

Age- and gender-related development of stretch shortening cycle during a sub-maximal hopping task

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ABSTRACT: The aim of this study was to analyse the effects of age and gender (and their interaction) on a stretch shortening cycle solicited during a hopping task. For this aim, 147 girls and 148 boys aged 11 to 20 years, who were enrolled in middle school or secondary school with no experience in sport activity, or training less than three times per week, performed 3×5 hops in place. Leg-stiffness, jump-height and reactive-strength indices were assessed using an accelerometer (Myotest). The participants were selected in order to form five age groups: 11-12, 13-14, 15-16, 17-18 and 19-20 years. Regression analysis between force and centre of mass displacement revealed spring-mass behaviour for all groups ($r^2 = .73-.89$), meaning that beginning at the age of 11 years, children are able to perform complex inter-muscular coordination of the lower limbs, revealing efficient neural control early in childhood. Leg stiffness increased from $24.7 \pm 10.6 \text{ kN} \cdot \text{m}^{-1}$ at 11-12 years to $44.1 \pm 14 \text{ kN} \cdot \text{m}^{-1}$ in boys, with a small increase until 16 years (+17%) and a large increase between 17 and 20 years (+32.7%). In girls, leg stiffness increased from $26.6 \pm 9 \text{ kN} \cdot \text{m}^{-1}$ at 11-12 years to $39.4 \pm 10.9 \text{ kN} \cdot \text{m}^{-1}$ at 19-20 years, with a curious decrease in leg stiffness at 17-18 years, probably due to an increase in the percentage of fat at this age (25%). While no gender effect was found, the reactive-strength index revealed that, from 15-16 years onward, boys were better able to produce high levels of force in a shorter time than girls. The age of 15-16 years is a threshold of maturity and gender differentiation, where the boys investigated are more efficient in the stretch shortening cycle.

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INTRODUCTION

As they grow, children and adolescents become increasingly efficient in their movements [1]. They develop more efficient and more adapted neuromuscular coordination from birth [2, 3], through childhood and to adolescence [4, 5, 6, 7]. More specifically, the stretch shortening cycle (SSC) is a key factor in explaining efficiency in human movement and locomotion [8], such as jumping or sprinting. Its role and efficiency in force production has been studied extensively [8, 9, 10, 11, 12, 13, 14]. The SSC is characterized by a successive and rapid combination of eccentric and concentric muscle contractions [15] of the lower limbs with no delay between them. The extensor contracts forcefully and rapidly [9] in response to the muscle lengthening. This is the muscle's concentric contraction, which is a voluntary shortening (controlled by the central nervous system [CNS] via α motor neurons) [16, 17]. The increase in force due to the SSC is explained by the storage and restitution of elastic energy in the series' elastic component [9, 18, 19, 20] and is also controlled by both supra-spinal feed-forward, which drives muscle spindles, and

short latency stretch reflexes contributing to the smooth generation of tension in the muscle by regulating muscle stiffness [9, 19].

The SSC's efficiency can be assessed by analysing a hopping in place task using biomechanical models. The most useful one is "the spring-mass model". This macroscopic model assimilates the lower limb to a massless vertical linear spring supporting a bowl containing the whole body mass [21, 22]. The spring-mass model calculates an index of leg stiffness (k_{leg}) [21, 22] in order to quantify the amount of force as a function of centre-of-mass displacement. It has been reported that k_{leg} was significantly correlated ($r = 0.78$) with a high rate of force development during jumping tasks [23] and to maximal velocity during a 100-m sprint [12, 24]. Another way of assessing SSC efficiency is to calculate the reactive strength index (RSI), which corresponds to the ratio of jumping height (H) to contact time [25, 26, 27]. RSI and leg stiffness are two different ways to describe the ability of an athlete to change quickly (without delay) from eccentric to concentric muscular contractions during dynamic jumping activ-

ity [26]. This kind of task requires a stretch shortening cycle to be highly efficient [18]. Further, a few studies have investigated the effects of age on k_{leg} and RSI by comparing men to adolescents or children. Wang et al. [28] reported that 18-year-old boys were 2.1 times stiffer than 6 year-old boys [28]. Furthermore, k_{leg} increased with age in a sample of 7-10 year-old children [29]. Adolescents (16-18 years) reveal higher values of k_{leg} than pre-adolescents (11-13 years), although this difference disappears when k_{leg} is normalized to body mass [30]. Further, these authors found that at the age of 12 years, pre-adolescents coordinate their lower limbs appropriately in order to behave like a spring mass. With regards to RSI, it has been reported that both 12- and 15-year-old subjects produced significantly greater RSI than 9-year-old subjects during maximal hopping by using supra-spinal feed forward input and short latency stretch reflexes to regulate high levels of k_{leg} and RSI [31].

