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# Slow Stretch-Shorten Cycle Characteristics: Gender and Maturation Differences in Singaporean Youths

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### Abstract

**Objective:** This cross-sectional study aims to compare the differences between the countermovement jump (CMJ) and concentric only squat jump (SJ) (no arm swing) and examine the differences and slow SSC ability of youths at different stages of maturation (pre-pubescent, pubescent and post pubescent).

**Methods:** 101 male and 109 female Singaporean youths were recruited and divided into different maturational status. The youths performed up to six trials of CMJ and SJ each on a force plate to determine the SSC augmentation found in a CMJ. Various variables and ratios were used to compare the differences between the CMJ and SJ. Comparisons were made across both genders and the three different maturations phases. Further analysis was conducted to determine if the dependent variables differed according to the gender and/or maturity status of the youths.

**Results:** Significant differences ($p<0.05$) were found between males and females across all of the SJ and CMJ variables with the exception of relative mean concentric power (MCP) for the CMJ and eccentric utilisation ratio (EURs) (jump height and peak force). Gender differences were observed for other variables and these differences increased with maturity. Variables in SJ performance across the maturational groups were different as compared to CMJ performance, where no significant maturational differences were observed.

**Conclusion:** It would seem that concentric force/power capabilities 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.

### Keywords

Stretch shorten cycle; Youth; Maturation; Plyometrics; Countermovement jump; Squat jump

## 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. Stretch-shorten cycle motion can either be a fast but small SSC motion (eg., Jogging), or a slow and bigger motion (countermovement jump). Unlike adults, the biological maturity of youth does not necessarily coincide with their chronological age and can differ by several years [1,2], 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.

It has been observed for females, that strength performance continues to increase during puberty however, no noteworthy changes occur post-puberty [3]. In males, it has been observed that the strength continues to increase as they grow older initially at an average rate. However, this strength increase accelerates during the male growth spurts, which can likely be attributed to the hormonal influx at this stage of maturation [4,5]. These strength changes across maturation could possibly have an effect on SSC performance.

Other factors that may affect SSC ability are changes in the elastic properties and stiffness of muscle across maturation. While the exact role of stored elastic energy (SEE) during SSC is debated in the literature [6-8], there is no study that denies its place in force potentiation during SSC motion, the pre-stretch generally believed to be a valid amplifier of power [9]. Differences in mechanical stiffness between maturational groups have been reported to differ from 84% to 334% [10,11]. For example, Elliot [10] 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 [11,12]. Similar finding concerning, muscle stiffness and maturation have also been observed in other studies [13-15]. 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 slow SSC ability is possibly affected to some extent by these changes across maturation.

In terms of documenting changes in slow SSC ability, the comparison of a concentric only jump (squat jump – SJ) to a slow SSC jump (countermovement jump – CMJ) is a simple and well-utilized approach. Since there is no countermovement (eccentric contraction) in the concentric only SJ, the difference between the two jumps is an indicator of the eccentric contributor of the slow SSC. Most studies using this methodology with adults, have reported a potentiation in CMJ performance of 18% to 30% as compared to the SJ [6,16]. While a great deal of research has investigated CMJ *vs.* SJ performance in adults [6,16,17], there has been 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%) [18-21]. A recent study [22] however, has suggested that this might not always be the

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case, at least for jump height. In that study children aged 12 to 14 years of age had a better SJ jump height (approximately 2 to 4%) as compared to CMJ. Children, 15 years of age 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 [23]and concentric strength [24] 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 [19,20,25]especially for the SJ [18]. 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 slow 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 [26] during a CMJ. Such an approach has not been used in youth and would give insight into slow SSC ability across maturation. Given this information the purpose of this study is to compare the differences between CMJ and SJ and examine the slow 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. The information gathered might provide information that can assist coaches in the planning and design of training programs for youths at the different maturational stages as part of a holistic long term development. Furthermore if differences exist, this might be suggestive of a possible window of trainability for the development of SSC during maturation.

