has suggested that this might not always be the case, at least for jump height. The investigators measured the jumping performances and SSC ability (CMJ vs. SJ) of children across chronological ages of 7 to 17 years of age and observed periods of accelerated adaptation in SSC across the ages of 14 to 16 years of age. However, in that same study, it was also observed that children aged 12 to 14 years of age had a slightly better mean SJ jump height (approximately 2 to 4%) as compared to 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 (Beunen, 1997). Since maximal isometric strength regardless of age is believed to be proportional to muscle size (Tonson, Ratel, Le Fur, Cozzone, & Bedahan, 2008), 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 when the children are more mature, they exhibit the expected adult like CMJ vs. SJ jump performance.

8.0 Conclusion

One of the consistent observations found in the various jump studies utilising youth subjects is the variability in the jumping performance due to motor control issues related to maturity. Therefore future studies on jumping performance with children should include a familiarisation jump session before the study or prior jump experience to address learning effects for each jumping strategy.

It is also important to highlight the main limitations of this article. For many of the relevant studies that do exist, most of them have presented the results in a graphical format. While this makes it easy to understand and look at the data does not provide the exact results, and the mean result has to be estimated. This is the first limitation of the study and does reduce the accuracy of the reported findings; however care has been taken to ensure that the reported findings or observations in this article do not differ from the original paper.

Compounded with that limitation would be the small sample size for many of the older studies which reduces the statistical significance of the observations and some degree of flexibility and caution is needed before taking these observations as conclusive. This is to some degree expected, considering that it is more difficult to conduct studies on youth population as compared to adults who can provide their own consent. Data is also more available for boys as compared to girls. Recent studies have shown to have quite a significant sample size. Nevertheless it is hope that future studies on youth, could possibly maintain or attempt to increase population sample. The final limitation would be due to the lack of studies on children itself, a few conclusions had to be referred or derived based on observations from adult and animal studies.

In summary, there have been very few studies that have investigated SSC ability during jumping performance in youth. Some of these studies have focused on adolescent or children during the pubertal years. A few of these studies have categorised maturation as adolescent and pre-adolescent or simply used chronological ages. As mentioned, the biological maturity of youth does not necessarily coincide with chronological age, and therefore the variability in SSC ability across different population and groups are likely to exist. The results reported in these studies are in some cases, conflicting. But to date, to the author’s knowledge, there have been no studies that have directly studied jumping potentiation across maturation i.e. pre~, at~ and post~pubescencence. Measuring SSC potentiation in children and determining if SSC potentiation differs across maturational stages should enable an understanding of optimal windows for trainability of the SSC. If windows of trainability do exist then this knowledge should enable better programming for children to optimise SSC plyometric ability as part of long-term development of the youth athlete.

CHAPTER 3: STRETCH-SHORTEN CYCLE ACROSS THE DIFFERENT MATURATIONAL STAGES

1.0 Introduction

In most forms of human locomotion such as running, hopping and jumping, muscle contraction is usually typified by a combination of eccentric-lengthening followed immediately by a concentric-shortening contraction termed the stretch-shorten cycle (SSC). SSC motion is the most natural form of muscle function, the benefits of which have been researched for many years in mostly adult populations. Unlike adults, the biological maturity of youth does not necessarily coincide with their chronological age and can differ by several years (Armstrong & Welsman, 2002; Malina, 2001, 2006), therefore it is important to note the biological age of an individual rather than the chronological age when documenting change in youth. Biological age as opposed to chronological age is determined by the youth's rate of development and maturational process. This maturational process can be divided into three significant phases, pre-pubescent, pubescent or post-pubescent, with each phase having unique characteristics that may lead to differences in SSC ability. For example, one of the main changes in males and females during puberty would be in rate of strength development. It has been observed for females that strength performance continues to increase during puberty, however no noteworthy changes occur post-puberty (Beunen & Simmons, 1990; Malina, Bouchard, et al., 2004). For males, it has been observed that the strength continues to increase as they grow older. This strength increase accelerates during the male growth spurts, which can likely be attributed to the hormonal influx at this stage of maturation (Asmussen & Heebøll-Nielsen, 1955; Asmussen, 1962; Carron & Bailey, 1974; Haubenstricker & Seefeldt, 1986). It may be that these strength changes in turn affect SSC performance across maturation.

Another factor that may affect SSC ability are changes in the elastic properties of muscle across maturation. Mechanical stiffness between maturational groups can differ from 84% to 334% (Elliot, 1965; O'Brien et al., 2010). For example, Elliot (1965) observed that the tensile strength of the human tendon for infants was 30 MPa and 100 MPa in adults, a difference of about 334%. Researchers have also reported differences in tendon stiffness (94% to 227%) between men and

8-11 year old boys (Kubo, Kanehisa, Kawakami, Fukunaga, & Fukanaga, 2001; O'Brien et al., 2010). Similar findings concerning muscle stiffness and maturation have been observed in other studies (Grosset, Mora, Lambertz, & Perot, 2007; Lin et al., 1997; Wang, chia Lin, & Huang, 2004). There is no doubt the stiffness/compliance of the musculotendinous unit affects storage and utilisation of elastic energy and therefore SSC ability, therefore it could be hypothesised that SSC ability is likely affected by these changes across maturation.

In terms of documenting changes in SSC ability, the comparison of a concentric only jump (squat jump – SJ) to a SSC jump (countermovement jump – CMJ) is a simple and well-utilized approach. Most studies using this methodology with adults have reported a potentiation in CMJ performance of 18% to 30% as compared to the SJ (Bobbert, Gerritsen, Litjens, & Van Soest, 1996; Komi & Bosco, 1978). While a great deal of research has investigated CMJ vs. SJ performance in adults (Bobbert et al., 1996; Komi & Bosco, 1978; McGuigan et al., 2006; Young, 1995), there is a paucity of research investigating this comparison in pre-pubescent and pubescent youths. Recently there have been a few studies that compared the CMJ vs. SJ in children and a few generalisations can be made. First, most researchers have reported superior CMJ performance (6.8 to 10.3%) (Gerodimos et al., 2008; Harrison & Gaffney, 2001; Harrison & Moroney, 2007; Richter et al., 2010). A recent study by Lloyd et al., (2011) however, has suggested that this might not always be the case, at least for jump height. Children aged 12 to 14 years of age had a better SJ jump height (approximately 2 to 4%) as compared to CMJ. 15 years old adolescents had similar CMJ and SJ heights. While the investigators did not directly address the superiority of the SJ as compared to the CMJ height, it was suggested that these unusual findings could be attributed to a combination of an increase in maximal isometric strength (Tonson et al., 2008) and concentric strength (Beunen, 1997) as opposed to SSC ability around pubescence. A second reason for these findings could be attributed to the greater variability in jumping performance in children (Gerodimos et al., 2008; Harrison & Moroney, 2007; Wang et al et al., 2002) especially for the SJ (Harrison & Gaffney, 2001). It has been suggested that this variability could be due to motor control issues related to maturity. Therefore researchers that compare the SJ and CMJ in children should ensure that the children are proficient or at the very least trained in both methods of jumping.

