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**Original Article**

# Influence of chronological age on reactive strength in 8 - 13-year-old female figure skaters

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**Abstract**:
The purpose of this study was to determine the influence of chronological age on changes in the reactive strength index as an indicator of the ability to shorten the stretch cycle in female figure skaters of young age. We hypothesized that throughout the age period 8–13 years, female athletes experience a gradual improvement in the reactive strength of the lower extremities. The reactive strength index, which is a sports performance indicator and an injury risk indicator, was determined in six age groups of female figure skaters aged 8 to 13 years (n = 350). The results of the Welch ANOVA test showed a significant effect of age on the reactive strength index ($F = 14.245$, $p < 0.001$). The post hoc Dunnett test revealed significantly higher values in 11-, 12- and 13-year-old participants compared to 8 and 9-year-olds and in 13-year-olds compared to 10-year -olds. Age was also significant for jump height ($F = 37.083$, $p < 0.001$) but not for contact time ($F = 1.458$, $p = .207$). The observed increase in the reactive strength index throughout ages 8-13 reinforces the improvement in reactive strength consistent with a few studies in nonathletes and supports the suggestion that the application of the training stimuli that drive the development of the stretch-shortening cycle should begin in early youth. The data also indicate that the improvement in reactive strength was related to the increase in force during the concentric phase, rather than to the shortening of the eccentric and amortisation phases of the stretch-shortening cycle.
**Keywords: Stretch-shortening cycle, neuromuscular, reactive strength index, youth, growth.**

## Introduction

The stretch-shortening cycle (SSC) is defined as a muscle action that involves preactivation of the muscle prior to ground contact, fast eccentric action, rapid transition between the eccentric and concentric phases, as well as fast concentric action (Komi, 2000). SSC forms the basis of human locomotion (Komi & Gollhofer, 1997). Throughout sports performance, athletes routinely use SSC actions in high-intensity movements such as jumping that require a high level of power produced in a short period of time. To achieve elite performance in figure skating, athletes require gradual and long-term development and optimization of specific figure skating skills such as step sequences, pirouettes, single and repeated jumps, acceleration, and deceleration of skating (Taylor, 2016; Vescovi & VanHeest, 2018). Most of these specific movements require efficient SSC action associated with a high level of neuromuscular coordination and muscle power production in the lower extremities (Comuk & Erden, 2012; Podolsky et al., 1990).

Previous literature (Lambertz et al., 2003) suggests that SSC function is likely to be affected by biological maturity. During growth and maturation, neuromuscular and structural changes occur that affect the function of SSC (Lambertz et al., 2003; Radnor et al., 2018). Some previous studies that examined the natural development of SSC capability with age and maturation have shown improvements with age (Lloyd et al., 2012a; Radnor et al., 2018). In a recent review article, Radnor et al. (2018) suggest that SSC performance increases non-linearly with age; however, this assumption is based on limited cross-sectional data. Due to the neural regulation of SSC function and the influence of structural properties of the musculo-tendon unit, it is necessary to consider the potential implications that growth and maturity may have on neuromuscular and structural adaptations.

As a result of the development of intrinsic neuromuscular properties during childhood, it is suggested that the neural regulation of SSC becomes more efficient (Lloyd et al., 2012a). Children, as opposed to adults, experience a smaller number of motor units (mainly type II muscle fibers) during volitional contraction, which is reflected in lower power production (Grosset et al., 2007). Children have also been found to have higher co-contraction of m. triceps surae and m. tibialis anterior than adults, but with age it gradually decreases (Lambertz et al., 2003). Co-contraction helps ensure joint stability, but excessive activation of antagonists increases the demands on the work of agonists and decreases power output (Frost et al., 2002). The function of SSC is also affected by the electromechanical delay of the muscle, i.e. the time period between the activation of the muscle and its subsequent mechanical activity. This period is shortened during growth and maturation, which positively

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affects the ability of SSC (Grosset et al., 2005). Children also have a reduced ability to use the feedforward mechanism to increase the level of muscle activity before contacting the limb with the pad, which negatively affects the function of SSC and, among other things, manifests itself by increasing contact time (Hobara et al., 2008; Oliver & Smith, 2010). Differences were found mainly when comparing jumps at higher frequencies (Oliver & Smith, 2010) and drop jumps (Lazaridis et al., 2010). During growth and maturation, children gradually switch from reactive mechanisms to preactivation mechanisms, and the function of SSC improves (Lloyd et al., 2012a). Previous research also suggested that SSC function improves by developing Golgi tendon organs and muscle spindles (Grosset et al., 2007).