The study of the evolution of k_{leg} and RSI with regard to age and gender could be very useful for the understanding of the SSC efficiency during pre-adolescence and adolescence. This understanding would provide recommendations for optimal drop height in plyometric exercises or for monitoring SSC training progress [27]. Moreover, while the gender effect is known to strongly affect these variables [32], it has never been investigated in children and adolescents. As stiffness is a function of force and centre of mass lowering, since force is itself related to muscle mass [33,34], it is expected that the age-related increase in muscular mass impacts on k_{leg} values will differ strongly between boys and girls during puberty.

Therefore, this study aimed to investigate the effects of age and gender (and their interaction) on a stretch shortening cycle occurring during a hopping task by comparing 295 youngsters (boys and girls) between the ages of 11 and 20 years.

MATERIALS AND METHODS

Participants. 147 girls and 148 boys aged 11 to 20 years took part in this study (Table 1). They were divided into five age groups (G1, G2, G3, G4 and G5 respectively) as follows: 11-12, 13-14, 15-16, 17-18 and 19-20 years. The inclusion criteria were: to be enrolled

in French middle school or secondary school with no experience in sport activity, or training fewer than three times per week. None of our participants had any expertise in physical activities involving jumping. The participants and the underage children's legal guardians (<18 years) gave their written consent to the testing protocols after having been informed of the aims and risks of the study. The experiment was approved by the University's ethics committee and was conducted according to ethical principles [35].

Procedures

A standardized 15-minute warm-up consisting of running at low speed, self-myofascial release, total body dynamic stretches and a supervised 5-minute familiarization with the jumping task were performed. During familiarization, multiple trials were performed in order to familiarize the participants with this kind of hopping task. The experiment consisted of three trials of "five hops in place" on a hard, flat surface to avoid differences in surface stiffness [36]. The participants were asked to hop in place five times as high as possible while reducing ground contact time. The instructions given were: "When the acoustic signal sounds, hop in place five times, with minimal knee flexion and a maximal jumping height. After the last jump, return to a vertical standing posture and wait for the final acoustic signal." Data recording began only if the bouncing technique was acquired. The best performance based on the value of leg stiffness was kept for further analysis. In order to ensure spring mass behaviour while hopping, the linearity of the force to displacement ratio was verified for each hopping test trial by measuring the slope with a regression coefficient, as shown in Figure 1. All of the participants were tested by the same experimenter during the first half of the day (between 10 and 12 a.m.) in order to avoid the effect of circadian fluctuations on jump height [37] as much as possible. The participants were also asked to refrain from drinking water during the four hours prior to test. In particular, the experimenter asked the participants to hold their hands on their waist while jumping in order to avoid arm swing interference [38]. Rest was set at 30 seconds between sets.

TABLE 1. Anthropometric characteristics of participants according to age groups and gender.

	Gender	Age groups (years)				
		11-12	13-14	15-16	17-18	19-20
Number	Girls	30	30	29	28	30
	Boys	31	29	28	29	31
Height (m)	Girls	1.58 ± 0.08 ^{bde}	1.64 ± 0.05	1.60 ± 0.05 ^{(*)de}	1.65 ± 0.04 ^(*)	1.67 ± 0.07 ^(*)
	Boys	1.55 ± 0.10 ^{bcde}	1.61 ± 0.07 ^{cde}	1.69 ± 0.05 ^{de}	1.76 ± 0.08 ^e	1.81 ± 0.08
Body Mass (kg)	Girls	44.60 ± 5.9 ^{(*)bcde}	55.03 ± 7.9 ^{(*)d}	56.30 ± 8.2 ^{(*)d}	65.45 ± 10 ^{(*)e}	56.69 ± 8.81 ^(*)
	Boys	47.89 ± 11 ^{bcde}	52.52 ± 14.6 ^{cde}	61.37 ± 11.1 ^{de}	68.01 ± 11.83 ^e	76.86 ± 11.54
%Fat	Girls	20.48 ± 1.3 ^{(*)d}	19.20 ± 4.2 ^{(*)cd}	20.50 ± 3.8 ^{(*)de}	25.03 ± 7.8 ^{(*)e}	21.22 ± 5.92 ^(*)
	Boys	15.49 ± 7.1 ^{bd}	11.68 ± 5.13 ^c	17.40 ± 4.84 ^d	12.23 ± 3.03	14.23 ± 3.60