In summary, it is quite likely that SSC ability may differ across maturation, however there is a paucity of research in this area and the findings that are published are conflicting, and confounded by a lack of research that has identified the maturation of subjects. Finally, most studies quantify this SSC ability via the difference in SJ and CMJ performance. Another method to quantify the differences in SSC ability is to measure the power absorbed (mean eccentric power) and power produced (concentric power) as a ratio (Cronin, McNair, & Marshall, 2002) during a CMJ. Such an approach has not been used in youth and would give insight into SSC ability across maturation. Given this information the purpose of this study is to examine the SSC ability of male and female youth at different stages of maturation (pre-pubescent, pubescent and post-pubescent). Quantifying SSC ability between maturation stages will provide insight into whether structure and performance remain the same during maturation. Furthermore if differences exist, this might be suggestive of a possible window of trainability for the development of SSC during maturation.

2.0 Methods

2.1 Subjects

A total of 209 youths (pre-pubescent = 62, pubescent = 88 and post-pubescent = 59) aged between 11 to 17 years of age, from the Singapore Sports School participated in this study (Table 5). One hundred and one of the youths were males, while the remaining 108 youths were females. Each subject had a minimum of three months resistance training experience and had undergone basic jump training (and landing) exercise conducted by the school's Strength and Conditioning Unit. Subjects as students of the Singapore Sports School had already given their own assent and parents had consented to their children to be tested, photographed and videotaped for testing and monitoring purposes. All ethical guidelines as determined by the Singapore Sports School Research and Ethics Committee were adhered to during each study.

Table 5. Subject Information

	Males			Females		
	Pre-Pubescent (*n=35*)	Pubescent (*n=33*)	Post-Pubescent (*n=33*)	Pre-Pubescent (*n=27*)	Pubescent (*n=54*)	Post-Pubescent (*n=26*)
Age (years)	13.3 ± (1.0)	14.6 ± (1.0)	15.2 ± (2.8)	12.0 ± (1.1)	13.7 ± (1.6)	15.1 ± (1.0)
Stature (cm)	145.37 ± (43.02)	160.13 ± (33.96)	165.09 ± (31.78)	136.06 ± (51.04)	161.87 ± (5.88)	164.38 ± (6.10)
Mass (kg)	46.97 ± (9.67)	52.56 ± (6.04)	59.37 ± (10.50)	45.68 ± (7.16)	53.45 ± (7.13)	55.33 ± (8.46)

Note: Age was determined on the date as of the test session.

2.2 Assessments and Equipment

All jumps were performed on a force plate (4060-10, Bertec Corporation, Columbus, Ohio) using Bioware (Type 2812A1-3, Version 3.2.6.104) software (Kistler Group, Winterthur, Switzerland). All data was collected at a sampling frequency of 500Hz.

2.2.1 Jump Assessment

Concentric only SJ as well as CMJ were performed and analysed in this study. Subjects performed the jumps without the aid of the arm swing by holding on to a plastic stick (weighing less than 0.5kg) on the shoulder as though they were performing a back squat. For the SJ, the subjects were required to squat and flex the knee to approximately 90 degrees (as determined by the investigator), maintaining the position for three seconds and jumping on the command of the tester (using the word ‘GO’). Signals from the force plate were visually scanned to ensure no countermovement took place. When a counter-movement was noted students were required to repeat the particular jump (up to 6 trials, excluding the familiarization jump). If subjects were not able to perform the SJ after 6 trials, they were requested to repeat the test at another time. The CMJ was performed using the same conditions but with the difference of immediate extension of the legs once the flexion of the knee was approximately 90 degrees.

2.2.2 Maturity Assessment

To determine the subject’s maturational stage, two criteria (Table 6a and 6b) based on height were used simultaneously to categorise subjects as pre-pubescent,

pubescent and post-pubescent and placed in the respective biological groups. The first criteria was their growth rate (Sherar, Mirwald, & Baxter-Jones, Thomas, 2005) defined as the increase in height (in centimeters) within the past 12 months. The second criteria was to observe if they had met the national average height for Singaporeans for the same chronological age as shown in Table 1b (School Health Service, Ministry of Health 1993).

Table 6a. Criteria for classification of youths into different maturational stages.

Biological group	**Criteria 1**	**Criteria 2**
Pre-pubescent	PHV < 8cm	Same or shorter than National average
Pubescent	PHV > 8cm	Same or shorter than National average
Post-pubescent	PHV < 8cm	Same or taller than National average
Adulthood	PHV < 1cm	PHV < 0.5 cm over 4 successive 6 months

PHV = Peak Height Velocity. Adapted from Sherar, Mirwald, & Baxter-Jones, Thomas, (2005)

Table 6b. National average (50th percentile) height for Singaporeans aged from 11 to 17 years of age.

Age (in years)	11	12	13	14	15	16	17
Average Height for Boys (in cm)	145	152	158	164	168	170	171
Average Height for Girls (in cm)	147	151	154	156	157	158	158

Note: *Based on the percentile chart of Growth Charts: Singapore children (The School Health Service, Ministry of Health, Singapore, 1993).*

Subjects who had increased at least 8 cm in height or more in the last 12 months and had not reached the national average or near the national average were classified as in the pubescent stage. Those who had shown this increase in the past 2 to 3 years and where the current increase in height was less than 8 cm (in the past 12 months) were classified as post-pubescent. Subjects (specifically the younger ones up to the age of 13) who had not met the above conditions were classified as pre-pubescent.