As children mature, increased cross-sectional muscle area contributes to greater muscle strength production achieved by both SSC phases of SSC (O'Brien et al., 2010a, 2010b). Greater strength during the eccentric phase is likely to contribute to better muscle resistance to stretching and more efficient storage of elastic energy (Cormie et al., 2010). Additionally, an increase in the angle between the longitudinal muscle and its fibres increases the muscle's ability to generate strength (Lieber & Fridén, 2000), passive muscle resistance, and consequently, limb resistance during SSC (Secomb et al., 2015). Throughout maturation, there are also changes in the size and structure of the tendons (Kubo et al., 2014). Specifically, enlargement of the cross-sectional area of the tendon prevails over increase in its length, thereby increasing the stiffness of the tendon. These changes may affect the force gradient that determines the production of force (Grosset et al., 2005).

Understanding changes in SSC during growth and maturation is essential to help develop appropriate performance enhancement and injury management strategies (Myer et al., 2013). Reactive strength, assessed by the reactive strength index (RSI) using field-based testing, has been suggested as a reliable measure of SSC capability, also in youth athletes (De Ste Croix et al., 2017; Lloyd et al., 2009). RSI is described as the ability to transition from eccentric to concentric muscle action and is also used to monitor stress on the muscle tendon complex during plyometric exercise (Flanagan & Comyns, 2008; Young, 1995). The reactive strength indicated by RSI increases with the level of performance, suggesting a potential training effect above natural development due to growth and maturation (Flanagan & Comyns, 2008). Low RSI values appear to be a measure of poor SSC function for athletes (Lloyd et al., 2009) and are considered a potential risk factor for ACL injury (Toumi et al., 2006; Raschner et al., 2012).

In previous cross-sectional studies, a gradual improvement in RSI was observed during adolescence due to the development of motor control (Di Giminiani & Visca, 2017; Lloyd et al., 2011, 2012a). However, Laffaye et al. (2016) showed no changes in RSI between 11-12 and 13-14 years, but then a significant increase from 13–14 to 15–16 years in middle school and secondary school boys and girls without experience in sports activity. There are only a few longitudinal studies on the athletic population; however, they focus on team sports players 13 years and older. In a study by Lehnert et al. (2020), the authors observed 13-year-old and 15-year-old female and male team sports elite players during a two-year period and found a nonsignificant increase in RSI in boys of both categories, while in girls they observed no trends in 13-year-olds and a nonsignificant decrease in 15-year-olds. As expected, the values were higher in boys, except 13-year-olds in the first year of study. A longitudinal study (De Ste Croix et al., 2021) explored the changes in RSI in elite youth soccer and basketball players aged 13–18 years and found increases in RSI.

Collectively, knowledge of changes in RSI during physical development of elite youth athletes of different sports using longitudinal studies can provide relevant information for training optimization, which can be used not only for the purpose of performance-related improvement of SSC functions, but also for injury prevention. Furthermore, a comparison of these findings with observations in nonathletic populations may also bring new information on the influence of natural development and sports training on the capability of SSC in youth. However, there are only a few cross-sectional studies on changes in RSI in non-athletic and athletic populations. Therefore, the main objective of this study was to determine the effect of chronological age on changes in SSC capability in young female figure skaters. We hypothesized that for 8 to 13 years, female figure skaters experience a gradual improvement in reactive strength of the lower limbs. To verify this hypothesis, we operationalized the reactive strength as RSI derived from the jump height and the contact time ratio. We were also interested in whether the possible developmental improvement in reactive strength is more affected by the shortening of contact time and/or increased jump height with age.