Note: values are means ± SD, (a) to (e) represent significant differences between age groups going from 11-12 to 19-20 years: a for 11-12, b for 13-14, c for 15-16, d for 17-18, e for 19-20, (*) Significant differences between boys and girls of each group age ($p < 0.05$)

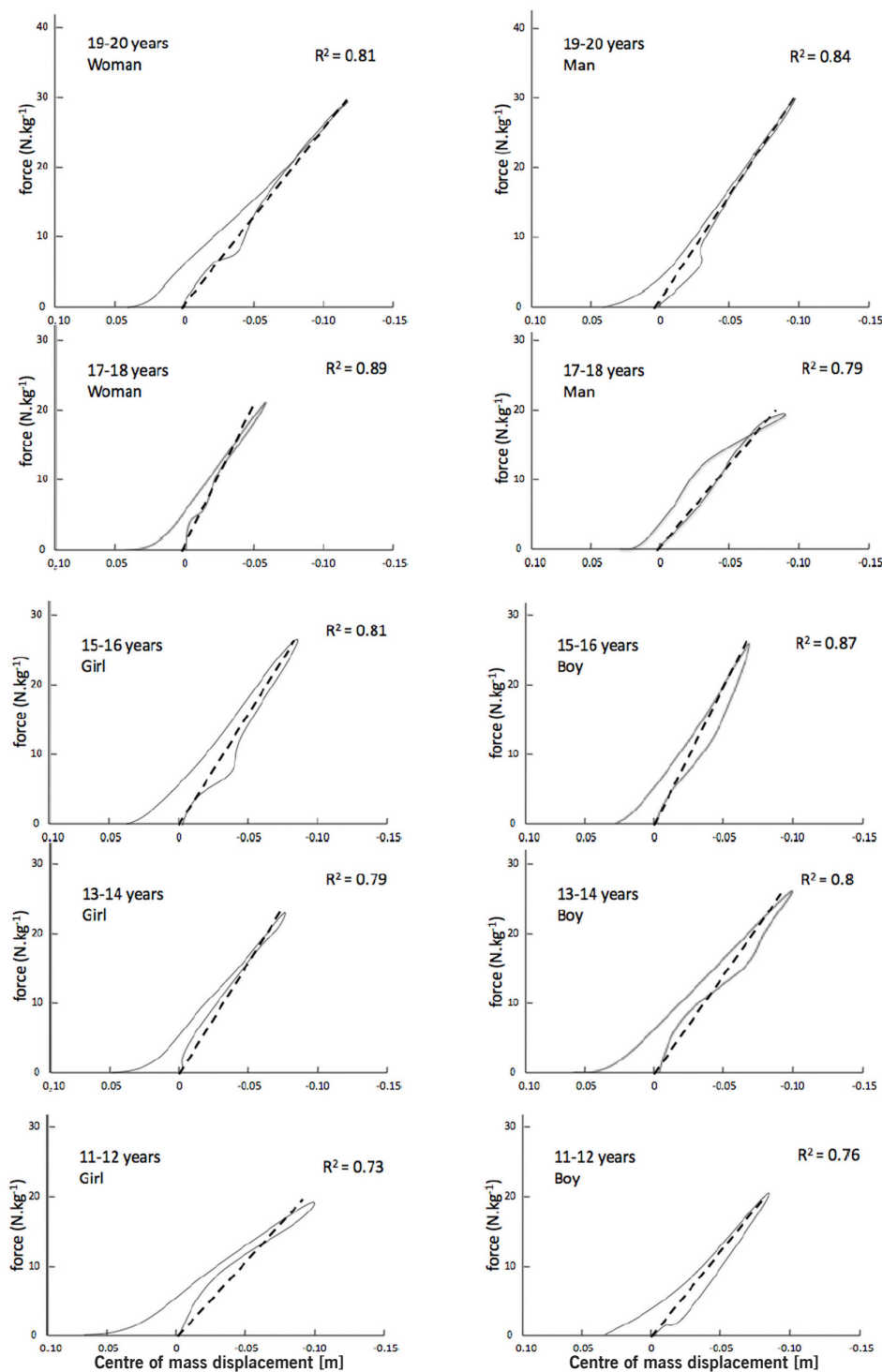


FIG. 1. Typical shape of spring-mass behaviour during the hopping in place test for females (left hand) and males (right hand).

Devices

The participants were equipped with an accelerometric system (Myotest, Myotest S.A., Switzerland) (length × width × depth: 9.5 × 5 × 1 cm; mass: 60 g; sampling frequency: 500 Hz), which was used according to the protocol described by Choukou et al. [39]. The device was attached to a belt and affixed vertically to the middle of the lower back. This device had previously been deemed valid for assessing vertical jump height and leg stiffness [39, 40, 41]. Body mass (BM), and percentage of fat (%FAT) were measured

by bioelectric impedance scales with 0.1% accuracy (Weinberger model DJ-156; Weinberger GmbH & Co, Germany) while an anthropometer with 0.1 cm accuracy measured body height (h).

Calculation of variables

Mechanical leg stiffness k_{leg} corresponds to the ratio of maximal ground reaction force (F) to the centre of mass displacement (Δ_{CoM}) during grounding, as proposed by Dalleau et al. [12] (Equation 1).

$$k_{leg} = F / \Delta_{CoM} \quad (\text{kN} \cdot \text{m}^{-1}) \quad (1)$$

Absolute k_{leg} ($\text{kN}\cdot\text{m}^{-1}$) was normalized by removing the effect of individual weight. For this purpose, the value of Force [N] was divided by the subject's weight exponent $2/3$ [42, 43, 44]. Jump height (H) was calculated according to the flight