2.3 Procedures

Subjects performed the test during their normal routine training sessions. These testing sessions were selected after a rest or recovery day to ensure that no strenuous aerobic/anaerobic exercise or resistance training occurred 20 to 24 hours prior to the first testing occasion. Prior to involvement all participants were briefed on the study requirements, risks and benefits. The subjects in each of the different maturational groups were randomly allocated to one of two groups, ensuring that all subjects began with a CMJ or SJ in each session. The objective of this randomization was to minimise order, learning and fatigue effects.

Subjects were required to attend a total of two sessions. The first session consisted of a briefing, determination of maturation and familiarisation of the test procedures and protocols. At the end of this session, the subjects were classified into the different maturational stages, understood the test protocols and were able to correctly perform the jumps. Any subjects that were unable to perform any of the jumps properly were given additional training during their routine training until they were deemed proficient by one of the school strength and conditioning coaches. Particular emphasis during the training sessions was placed on the SJ, since the SJ is not a usual jump for most of the subjects as compared to the CMJ which was part of the school's basic jump training for its students. This minimized the possibility that a poor execution of the SJ would increase the ratio of difference between CMJ and SJ as highlighted by Harrison & Gaffney (2001). Once the subjects were deemed proficient in both jumps, they were then scheduled for the second session, where the actual test was conducted.

In both sessions, participants performed their standard warm-up routine (pre-training) excluding any static stretching, as this type of stretching was likely to affect their jump performance. The warm-up routines consisted of dynamic warm-up and some movement preparation exercises (including a trial jump for each of the jumps and tuck jumps). Participants were given 3 to 6 trials (excluding the familiarization jump), until a plateau in their jump performance was observed. The best two results from each jump condition was recorded, averaged and used for analysis.

2.4 Data Analysis

The dependent variables of interest are listed below. All data was either obtained directly from the force plate or calculated from obtained data and are listed below.

Relative Peak Force (N/kg): Highest force generated during concentric phase of jump in relation to subject's bodyweight

Relative Peak Power (W/kg): Highest power generated during concentric phase of jump in relation to subject's bodyweight

Jump Height (cm): Calculated via flight time (9.81*flight time*flight time)/8 (Flanagan & Comyns, 2008).

Relative Mean Concentric Power (W/kg) (MCP): Mean power generated during concentric phase of jump in relation to subject's bodyweight.

Relative Mean Eccentric Power (W/kg) (MEP): Mean power generated during eccentric phase of jump in relation to subject's bodyweight.

Vertical Stiffness (k): The ratio between the relative peak force and jump height (T. a McMahon & Cheng, 1990).

Eccentric Utilisation Ratio (EUR): The ratio between a countermovement jump and a concentric only squat jump. The ratio is calculated using relative peak force and jump height (McGuigan et al., 2006).

Mean Eccentric Power / Mean Concentric Power (MEP/MCP): The ratio between relative mean eccentric power and relative mean concentric power.

2.5 Statistical Analysis

Statistical analyses were performed using a statistical software program (SPSS 15.0 for windows, SPSS, Inc., Chicago, IL, USA). The mean and standard deviation were used as measures of centrality and spread of data. A two factor

ANOVA with post hoc contrasts comparing gender with maturational stages was performed to determine if significant differences existed between the three maturational groups in the dependent variables of interest. An alpha level of 0.05 was used for all statistical analyses.

2.6 Results

The results of the different jump conditions for both males and females across the different maturational groups are provided in Table 7. In general, significant differences ($p < 0.05$) were found between males and females across all of the SJ and CMJ variables with the exception of relative MCP for the CMJ and EURs (jump height and peak force). Only three interaction (gender*maturation) effects were noted (MEP, SJ Relative PF and vertical stiffness).

For the SJ, the male pre-pubescent athletes differed significantly to the other maturational groups on all the variables of interest with the exception of relative mean concentric power. Pubescent (~8 to 16%) and post-pubescent males (~9 to 17%) performed better than the pre-pubescent males. The greatest differences observed in the more mature males compared to the pre-pubescent males was in the jump height (~14 to 17%) and relative peak power (~11 to 16%). For the females however, there were no significant differences noted for any of the variables across maturational groups. The average difference in performance across the jump variables when comparing the pre-pubescent to both pubescent and post-pubescent females was about -6 to 9%. Similar to the males, the greatest difference was observed in the jump height (8.6%).

With regards to the countermovement jump, vertical stiffness was observed to be of the greatest difference for both males (21%) and females (61%) between the pre-pubescent and post-pubescent groups. The average difference in the variables of interest was between -4 to 15% when comparing the pre-pubescent males and pubescent males and about -5 to 20% between pre-pubescent and post-pubescent males. Other than vertical stiffness, no between maturation group differences ($p < 0.05$) were found for the males, whereas for females, only relative mean eccentric power was found to differ significantly between pre-pubescent and pubescent groups. It should be noted that the power absorption (MEP) was approximately 25%

of the power produced (MCP). Differences for the other jump variables ranged from ~ -5 to 20% for pre-pubescent and pubescent females and ~-1 to 61% between pre-pubescent and post-pubescent females.

The most noticeable differences (~9 to 10%) were observed in terms of the peak force EUR for both genders. The greatest benefits of the countermovement observed in the prepubescent males (1.17) and females (1.20). The prepubescent males differed significantly to the other maturation groups while the differences in the females were only observed for the prepubescent-pubescent comparisons. With regards to peak power EUR, similar differences of about 1 to 9% were observed between prepubescent male and females compared to the more mature groups. The only comparison to differ significantly (-7.8%) was between the male prepubescent and post-pubescent groups. In terms of MEP/MCP ratio, the power absorption to production ratios were very similar between males and females, the female pubescent and post-pubescent comparison was the only significant difference (-24%) observed.