## Material & methods

*Participants.* Six age groups of elite female figure skaters aged 8 to 13 years participated in the study (n = 350). The participants had trained in figure skating from 6 years of age at the latest and in the year of measurement participated in the Talented Youth Training Project of the Czech Figure Skating Association (CFSA). Figure skaters trained in their clubs according to the CFSA training programme. In the 3-month preseason, they participated in five training units a week which consisted of off-ice training including gym, track and field activity, sports games, dance, yoga, semispecific figure skating skills, flexibility, and conditioning (including plyometrics). In the six-month competitive season, figure skaters participated in nine training units a week with seven on-ice units and two off-ice units, which contained nonspecific conditioning, yoga, and active recovery. The exclusion criteria were the absence of training in the last two weeks and more serious health problems 6 weeks prior to measurements, as well as an acute health problem at the time of measurement. The study was in accordance with the Declaration of Helsinki on the use of human subjects. The parents of all figure skaters declared an agreement with participation in the testing by signing an informed consent to participate in the CFSA Talented Youth Project. All figure skaters and their parents were also fully informed of the testing procedures that would be used. Body height was measured barefoot in standing position using a wall mounted measuring band with an accuracy of 1 cm. Body mass was measured with TANITA BC 545 (Tanita, Japan) with an accuracy of 500 g.

*Measures.* RSI (ms), contact time (s) and jump height (cm) were determined during a 10 s repeated vertical jump test with the upper limbs fixed at the hips performed on a mobile contact mat (FITRO Jumper, Fitronic, Bratislava, Slovakia). The FITRO jumper is a reliable jump ergometer, which measures contact time and flight time with an accuracy of 1 ms (Tká et al., 1990). The height of the jump was derived from the flight time (tf) using the formula: jump height = (g x tf2) / 8. The RSI variable was calculated using the following equation: RSI = jump height (cm) / contact time (s) (Flanagan and Comyns, 2008). Participants were instructed to maximize jump height and minimize ground contact time. The participants performed three tests wearing trainers with a 30 s rest between the trials. In each trial, three hops with the highest RSI values were averaged and the highest average RSI of the three trials was used for the subsequent analysis. This approach to measuring SSC capability using field-based rebound tests has been shown to be reliable in youth populations (Lloyd et al., 2009).

*Procedures.* The day before the test, the participants were not subjected to high-intensity exercises. At the beginning of the measurement, they received basic information about the testing procedure and participated in an anthropometric measurement. The test was preceded by an individual 10-minute warm-up with a focus on jumping and running readiness with maximum effort. At the end of the warm-up, the participants were accustomed to the physical test protocol.

*Statistical analysis*. Before testing, the effect of age on RSI, contact time, and jump height, as well as assumptions of normality, were tested using the Shapiro-Wilk test, normal P-plots, and box-plots. As the variables from three age groups were not of normal distribution, we excluded six outliers detected as those scores beyond the limits corresponding to 1.5 times of the interquartile range (Thode, 2002). After exclusion of outliers, the data met the assumptions of normality. The assumptions of homoscedasticity were tested by the Leven test, and it was demonstrated that the assumptions were violated. Therefore, to test the effect of age on RSI, contact time, and jump height, Welch's ANOVA test was used. Pairwise comparisons were made using the Dunnett test. The level of α = .05 was established for the tests. Data analysis was performed using the Social Sciences Statistical Package (SPSS, v. 21.0 for Windows; SPSS Inc, Chicago).

## Results

The basic anthropometric measures are presented in Table 1. Figures 1, 2, and 3 show age-specific variation of RSI, jump height, and contact time.

**Table** 1 *Anthropometric characteristics (mean ± standard deviation) by age groups*

| Age | BH | BM | BMI |
|---|---|---|---|
| 8 years (n = 49) | 129.3 ± 4.4 | 26.8 ± 2.7 | 16.0 ± 1.03 |
| 9 years (n = 61) | 133.3 ±5.3 | 29.0 ± 3.2 | 16.3 ± 1.1 |
| 10 years (n = 73 | 137.4 ± 5.0 | 31.2 ± 3.4 | 16.5 ± 1.2 |
| 11 years (n = 62) | 142.7 ± 5.9 | 34.2 ± 3.7 | 16.7 ± 1.1 |
| 12 years (n = 55) | 147.2 ± 6.4 | 37.5 ± 5.1 | 17.2 ± 1.2 |
| 13 years (n = 44) | 153.4 ± 6.1 | 43.1 ± 5.7 | 18.2 ± 1.4 |

Note. BH = body height (cm); BM = body mass (kg); BMI = body mass index (kg/m$^2$)