time method [39]. The reactive strength index (RSI) corresponds to the ratio of jumping height to ground contact time (CT). The contact time corresponds to the time that elapses from the moment of maximal velocity to the moment of minimal velocity after touch-down [39]. The first hop served as a countermovement jump (impetus) and was consequently excluded from the analysis. Finally, six jumps were performed and only five were analysed.

Statistical analyses

Age and gender differences for all parameters studied were analysed using a two-way analysis of variance (ANOVA) with Fishers' LSD post-hoc test showing age- and gender-related differences when significance was found. Statistical tests were processed via STATISTICA software (version 7, StatSoft Inc, Tulsa, OK, USA). The criterion for statistical significance was set at $p < 0.05$ and effect size (η^2) was defined as small ($\eta^2 > 0.01$), medium ($\eta^2 > 0.09$) or large ($\eta^2 > 0.25$) [45].

RESULTS

Anthropometry. Significant main effects on height, body mass (BM) and percentage of fat (%FAT) were found for gender and age, as well as a significant age \times gender interaction ($p < 0.05$). The results showed that body height increased significantly with age in boys while it only increased between 11-12 years, 13-14 years, 15-16 years and 17-18 years in girls. Gender differences were observed beginning at the age of 15-16 years, with an obvious difference in 19-20 year olds. In addition, BM increased significantly in all age groups in both genders except between 13-14 and 15-16 year old girls. %FAT increased significantly at 15-16 and 17-18 years old in girls while it decreased at 11-12 to 13-14 years old and increased at 15-16 years in boys.