Table 7: Means (± SD) for vertical jump variables of interest across maturational stages for males and females

Variables	Males			Females		
	Pre-Pubescent (n=35)	Pubescent (n=33)	Post-Pubescent (n=33)	Pre-Pubescent (n=27)	Pubescent (n=54)	Post-Pubescent (n=26)
Squat Jump						
Relative Peak Force (N/kg)	19.4 (±2.58)*^	20.9 (±2.59)*	21.2 (±1.88)^	19.5 (±2.53)	18.4 (±3.82)	19.53 (±4.09)
Relative Peak Power (W/kg)	43.9 (±15.0)*	51.0 (±10.8)*	48.7 (±10.1)	35.7 (±13.4)	37.8 (±9.54)	39.5 (±8.98)
Relative MCP (W/kg)	14.8 (±8.27)	16.8 (±5.58)	16.4 (±6.03)	13.2 (±4.69)	13.6 (±5.84)	12.8 (±4.64)
Jump Height (m)	0.28 (±0.09)‡ *^	0.32 (±0.06)*	0.33 (±0.08)‡ ^	0.23 (±0.04)‡	0.25 (±0.04)	0.25 (±0.04)‡
Countermovement Jump						

Relative Peak Force (N/kg)	23.5 (±5.08)	22.4 (±3.10)	22.2 (±1.74)	21.0 (±8.66)	19.9 (±5.35)	20.7 (±6.85)
Relative Peak Power (W/kg)	43.1 (±17.5)	48.9 (±18.1)	46.2 (±13.4)	38.0 (±14.7)	41.9 (±10.6)	43.1 (±15.1)
Relative MCP (W/kg)	21.8 (±8.89)	24.7 (±7.84)	24.5 (±5.33)	21.6 (±4.44)	21.1 (±4.69)	22.7 (±9.07)
Relative MEP (W/kg)	6.56 (±2.07)	6.58 (±1.63)	6.58 (±1.53)	4.85 (±2.52)*	6.09 (±1.45)*	5.35 (±1.16)
Jump Height¤ (m)	0.31 (±0.08)	0.35 (±0.07)	0.34 (±0.07)	0.26 (±0.05)	0.27 (±0.04)	0.27 (±0.04)
Vertical Stiffness	2.43 (±0.49)†‡ ^	2.79 (±0.72)† ^	2.96 (±0.77)‡	2.94 (±1.17) †‡ ^	3.53 1.43) † #	4.97 (±2.38)‡ ^#
			Ratios (EUR)			
EUR PF	1.17 (±0.22)†‡*^	1.05 (±0.08)† *	1.06 (±0.07)†‡ ^	1.20 (±0.28)†‡ *	1.07 (±0.17)† *	1.08 (±0.12)†‡
EUR PP	1.02 (±0.03)*	1.01 (±0.07)	0.94 (±0.21)*	1.04 (±0.12)	1.03 (±0.10)	1.05 (±0.13)
EUR Jump height	1.11 (±0.11)	1.06 (±0.07)	1.06 (±0.11)	1.07 (±0.18)	1.05 (±0.11)	1.07 (±0.09)
MEP/MCP	0.30 (±0.11)	0.27 (±0.10)	0.26 (±0.07)	0.25 (±0.11)	0.29 (±0.09)#	0.22 (±0.08) #

Note: MCP = Mean Concentric Power, MEP = Mean Eccentric Power, EUR = Eccentric Utilisation Ratio; † - Maturational differs significantly between Pre-Pub & Pub, ‡ - Pre-Pub & Post Pub, ¥ - Pub & Post Pub;

2.7 Discussion

In terms of the SJ and CMJ, males were found on average to produce significantly greater relative power (21% for SJ, 11% for CMJ), and jump height (21% for SJ, 20% for CMJ) than their female counterparts. Greater relative force was also observed (6% for SJ, 9% for CMJ) for the boys though not significant. Even after leg strength was controlled for mass via ratio scaling, males' strength and power were significantly superior to females, suggesting factors such as neural and hormonal characteristics may be more influential than muscle mass and size. These strength differences between gender are consistent with other studies in both adults and youths and are not unexpected (Barber-Westin, Noyes, & Galloway, 2006; Beunen & Simmons, 1990; Granata, Wilson, & Padua, 2002; Haubenstricker & Seefeldt, 1986; Padua et al., 2006; Padua, Arnold, Carcia, & Granata, 2005). However, it needs to be acknowledged that while gender differences exist for lower body strength even during youth, the difference is not as significant when compared to the upper body (Asmussen, 1962; Carron & Bailey, 1974).

The gender differences in general were greater in the more mature groups as compared to the pre-pubescent group. For the CMJ for example, the gender differences increased with greater maturity (- 7% difference for pre-pubescent, 16% for pubescent and 21% for post-pubescent). A similar trend was observed for the SJ (7% vs. 20% vs. 18%). This observation is consistent with the findings reported by other researchers. It has been observed that gender differences in strength are relatively minor during childhood and become increasingly greater by age 16 (Beunen, Colla, Simons, & et al., 1989; Beunen & Simmons, 1990; Carron & Bailey, 1974). Other researchers have observed similar trends for performance tasks such as speed, agility (shuttle run) and explosive strength (horizontal and vertical jumps and distance throw). In general, female performance increases up to the age of 13 and 14 before it starts to plateau (Beunen & Simmons, 1990; Haubenstricker & Seefeldt, 1986). The plateau does not seem to be observable in males until a much later age.

The SJ is a concentric only jump, therefore its performance is largely determined by the contractile ability of the muscle i.e. minimal contribution from the elastic components. The heights jumped in this study are consistent with those found in the literature. For example, jump height for the pre-pubescent group was 0.28±0.09 m, which is similar to the SJ jump height observed by Lloyd et al. (2011) (0.26 to 0.31m) for a group of 11 to 14 year olds males and was about 0.30 m in young adolescents in the study by Gerodimos (2008). Peak force for pre-pubescents, 19.4 N/kg^{-1} (males) and 19.5 N/kg^{-1} (females) was similar to the peak force generated from a squat jump (20.5±1.5 N/kg^{-1}) in pre-pubescent children (males and females combined) of about 6 years of age (Harrison & Gaffney, 2001). There is however, a huge difference for peak power. Harrison and Gaffney observed a peak power of 28±3 W/kg^{-1} while the pre-pubescent youths in this study generated a greater peak power output, an average of 39.8 W/kg^{-1} (43.9 ±15.0 W/kg^{-1} for males, 35.7 ±13.4 W/kg^{-1} females). The pre-pubescent youths in this study are youth athletes, which could possibly explain the greater ability in power generation than would be expected from untrained youths.