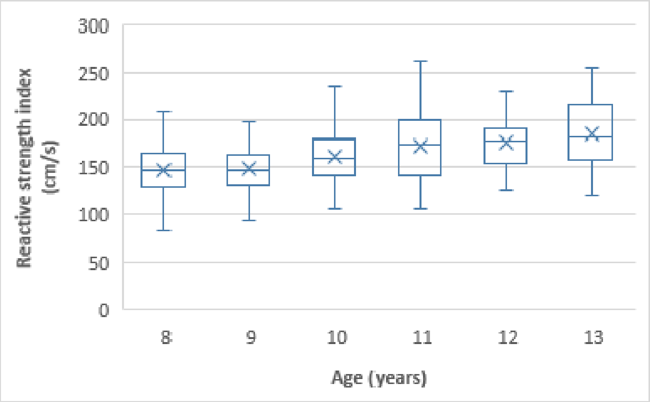

**Figure 1** *Reactive strength index by age*

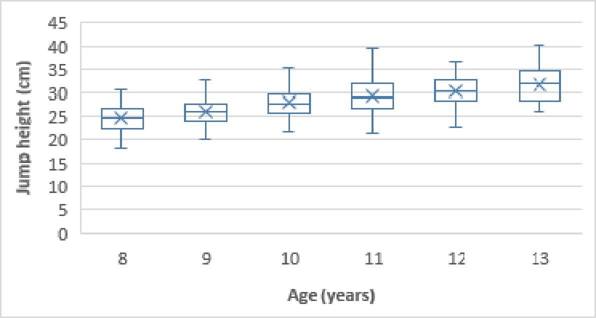

**Figure 2** *Jump height by age*

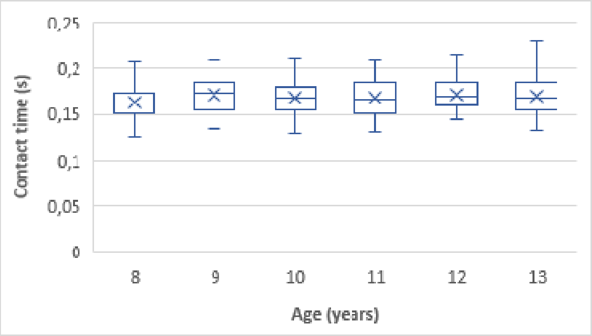

**Figure 3** *Contact time by age*

The results of the Welch ANOVA test showed a statistically significant effect of age on RSI, F = 14.245 (5; 150.9), $p < 0.001$. The Dunnett post hoc test revealed a significantly higher RSI in participants aged 11, 12 and 13 years compared to those aged 8 and 9 years (Table 2). The RSI of the 13 year old participants was also higher, compared to the 10 year old participants (Table 2).

**Table 2** *Results of the post hoc tests for the reactive strength index*

| Age | 8 years | 9 years | 10 years | 11 years | 12 years | 13 years |
|---|---|---|---|---|---|---|
| 8 years | – | 4.84 | 5.00 | 5.88 | 5.18 | 6.40 |
| 9 years | 1.30 | – | 4.66 | 5.60 | 4.85 | 6.14 |
| 10 years | 15.50 | 14.20 | – | 5.74 | 5.01 | 6.27 |
| 11 years | 24.83* | 23.53* | 9.33 | – | 5.90 | 6.99 |
| 12 years | 28.20* | 26.91* | 12.71 | 3.37 | – | 6.41 |
| 13 years | 38.22* | 36.93* | 22.73* | 13.40 | 10.02 | – |

Note. The results for the standard error are shown above the diagonal, and the results for the mean difference are shown below the diagonal. *$p < 0.05$.

Age was statistically significant for jump height: F(5, 151.73) = 37.083, $p < 0.001$. Pairwise comparisons showed a significant increase in jump height with age (Table 3). The jump height was not significantly different between two consecutive years of age, with the exception of a significantly higher jump height in 10-year-olds compared to 9-year-olds (Table 3).

**Table 3** *Results of the post hoc test for jump height*

| Age | 8 years | 9 years | 10 years | 11 years | 12 years | 13 years |
|---|---|---|---|---|---|---|
| 8 years | – | 0.54 | 0.54 | 0.64 | 0.57 | 0.67 |
| 9 years | -1.41 | – | 0.54 | 0.63 | 0.57 | 0.66 |
| 10 years | -3.29* | -1.88* | – | 0.63 | 0.56 | 0.66 |
| 11 years | -4.52* | -3.11* | -1.23 | – | 0.65 | 0.74 |
| 12 years | -5.77* | -4.35* | -2.47* | -1.25 | – | 0.68 |
| 13 years | -7.15* | -5.74* | -3.86* | -2.63* | -1.38 | – |

Note. The results for the standard error are shown above the diagonal, and the results for the mean difference are shown below the diagonal. *$p < 0.05$.