## Methodology

To observe the SSC ability of youths, youths of both genders (n=209) across the three different maturity status (pre-pubescent, pubescent and post-pubescent) performed up to six trials of CMJ and SJ each to determine the SSC augmentation found in a CMJ. Various variables and ratios were used to compare the differences between the CMJ and SJ. Comparisons were made across both genders and the three different maturations phases. Further analysis was conducted to determine if the dependent variables differed according to the gender and/or maturity status of the youths.

### Subjects

101 male and 108 female youths aged between 11 to 17 years of age, from the Singapore Sports School (SSS) participated in this study (Table 1). One of the main inclusion criteria was that youths must have completed a minimum of three months resistance training experience and had undergone a structured (progressive) basic jump (and landing) training program, conducted by the school's strength and conditioning unit were selected for this study. This is done to ensure that the youths are familiar with both the CMJ and SJ [18] and minimise the variability in jumping performance. The youths were tested only during the off-season and during and as part of their normal routine strength and conditioning training.

Participants as students of the Singapore Sports School had already given their own assent and parents had consented to their children to be tested for monitoring purposes. All ethical guidelines as determined by the Singapore Sports School Research and Ethics Committee were adhered to during each study. No data is linked or identified to any participants.

### Maturity assessment

To determine the subject's maturational stage, two criteria based on height were used simultaneously to categorise subjects as pre-pubescence, pubescence and post-pubescence [27,28]. The first criteria was their growth rate defined as the increase in height (in centimeters) within the past 12 months [27,29,30]. The second criteria was to observe if they had met the national average height for Singaporeans for the same chronological age [31].

Subject's height has been constantly monitored, about 8-9 measurements a year during the school terms. 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 [30]. Subjects who had shown this increase in the past 2 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.

### Jump assessment

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.

Concentric only SJ as well as CMJ were performed and analysed in this study. Since there is no countermovement (eccentric contraction) in the concentric only SJ, the difference between the two jumps is an indicator of the eccentric contributor of the slow SSC. Subjects performed the jumps without the aid of the arm swing by holding on to a plastic stick (weighing less than 0.5 kg) on the shoulder as though they were performing a back squat. For the SJ, the subjects

**Table 1:** Physical Characteristics of Participants (Means ± SD).

| | Males (*n=101*) | | | Females (n=108) | | |
|---|---|---|---|---|---|---|
| | Pre- Pubescent | Pubescent | Post- Pubescent | Pre- Pubescent | Pubescent | Post- Pubescent |
| | (*n=35*) | (*n=33*) | (*n=33*) | (*n=27*) | (*n=54*) | (*n=26*) |
| Age (years) | 13.3 | 14.5 | 15.1 | 12.0 | 13.7 | 15.1 |
| | ± 1.04 | ± 0.96 | ± 2.80 | ± 1.12 | ± 1.62 | ± 1.00 |
| Stature (cm) | 145 | 160 | 165 | 136 | 161 | 164 |
| | ± 43.0 | ± 33.9 | ± 31.8 | ± 51.0 | ± 5.88 | ± 6.10 |
| Mass (kg) | 46.9 | 52.6 | 59.4 | 45.7 | 53.5 | 55.3 |
| | ± 9.67 | ± 6.04 | ± 10.5 | ± 7.16 | ± 7.13 | ± 8.46 |

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were required to squat and flex the knee to approximately 90 degrees (as determined by the investigator), maintaining the positions for about three to four 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 countermovement was noted students were required to repeat the particular jump (up to 6 trials, excluding the familiarization jumps). 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.

### 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 formal sessions. The first session consisted of a briefing, determination of maturation and familiarization of the test procedures and protocols. At the end of the session, the subjects were classified into the different maturational stages, understood the test protocols and were able to correctly perform the jumps. 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 either 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 [18]. 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, subjects 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 were recorded, averaged and used for analysis.

### Data analyses

The dependent variables of interest are listed below. All data was obtained directly from the force plate or derived from this data as listed below.