As force and power production are likely to increase with maturation (Belanger & Mccomas, 1989; Davies et al., 1983; Maughan et al., 1984; Neu et al., 2002), it is logical to assume that the jump variables under investigation in this study would increase as the individual matures. The findings from this study confirm such a contention; there were significant differences (9 to 17%) across maturational groups. Post-pubescent male subjects jumped higher (17%) and generated significantly greater relative peak force (9%) and power (11%) as compared to the pre-pubescent subjects. Similar results in terms of jump height were observed in two other studies (Coelho, Figueiredo, Moreira, & Malina, 2008; Lloyd et al., 2011). Males of 16+ and 15 years of age jumped higher than males at 13 years of age (27% and 11% respectively) (Lloyd et al., 2011), while 15 year old basketball youths jumped higher (10%) than 14 year old youths (Coelho et al., 2008).

Coelho et al. (2008) divided his subjects into three maturational groups; early, late pubescent and mature, based on Tanner's method. The late pubescent group jumped the highest and performed better than the early pubescent (4%) and mature (15%) youths. The mature youths actually had the lowest jump height among the three maturational groups. In summary, the chronologically older males performed better than the younger males, but when based on maturational age the mature males actually performed worst. While the findings of our study are different from Coelho et al. (2008) and Lloyd et al. (2011), it does highlight the need for measurement of biological age.

It is important to note we have normalized most variables by body mass, as it has been observed that post peak height velocity (PHV) is a period where an increase muscle mass or weight increase (PWV) has been observed (Beunen, 1997). During male adolescence it has been noted that there is a correlation between muscle strength with the increase in cross-sectional area (CSA) of both muscle and the muscle fibres. This increase in CSA and muscle fibres during post-pubertal adolescence has been described as testosterone-dependent of which males experience an increase in testosterone production during puberty (Ikai & Fukunaga, 1968). These reasons likely explain the significant increase in SJ ability during maturation.

It was interesting to note that the same was not true for relative mean power averaged over the concentric phase. While the pre-pubescent males generated less (11%) MCP it was not significantly different to the more mature subjects. Since there was a significant increase in relative peak force and power, but non-significant increases in mean concentric power, it seems the ability to produce higher relative force and power increases with maturation but maybe velocity is less influenced given power is the product of force and velocity.

When the SJ comparisons were made between the female maturity groups no significant differences ($p < 0.05$) were observed. The average gains across maturity were about 3 to 8%, with the pre-pubescents' actually performing equally if not better in variables such as relative MCP and peak force. Comparing these results to other studies is problematic given that no studies to the authors' knowledge have measured SJ performance in female youths. Therefore these findings are novel and unexpected, and highlight a potential area for further investigation.

In terms of muscle growth, females are disadvantaged during puberty as compared to males. As mentioned previously the development of muscle tissue during post-pubertal adolescence has been described as testosterone-dependent (Ikai & Fukunaga, 1968). While males experience almost 10 times more increase in testosterone production during puberty (Wilmore & Costill, 1994), the females do not. Therefore females do not experience the rapid acceleration of muscle growth at puberty. However, they still continue to experience muscle growth albeit much lesser than boys. These differences will continue to increase and become quite significant at the age of 16 years old (Malina & Bouchard, 1991). This testosterone dependent adaptation may provide a possible explanation as to why there were little gains with age once controlling for body mass changes for the female subjects and possibly the significant interaction effect noted for peak force for SJ.

The change in the CMJ variables of interest with maturity was not as obvious as compared to the SJ, as the only variables to differ significantly across genders were vertical stiffness and relative MEP. The non-significant differences between maturity groups in the variables of interest are difficult to explain given the results of the SJ. It can only be speculated that somehow the effects of the eccentric countermovement on the ensuing concentric phase was similar across maturation. That is, the differences in eccentric force capability and the subsequent effects on concentric force capability are less pronounced with maturation. Another possible explanation of the non-significant differences is the movement variability associated with SSC motion as indicated by the magnitude of the standard deviations for the two peak measures. Interestingly however, the variability of the other CMJ measures was very similar to the SJ measures.

The younger subjects (both males and females) had a lower vertical stiffness (~14 - 60%) as compared to the more mature subjects. This is consistent with the literature, where changes in the elastic properties across ages (Danielsen & Andreassen, 1988; Elliot, 1965; Korff, Horne, Cullen, & Blazevich, 2009; Kubo, Kanehisa, & Fukunaga, 2001; O'Brien et al., 2010) and across genders in adults (Granata et al., 2002; Kubo, Kanehisa, & Fukunaga, 2003; Padua et al., 2005) have been observed. Differences in mechanical stiffness between maturational groups can differ from 84% to as much as 334% (Elliot, 1965; O'Brien et al., 2010) with stiffness increasing with maturity. It is difficult to compare the stiffness values directly with other research, as other studies on youth have utilised different methods of measuring stiffness such as leg stiffness and absolute stiffness during hopping and running tasks, instead of the vertical stiffness calculation as derived from McMahon and Cheng's (1990) study.

Vertical stiffness has also been suggested as an indication of eccentric strength (McMahon & Graham-Smith, 2010) in that to increase stiffness you need to decrease the rise and fall of the centre of mass (COM - vertical displacement) or increase peak force capability. Given that the relative peak forces did not change significantly with maturation it is assumed that the displacement of COM decreased with maturation and that was the major contributing factor to the increase in vertical stiffness and possibly MEP in the females. This increase in stiffness across maturation was particularly obvious in the females. Two likely reasons can explain this increase in stiffness. The first, stretch reflex potentiation has been observed to be related to the individual's maturity (Finan & Smith, 2005; Grosset, Mora, Lambertz, & Pérot, 2007; Lin, Brown, & Walsh, 1997). While the central mechanisms that control stretch reflex in children are believed to be mature by the time they reach pre-pubescence (Grosset et al., 2007; Scammon, 1930) the mechanically induced reflex and twitch time increase with maturity to the point of adulthood, which is likely due to the maturation of the sensorimotor pathways before it slowly deteriorates again as one grows older (Lin et al., 1997). 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 all of which improve with maturation (Grosset et al., 2007).