Unlike RSI and jump height, age was not significant for contact time: F(5, 151.33) = 1.458, p = .207. Furthermore, pairwise comparisons did not reveal significant differences in contact time between age groups.

## Discussion

To our knowledge, this is the first cross-sectional study to analyze changes in SSC capacity during growth and maturation determined by RSI in elite female athletes. Data show a gradual improvement in reactive strength from 8 to 13 years in female youth figure skaters, although significantly higher RSI values were observed only in 11, 12 and 13-year-old participants compared to 8 and 9-year-olds and in 13-year-old participants compared to 10-year-olds (Table 3). The functional and structural adaptation proposed that could explain the increase in RSI with age may particularly include changes in the neuromuscular system and the musculo-tendon unit, including, in particular, an increase in motor unit recruitment, preactivation, decreased cocontraction, increases in muscle and tendon stiffness, tendon size, pennation angle, and fascicle length (Radnor et al., 2018).

Our finding on young female figure skaters supports previous evidence for the non-linear development of the SSC capability with chronological age and maturation in young people (Lloyd et al., 2011, 2012a). In a cross-sectional study in 7-17-year-old male schoolchildren (Lloyd et al., 2011), no significant differences were observed between consecutive age groups in the case of RSI, but the smallest worthwhile changes between age groups in RSI indicated natural-occurring accelerated adaptation. The largest mean differences in RSI occurred between age groups 10 and 11 and also between 13 and 14, 15 and 16+. We assume that the significant differences between 9-year-olds and 11-year-olds found in our study and the differences between 10-year-olds and 11-year-olds observed in the study by Lloyd et al. point to a similar positive developmental trend suggesting that this period of growth and maturation could be important for SSC adaptation. The authors further suggested that the similarity to the results found in the case of counter-movement jump and squat jump implies the existence of similar naturally occurring accelerated adaptations and that the similarity in developmental trends between RSI and counter-movement, as well as squat jump heights, may suggest concentric strength impacts on RSI development. However, it should be mentioned that, contrary to the results of our study, Lloyd et al. observed a decrease in reactive strength and also relative leg stiffness between 11 and 12 years, which the authors justified by the fact that the 12 year old boys were in the peak height velocity period. In another study mentioned above (Lloyd et al., 2012a), the authors observed groups of schoolboys aged 9, 12, and 15 years and reported significantly higher RSI in both 12 and 15 years of age than in 9 years of age. However, the results of the current study are not consistent with the findings of the study exploring developmental changes in SSC in the 11-20-year-old nonathletic population of both sexes (Laffaye et al., 2016). In this study, the data did not show any change in RSI between age groups before the age of 13 in both girls and boys.

The gradual improvement of RSI with age observed in the current study should be considered positively both from the point of view of injury prevention (Raschner et al., 2012) and performance improvement (Flanagan & Comyns, 2008). It is difficult to account for any training effects in the current study, as we did not monitor the training process of the female figure skaters included in our study. However, as indicated in the methodology section, the figure skaters included in the study trained in their clubs according to the CFSA training programme, which consisted of typical age-related training for youth athletes, including plyometric exercises. Therefore, we presuppose that the reason for the increase observed (although nonsignificant) between 11 and 12 and in particular between 12 and 13 years of age in girls could be both the natural developmental changes in the neuromuscular system (this influence is nonconclusive based on the previously mentioned studies) and the effects of a regular training process which supports the neuromuscular adaptation processes (Flanagan & Comyns, 2008). Previous studies examining the natural development of SSC capability with age and maturation have shown improvements with age and suggest that training, especially plyometric training, could induce greater improvements in SSC with growth and maturation (Lloyd et al., 2012b; Radnor et al., 2018; Ramirez-Campillo et al., 2018).