**Relative peak force (N/kg):** Highest force generated during concentric phase of jump in relation to subject's mass

**Relative peak power (W/kg):** Highest power generated during concentric phase of jump in relation to subject's mass

**Jump height (cm):** Calculated via flight time (9.81*flight time*flight time)/8

**Relative mean concentric power (W/kg) (MCP):** Mean power generated during concentric phase of jump in relation to subject's mass

**Relative mean eccentric power (W/kg) (MEP):** Mean power generated during eccentric phase of jump in relation to subject's mass

**Vertical stiffness (k):** Ground reaction force divided by vertical movement of the center of mass.

**Eccentric utilisation ratio (EUR):** The ratio between a countermovement jump and a concentric only squat jump. The ratio is calculated using both relative peak force and jump height [17].

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

### Statistical analyses

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.

## Results

The results of the different jump conditions for both males and females across the different maturational groups are shown in table 2A (squat jump) and in table 2B (countermovement jump). 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 Peak Force 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 - 17%) and relative peak power (11 - 16%). For the

**Table 2a:** Means (± SD) for squat jump variables across maturational stages for males and females.

| Variables | Males | | | Females | | |
|---|---|---|---|---|---|---|
| | Pre-Pub (*n=35*) | Pub (*n=33*) | Post-Pub (*n=33*) | Pre-Pub (*n=27*) | Pub (*n=54*) | Post-Pub (*n=26*) |
| 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)‡ |

Note: *=Pre-Pub & Pub differ significantly; # - Pub & Post-Pub differ significantly; ^ -Pre-Pub & Post-Pub differ significantly

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**Table 2b:** Means (± SD) for countermovement jump variables across maturational stages for males and females.

| Variables | Male | | | Male | | |
|---|---|---|---|---|---|---|
| | Pre-Pub (*n=35*) | Pub (*n=33*) | Post-Pub (*n=33*) | Pre-Pub (*n=27*) | Pub (*n=54*) | Post-Pub (*n=26*) |
| 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)‡ ^# |

Note: *=Pre-Pub & Pub differ significantly; # - Pub & Post-Pub differ significantly; ^ -Pre-Pub & Post-Pub differ significantly

**Table 2c:** Means (± SD) for ratios when comparing countermovement jump vs squat jump across maturational stages for males and females.

| Variables | Males | | | Females | | |
|---|---|---|---|---|---|---|
| | Pre-Pub (*n=35*) | Pub (*n=33*) | Post-Pub (*n=33*) | Pre-Pub (*n=27*) | Pub (*n=54*) | Post-Pub (*n=26*) |
| 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

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.

For EUR, the most noticeable differences (~9 to 10%) were observed in terms of the peak force EUR for both genders (Table 2C). The greatest benefits of the countermovement (1.17 and 1.20) were 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 was very similar between males and females. The only significant difference (-24%) observed was between the female pubescent and post-pubescent.

## Discussion

In terms of the SJ and CMJ, males were found on average to produce greater relative force (6% for SJ, 9% for CMJ), relative power (21% for SJ, 11% for CMJ), and jump height (21% for SJ, 20% for CMJ) than their female counterparts. Even after leg strength was controlled for mass via ratio scaling, male's strength and power were significantly superior to females, suggesting qualitative factors (neural and/or hormonal) may be more influential than quantitative factors (muscle mass and size). These strength differences between gender are consistent with other studies in both adults and youths and are not unexpected [3,32-35].

The gender differences in general were greater in the more mature groups as compared to the pre-pubescent group. For the CMJ, the gender differences increased with greater maturity - a 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%) which 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 years old [3,5,36]. 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). Generally, female performances increase up to the age of 13 and 14 before it starts to plateau [3]. The plateau does not seem to be observable in males until a much later age.

The SJ performed in this study was 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 [20,22]. 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. [22] (0.26 to 0.31 m) for a group of 11 to 14 year olds males and was about 0.30 m in young adolescents in the study by Gerodimos [20]. Relative 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 [18]. In terms of power, Harrison and Gaffney [18] observed a peak power of 28 ± 3 $W.kg^{-1}$ while the pre-pubescent youths in this study generated greater peak power output (43.9 ± 15.0 $W.kg^{-1}$ for males, 35.7 ± 13.4 $W.kg^{-1}$ females). Several factors could possibly explain the greater ability in power generation. The pre-pubescent subjects in this study were older (chronologically) and are also youth athletes, actively participating in sports when compared to the subjects in the study by Harrison and Gaffney. The subjects in this study were also properly trained in the squat jump, prior to the tests, while the youths in the other studies may have shown immature jumping patterns [15-37] and unlikely to have been trained in the squat jump.