The second reason for the differences may be attributed to the changes of the architecture of the muscle-tendon unit (Bailey et al., 1998; Diamant et al., 1972; O'Brien et al., 2010; Parry, Barnes, et al., 1978; Parry, Craig, et al., 1978; Reed & Iozzo, 2003). Besides just pure overall increase in tendon size, length, and collagen fibril diameter with maturity, increases have been observed for fibril density or packing and cross-linking within the collagen itself (Bailey et al., 1998; Reed & Iozzo, 2003). Another architectural change could be the reduction of collagen crimping which contributes to increased stiffness. Collagen fibres are packed in parallel in wavy lines (Diamant et al., 1972; Rigby, 1964). The crimp refers to the "waviness" of the fibril that contributes to the nonlinear stress strain relationships. As the collagen fibrils becomes "uncrimped", their 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 age (Kastelic et al., 1980; Patterson-Kane et al., 1997).

Also it needs to be noted that this time period is a stage where bone grows in length without an accompanying increase in muscle length leading to reduced flexibility (Bachrach, Hastie, Wang, Narasimhan, & Marcus, 1999; Kendall & Kendall, 1948; Xu, Nicholson, Wang, Alén, & Cheng, 2009). As a result of this growth there may be a reduction in tissue compliance, which explains the vertical stiffness results. Furthermore, this reduction in compliance with maturation, could be a contributing factor that limits force and power production for the CMJ as opposed to the SJ. That is, the ability to store and utilise elastic energy is compromised.

The EUR gives an indication of SSC augmentation by comparing the SJ and CMJ as a ratio (McGuigan et al., 2006). Most adult athletes will have an EUR of at least one as it is expected that the countermovement will improve performance by between 18% to 30% in adults (Bobbert et al., 1996; Komi & Bosco, 1978; McGuigan et al., 2006). A high EUR will mean that the ability or SSC augmentation of the athlete is high. Interestingly the EURs were significantly higher in the pre-pubescent as compared to the mid- and post pubescent athletes. This can most likely be explained by the increased compliance of the tissues in the pre-pubescent subjects (i.e. opposite to increased stiffness in the more mature subjects), a more compliant tissue able to store and release elastic energy to better effect (Bobbert, 2001; G. a Lichtwark & Barclay, 2010; Roberts, 2002). Nevertheless, the magnitude of the SSC augmentation for all three groups was consistent with other findings, the CMJ found to be superior by about 6.8 to 10.3% for jump height and up to 17% for peak force (Gerodimos et al., 2008; Harrison & Gaffney, 2001; Harrison & Moroney, 2007; Richter et al., 2010).

The ratio of MEP to MCP (MEP/MCP) showed a similar trend to the EUR where it was observed to decrease with maturity, however, the only significant difference was between pubescent and post-pubescent females. The ratio indicates the individual's efficiency in absorbing and producing power, any decrease in the ratio influenced by either a decrease in relative mean eccentric power or an increase in relative mean concentric power. It would seem from our results that the ability to absorb power and/or the eccentric strength of the subjects is similar with maturation, whereas the increases in power output (relative MCP) with maturation may better explain the trending changes in the ratio. That is, concentric force and power are more likely influenced by maturation than eccentric force and power. Furthermore, it may be that faster CMJ eccentric components may be of greater influence on this ratio, as it has been argued that movements that are of longer duration, slower eccentric velocity and greater range of motion, such as the CMJ may not benefit from the eccentric work as do faster, shorter duration SSC movements (Chapman et al., 1985; Komi & Gollhofer, 1997).

3.0 Conclusion

Naturally as an individual grows and matures, their jump performance also improves, which is to be expected and has been observed to a certain extent in this study. Gender differences were also observed and these differences increased with maturity. Differences in SJ performance across the maturational groups were different as compared to CMJ performance, where no significant maturational differences were observed. It would seem that concentric force/power capabilities (i.e. SJ performance) are more likely to be influenced by maturation than eccentric force and power. Furthermore it appears that the eccentric capability and thus SSC augmentation is optimal around pubescence and with maturity this ability diminishes to some extent. These changes are most likely best explained by growth related factors (i.e. increase in bone length and loss of tissue extensibility around PHV) as well as maturational factors (i.e. changes in tissue compliance/stiffness).

Given these findings it would seem that pre-pubescent athletes would react favorably to plyometric type training given their eccentric force power capability and proposed compliance of their tissues. With maturation it would seem advantageous for the youth coach to consider including eccentric training, especially around the pubescent years. While this study encourages early eccentric training, it is also important to remember that eccentric training should not be viewed as solely a part of plyometric training, but as a pre-requisite. That is, eccentric strength training focusing on stability and alignment would be a pre-requisite to jump type training. Since pubescence is also a time period where flexibility seems compromised due to the growth spurt in skeletal development, it is recommended that a regular stretching routine is included in the training protocol of youths, especially during pubescent and post-pubescent years. The purpose of this stretching is to retain tissue compliance, which should help maximise the storage of elastic energy especially for sports that have a high SSC demand. A regular stretching program will also serve to maintain or increase flexibility and minimise injury risk factors that are commonly associated with growth spurts in youth such as Osgood-Schlatter disease. This is especially important to remember for those dealing with the youth athlete, ensuring longevity in sports as well as continued active involvement in long term development of the athlete, a primary focus of the youth coach.

CHAPTER 4: GENERAL SUMMARY

1.0 Summary

In the past decade there has been an increasing awareness as to the importance of training specific to the needs of the youth athlete. The belief that youths are not simply “mini-adults” is beginning to permeate the training philosophy of youth coaches. Unlike adults, the biological maturity of youth does not necessarily coincide with their chronological age and can differ by several years. This realization has led to the increased awareness of growth and maturation and especially the biological changes and physical developments that accompany each stage of maturation. The development of fitness components such as speed, power, endurance and strength in youths has been the topic of research in the past few decades. An associated area that is topical and underlies many of these fitness components is SSC ability across maturation. Research in this area is somewhat conflicting, thus this thesis sought to examine SSC potentiation at different stages of maturation and gain a better understanding of its development to assist in the development of training programs for youths.