In our study, we also focused on whether the potential improvement in reactive strength was more affected by the shortening of the contact time or by the increase in jump height. Data showed a significant main effect on jump height for age (Figure 2), although jump height was not significantly different between two consecutive year groups, except for the comparison between 10 year old girls of 9 years of age (Table 3). On the contrary, for contact time, the effect of age was not confirmed, and the data showed that contact time was relatively stable in the observed age groups. These results show that the improvement in RSI occurred, in particular, due to the increase in jump height. As indicated already, there are many functional and structural adaptations that could explain this finding. However, we assume that the main reasons could be increased muscle cross sectional area in conjunction with a higher proportion of type II muscle fibers with a greater ability to rapidly generate force due to a faster shortening velocity compared to type I fibers, improved ability to recruit muscle fibers, and increased co-contraction of agonist and antagonist due to desensitisation of the Golgi tendon organs, resulting in greater net force output (O'Brien et al., 2010a, 2010b; Radnor et al., 2018).

Our findings on jump height and contact time are similar to the findings of the cross-sectional study by Laffaye et al. (2016) in untrained girls and boys, where jump height increased until 15-16 years and contact time showed a slight fluctuation in girls and did not differ in boys in bilateral maximal vertical hops in place. Furthermore, in a study on 13 to 19-year-old female and male volleyball players (Polakoviová et al., 2018), the influence of age was reported in the case of jump height, but not in contact time in both genders. Similar trends were demonstrated in the study in male youth aged 9, 12, and 15 years (Lloyd et al., 2012a), where the authors reported significant changes with age in jump height but not in contact times in bilateral maximal vertical hops in place. However, it should be noted that our finding on relatively stable and short contact time in observed age categories is not in line with the statement that contact time in children is longer compared to adults and is reduced during physical development (Hobara et al., 2008; Oliver & Smith, 2010; Radnor et al., 2018). Regarding contact time, our data indicate that in the case of young figure skaters involved in our study, RSI is more indicative of fast SSC since the average values of contact time ranged between 163 and 170 ms.

Regarding the fact that also during prepubescence children are sensitive to neuromuscular training and with regard to the small number of studies focused on the evaluation of the efficiency of such programs in pre-peak height velocity athletes (Lloyd et al., 2016), we assume that further research focused on the verification of the neuromuscular training programs in female athletic population of this developmental stage is needed. The findings of these research studies could support the assumption that the development of 'explosiveness' should be one of the priorities in youth and therefore should be an important component of the strength and conditioning programmes of young athletes (Lloyd & Oliver, 2012). Further examination of the adaptations that occur due to such training stimuli could positively influence SSC capability not only at the current stage of development but also in the following developmental periods and could have an important practical implication. This especially applies to those athletes who participate in sports like figure skating in which explosive power and speed are important factors of sport performance (Comuk & Erden, 2012; Podolsky et al., 1990). Specifically, in figure skating, characteristics such as jump height, speed, and magnitude of the force, and especially flight time, are determining factors for learning and improving specific skills such as individual jumps and their difficulty given by the number of revolutions (Poe, 2002). From a gender perspective, training-induced improvement in reactive strength in early childhood is important, in particular, in female athletes, who demonstrate lower SSC ability compared to males (Laffaye et al., 2016; Lehnert et al., 2020). However, there is still a lack of information on how growth- and maturity-related adaptations and concomitant training-induced adaptations influence the SSC capabilities in pre-peak height velocity of girls from the nonathletic population. The limitation is that in our study we analyzed results of female figure skaters up to 13 years of age. The reason was that only a small number of older female figure skaters participated in the Talented Youth Project of the CFSA.

## Conclusions

The current study on female figure skaters in youth points to a gradual improvement in reactive strength in youth, as observed in a few previous studies, mostly in the nonathletic population. However, compared to previous studies, our data show an increase in RSI during the observed developmental period of 8 to 13 years. Jump height data and contact time data also indicate that the improvement in reactive strength was related to the increase in force during the concentric phase of the SSC rather than to the shortening of the eccentric and/or amortisation phases of the SSC. Regarding the fact that RSI is considered both a sports performance indicator and an injury risk indicator, this finding has an important implication for sports practice, suggesting that systematic application of training stimuli that drive the development of SSC should start even at the prepubescent age. Well-designed longitudinal studies are needed to deepen our knowledge about the natural development of SSC and the related underpinning mechanisms in youth athletes. Experimental studies evaluating the effects of properly created and executed neuromuscular training programs in prepubescent athletic populations will also be valuable. These studies could bring important new information, which could help reduce the high rate of injury and enhance the increase in sports performance, especially during the subsequent developmental periods.

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