As force and power production is likely to increase as one matures [38-41], it is logical to assume that the jump variables under investigation in this study will increase as the individual matures. The finding from this study confirms such a contention as 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 [22,42]. Males of 16+ and 15 years of age, jumped higher (27% and 11% respectively) than males at 13 years of age [22], while 15 year old basketball youths jumped higher (10%) than 14 year old youths [42].

Coelho et al. [42] divided his subjects into three maturational groups, early, late pubescent and mature, based on Tanner's method. Based on maturation, 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 chronological older males performed better than the younger males, but when based on maturational age, the mature males actually performed worst. While the findings of this study are different from Coelho et al. [42] and Lloyd et al. [22], it does highlight the need for measurement of biological age.

Most variables have been normalized by body mass, as it has been observed that post peak height velocity (PHV) is a period where an increase muscle mass or body weight increase (peak weight velocity - PWV) has been observed [24]. During male adolescence it has been noted that there is a correlation between increase in muscle strength with increase in cross-sectional area (CSA) of both muscle and the thickness of muscle fibres. This increase during post-pubertal adolescent has been described as testosterone-dependent of which males experience an increase in testosterone production during puberty [43]. These factors could possible contributed to 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-pubescent 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 author's knowledge have measured SJ performance in female youths. Therefore these findings are novel and unexpected, and highlight a potential area for further investigation.

Females continue to gain significant mass (kg) as they mature (Table 1); however their muscle mass and strength do not necessarily grow at the same rate. In terms of muscle growth, females are disadvantaged during puberty as compared to males. The development of muscle tissue during post-pubertal adolescent has been described as testosterone-dependent [43]. Males experience almost 10 times more increase in testosterone production during puberty than females [44], therefore females do not experience the rapid acceleration of muscle growth at puberty. These differences will continue to increase and become quite significant at the age of 16 years [2]. 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 were 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 [10,11,45,46] and across genders in adults [32,33,47] have been observed. Differences in mechanical stiffness between maturational groups can differ from 84% to as much as 334% [10,11] 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 study [48].

Vertical stiffness has also been suggested as an indication of eccentric strength [49]. Given that the vertical forces (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. A similar observation was found between adults and prepubescent children [50]. 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 [13,14]. While the central mechanisms that control stretch reflex in children are believed to be mature by the time they reach pre-pubescence [13,51]the mechanically induced reflex and twitch time increases 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 [14]. Other possible contributors to the development of the stretch reflex could possibly be improved spindle sensitivity and/or increased gamma drive ($\gamma$) of the muscle spindles all of which improve with maturation [13].

The second reason for the differences may be attributed to the changes of the architecture of the muscle-tendon unit [11,52-55]. 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

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[54,55]. Another architectural change, would be the reduction of collagen crimping which contributes to increased stiffness. Collagen fibres are packed in parallel in wavy lines [52,56]. The crimp 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 [57,58].

It needs to be noted that this time period is a stage where bone grows in length without an accompanying increase in muscle length [59,60]. As a result of this growth there may be a reduction in tissue compliance, which could possibly have an effect on the vertical stiffness. 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 [17]. 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 [6,16,17]. 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 subjects. A possible contributor to the higher EUR would be 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 is able to store and release elastic energy to better effect [61-63]. The compliance level of the pre-pubescent subjects could have been a more optimal level for better jumping performance compared to the compliance level of the more mature subjects. The more mature subjects could have experienced a changed in tissue compliance due to the growth in stature during the maturation process. 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 [18-21].

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. It may be that faster CMJ eccentric muscle action 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 [64].

Being a cross-sectional study, this study has the typical limitations of such a study design. It is suggested that a follow-up study that actually tracks the actual changes for each individual youth as they mature would provide a more accurate view and better understanding. The study has also selected to use a non-invasive measure of determining maturity due to practical, cultural and ethical reasons. A more invasive method such as using the Tanner Scale or using radiography (hand-wrist or cervical) may have increase the accuracy and sensitivity of the maturational classification as compared to using PHV.

## 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).

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