From the experimental study it was observed that most of the SJ variables differed significantly ($p < 0.05$) across the maturational stages, however, the same was not true for the CMJ. It was proposed that concentric or contractile ability (i.e. concentric force and power production) was maturity dependent. Eccentric ability however, for the most part differed little across the maturation groups, leading to the contention that eccentric ability was not maturity dependent and is well developed in the pre-pubescent athlete. This finding most likely explains the lack of difference in CMJ performance across the maturational stages.

Another notable finding was that vertical stiffness increased with maturity. This increased vertical stiffness is not surprising especially during adolescent growth spurt, where skeletal growth outpaces muscular growth. Furthermore, changes in reflex activity and tissue extensibility were other factors thought to influence this change in stiffness. It was also thought that these factors could explain the CMJ findings and the difference in the EUR PF ratio across maturation.

2.0 Practical Applications

While there are many ways to classify youths, this thesis selected a non-invasive method to classify youths as either pre-pubescent, pubescent and post-pubescent based on PHV. This method of classification is relatively easy to use and is recommended for use by youth coaches who are interested in using maturation as an indicator of training specificity.

The main finding of the thesis was that SSC potentiation was observed across all maturation groups, with the greatest potentiation noted in the pre-pubescent group. Youth coaches who want to integrate SSC type of training however, should take note of a few factors:

2.1 Vertical Stiffness increases with maturity

It is possible that increased vertical stiffness combined with the overall muscle tightness associated with growth and maturation, could be a contributing factor that limits the mean force and power production during the CMJ. Therefore it is highly recommended that a regular stretching routine to be included in the training protocol of youths especially during pubescent and post-pubescent years. The stretching program should include dynamic and static type activities to increase tissue compliance and thus maximise the storage of elastic energy. Furthermore, regular stretching is needed to maintain or increase flexibility and minimise risk factors and/or injuries associated with growth spurts in youth such as Osgood-Schlatter disease.

2.2 Eccentric ability in youth

This study has observed that the eccentric ability is not dependent on maturity and is well developed in the pre-pubescent athlete. The youth coach might want to consider including a little extra time on overall eccentric training and ability in youth, beginning in the pre-pubescent years and certainly emphasizing this type of training during pubescence and post-pubescence. An eccentric training program for youths should initially focus on full range of motion and correct alignment and stability. After exhibiting competency in these fundamental movement patterns, activities should progress to smaller amplitude higher velocity type movements similar to those observed in a sporting context.

3.0 Limitations and Delimitations

The authors note and acknowledge the following limitations and delimitations of the research performed.

3.1 Peak Height Velocity as a maturational selection tool

This thesis has opted to utilise height monitoring through PHV as the method of classifying maturation. This was the method of choice due to its ease of use and non-invasiveness. Nevertheless, it is not without its limitations:

- Accuracy of growth charts is based on population studies from different parts of the world. Socio-economic and nutritional (Berkey et al., 2000) histories significantly influences these charts. Using data charts derived from one country may not apply to another. This is especially true when data derived from developed countries are compared to that of developing countries. For this study, we have managed to utilize Singaporean growth charts. The reader needs to be cognizant of this limitation if comparisons to other ethnic groups are made.
- The study used the only available growth charts for a Singaporean population from 1993, which might possibly be slightly dated. Growth charts are derived from longitudinal studies. These studies track data from birth to early adulthood and take at least 20-25 years to conduct. As such, these studies are not only expensive but require long term logistics, consistent methodologies and dedicated resourcing.
- For females, menarche marks the start of the pubertal phase in the female adolescent (Malina, Bouchard, et al., 2004). While this is slightly more invasive, it is probably a much more accurate measurement tool then height monitoring for females. This could actually be combined with height monitoring to offer a more accurate assessment of maturation in female youths.

3.2 Small sample of pre-pubescent females

This thesis only managed to collect data from 27 pre-pubescent females as opposed to other maturational groups and gender. This may limit the strength of the findings for this group.

3.3 Trained Youth Athletes versus Average Sedentary athletes

This thesis utilised trained youth athletes, every youth measured in this study was a trained youth athlete participating in one of nine sports who have shown early success in their chosen sport. While the author believes the findings are still indicative of the youth population, it is suggested that this knowledge be factored when comparing against sedentary populations.

3.4 Difference between Races

This thesis measured the SSC ability of youth across three different races. Chinese, Indian and Malays. While the author believe the findings in general are still indicative of the youth population, racial differences may be apparent and it is definitely an area for future research.

4.0 Direction for Future Research

This thesis has made an original contribution to knowledge pertaining to the development of the SSC across different maturational stages. However, due to the lack of research performed on youth according to their biological age as opposed to chronological age, a number of areas still require investigation.

4.1 Influence of sports training to SSC development.

This study has measured the general youth population participating in sports. It would be interesting to compare the SSC development across maturational groups across the different sports, sports with high SSC requirements and sports with low SSC requirements. This could possibly give insight into the trainability of SSC potentiation in youth.

Whilst this study compared a number of measures it may be that other variables such as rate of force development (eccentric and concentric), work or impulse may give greater insight into understanding SSC potentiation across maturation. Given that impulse determines take-off velocity, this variable would seem especially important. Whether the importance of SSC potentiation in horizontal movements across maturation will also need to be determined.

4.2 Difference in SSC development between races

This study has measured the SSC potentiation in Singaporean youths. general youth population. This study measured youth of all ethnicity. While the differences between the ethnic races are not likely to seriously affect the findings and observations, it may be another area for future research.

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ABBREVIATIONS AND GLOSSARY

ABBREVIATIONS

ATF	Athlete Tendon
Ca^{2+}	Calcium
CC	Contractile Component
CMJ	Countermovement Jump
DJ	Drop Jump
EMG	Electromyography
EUR	Eccentric Utilisation Ratio
MVC	Maximal Voluntary Contraction
PEC	Parallel Elastic Component
PEVK	Proline-, glutamate-, valine-, and lysine-rich
PHV	Peak Height Velocity
PPS	Plyometric Power System
PSA	Prestretch Augmentation
PSV	Peak Speed Velocity
ROM	Range of Motion
PWV	Peak Weight Velocity
RSI	Reactive Strength Index
SBJ	Standing Broad Jump or Standing Long Jump
SEC	Series Elastic Component
SEE	Stored Elastic Energy
SJ	Squat Jump
SQAT	Strength Qualities Assessment Test
SSC	Stretch Shorten Cycle
TT	Tetanic Tensions
VJ	Vertical Jump
Vs.	Versus

UNITS OF MEASUREMENT

cm	Centimetre (unit of length)
CV	Coefficient of variation
K	Stiffness
K_{leg}	Leg Stiffness
kg	Kilogram (unit of mass)
m	Metre (unit of length)
ms	Millisecond (unit of time)
ms-1	Metres per second
$N.kg^{-1}$	Newton per kilogram per second squared
N/kg	Newton (unit of force) / Kilogram (unit of mass)
Nm/rad	Newton meter / radian (unit of torque)
Nm/rad/%	Percentage difference of torque, newton meter / radian
SD	Standard Deviation
W	Watts
W/kg	Watts / Kilogram (unit of mass)
$W.kg^{-1}$	Watts / Kilogram per second
%	Percentage
º/Nm	º/Nm

GLOSSARY

Adolescence	Generally viewed as occurring between the ages of 12 to 18 years where great physical and mental development occurs such as puberty.
Biological Age	The active rate at which the body is aging. Focuses on senescent changes in biological and physiological processes
Chronological Age	Current age in time (years and months), calculated from the birth date.
Coach	An individual that provides direction, instruction and training to another individual or team in the operations of a sport or physical skills.
Compliance	The inverse of stiffness.
Growth	Growth refers to the progressions in the size and shape of the body, its organs and circulatory systems until adulthood is reached
Growth Spurt	Refers to the rapid increase (intense) in the rate of growth of the individual during adolescence.
Maturation	Refers to the process whereby humans progress from childhood to adulthood. The timing and tempo of this process varies from individual to individual because we all have our own biological clocks.
Maturity	Refers to the stage of maturation of the individual. Also commonly used to refer to sexual maturity, where the individual is capable of sexual reproduction
Power	The rate at which mechanical work is performed (Power = force x distance/time)
Post-Pubescent	Occurring after puberty.
Pre-Pubescent	At the age immediately before puberty; often marked by accelerated growth. Before the age at which a person is first capable of sexual reproduction.
Pubescent	The age at which is just capable of sexual reproduction of offspring
Puberty	the period or age at which a person is first capable of sexual reprod uction of offspring:

Stiffness	The rigidity of an object. The object ability/extent to resists deformation in response to an applied force. The complimentary and opposite concept is compliance.
Strength and Conditioning coach	A coach whose job is the physical and physiological development of athletes for elite sport performance.
Torque	Moment of Force
Velocity	The rate of change of displacement with respect to time. Expressed as the ratio of displacement and time (d/t)
Youth	Generally refers to the time period between childhood and adulthood (maturity).

APPENDICES

Appendix 1: Sample of Informed Consent Form

6 November 2008

SINGAPORE
SPORTS SCHOOL

Dear Parents,

INFORMED CONSENT FOR PARTICIPATION IN SPORTS SCIENCE TESTING- YEAR 2009 SEC 1 INTAKE

As part of our approach to training and enhancing performance towards sporting excellence, it is deemed necessary that your son/daughter be involved in various sports science testing. The tests will provide coaches an insight into the areas of weaknesses and strengths, so that they can plan and implement appropriate training program. The tests in the respective Sports Science areas include:

- **Sports Physiology and Strength and Conditioning**
  Anthropometry (e.g. skinfolds, girth and limb length measurements), Fitness Assessments (e.g. VO_2 max testing on treadmill and/or cycle ergometer), Blood glucose, blood iron and lactate tests through finger-prick.
- **Sports Biomechanics**
  Power and movement analysis using force platforms and high-speed camera systems; performance through analogue and/or digital video capture.
- **Sports Physiotherapy**
  Musculoskeletal screening to determine joint flexibility, stability, imbalance and abnormalities.
- **Sports Psychology**
  Written and oral interviews on profile and other psychological tests.

Withdrawal
The tests will cease pre-maturely when the student requests to stop or when sports scientists observe any signs that require the tests/interviews to be stopped. All care will be taken to minimize any risks involved in the tests.

Informed consent
As part of the testing process, photography and videography of the trial process and procedures will be carried out for analysis and documentation purposes. All photos and videos will be kept by the School and viewed in confidentiality by relevant personnel only. Signing the attached informed consent form indicates your willingness to allow your son/daughter to be tested, photographed and videotaped for tests indicated above to the specified procedures of the Sports Science Academy in the Singapore Sports School. Participation in the tests is strongly encouraged and we look forward to your consent.

For enquiries, please contact Mr. Gobinathan Nair, the Assistant Director for the Sports Science academy at 67618644 or gobinathan@sportsschool.edu.sg

Yours sincerely,

Chua Choon Seng
Director of Corporate Services

Attn: Mr. Gobinathan Nair
Singapore Sports School
1 Champions Way
Singapore 737913

INFORMED CONSENT FORM

I acknowledge that:

1. I have read the letter and information sheet and have been given the opportunity to ask questions and discuss about the tests to my satisfactions:
2. I understand the purpose of the various sports science tests;
3. I have been informed that my child is free to withdraw from the tests at any time without prejudice;
4. I have been informed that any information provided to the School will be safeguarded and remains confidential;
5. I have been informed and agree that my child be photographed and/or videotaped during the trial for documentation and analysis purposes.

I, _______________ (name of parent/legal guardian*), ________ (NRIC no), being the parent/legal guardian * of ________________________ of the ____________________ academy, have read your letter and understood the contents.

I consent/do not consent* to my child's participation in the sports science test.

Name of student: ___________________________

Relationship to student: ___________________________

___________________________ ________________
Signature Date

*please delete accordingly

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Programme	MASTER OF SPORTS AND EXERCISE	**Year of submission (for examination)**	2013
Research Output	**Thesis** ☒ **Exegesis** ☐	**Dissertation** ☐	**Points Value** 120
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