Leg stiffness

k_{leg} behaviour is averaged for all groups in Figure 1, revealing a linear force/centre of mass displacement slope (ranging from $r^2=0.73$ at 11-12 years for girls to $r^2=0.89$ at 17-18 years for girls). A significant main effect for absolute k_{leg} was found for age [$F(4,289)=20.95$, $p < 0.0001$, $\eta^2=0.23$], a trend for gender [$F(1,289)=2.30$, $p=0.12$; $\eta^2=0.08$], with higher values in boys ($32.7 \pm 13.4 \text{ kN}\cdot\text{m}^{-1}$) than in girls ($30.8 \pm 10.3 \text{ kN}\cdot\text{m}^{-1}$), and an age \times gender interaction [$F(4,285)=3.56$, $p < 0.01$, $\eta^2=0.05$]. Absolute leg stiffness progressively increased in boys from $24.7 \pm 10.6 \text{ kN}\cdot\text{m}^{-1}$ at 11-12 years to $44.1 \pm 14 \text{ kN}\cdot\text{m}^{-1}$ at 19-20 years (Figure 2), while two significant peaks were observed for girls' absolute leg stiffness at the age of 15-16 years ($34 \pm 5 \text{ kN}\cdot\text{m}^{-1}$) and 19-20 years ($39.4 \pm 11.1 \text{ kN}\cdot\text{m}^{-1}$), with the highest value in the oldest girls. A significant gender difference was observed only in the 17-18 years age group, with

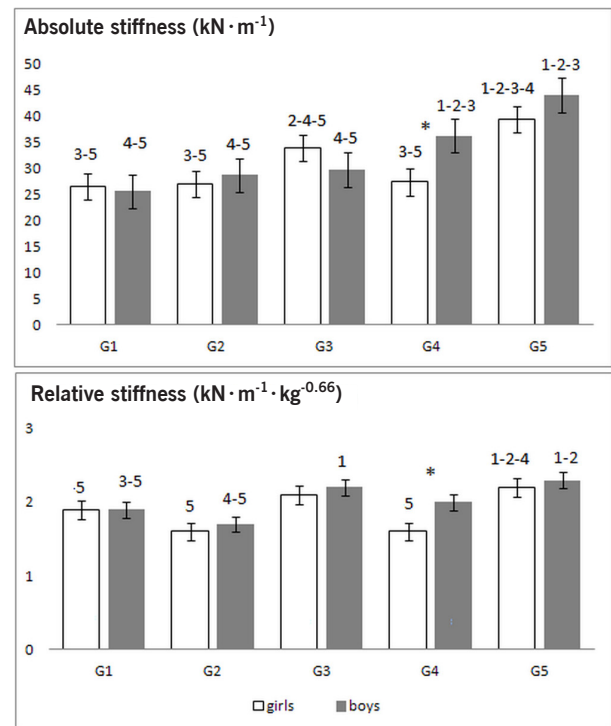


FIG. 2. Variation of absolute and body-mass-independent leg stiffness according to age and gender.

higher values in boys compared to girls at that age (+24.8%). When normalized (Figure 2), leg stiffness shows a similar effect, with a gender difference only at G4, with higher values in boys ($2.08 \pm 0.57 \text{ kN}\cdot\text{m}^{-1}\cdot\text{kg}^{-0.66}$) compared to girls ($1.61 \pm 0.51 \text{ kN}\cdot\text{m}^{-1}\cdot\text{kg}^{-0.66}$).

Reactive strength index

A significant main effect on RSI was found for gender [$F(1,289)=15.00$, $p < 0.001$, $\eta^2=0.05$], age [$F(4,289)=26.84$, $p < 0.0001$, $\eta^2=0.26$], and an age \times gender interaction [$F(4,285)=5.12$, $p < 0.05$, $\eta^2=0.06$]. RSI increased between 13-14 and 15-16 (+33.7%), decreased at 17-18 (-27.4%), and increased at 19-20 (+32.2%) in girls, while it increased significantly only between 13-14 and 15-16 (+58.1%) and between 17-18 and 19-20 (+20%) in boys. Gender differences for RSI were observed only from the age of 17 years, with lower values in girls compared to boys (Figure 3).

Contact time

There was a significant main effect on contact time for age [$F(4,289)=5.8$, $p < 0.05$, $\eta^2=0.08$] and an age \times gender interaction [$F(4,285)=2.66$, $p < 0.05$, $\eta^2=0.05$]. However, gender differences for CT were not significant. Age did not affect CT in boys, while contact time showed slight fluctuations (Figure 3).

Jump height (H)

Significant main effects on jump height were reported for gender [$F(1,289)=40.55$, $p < 0.0001$, $\eta^2=0.14$] and age [$F(4,289)=30.68$,

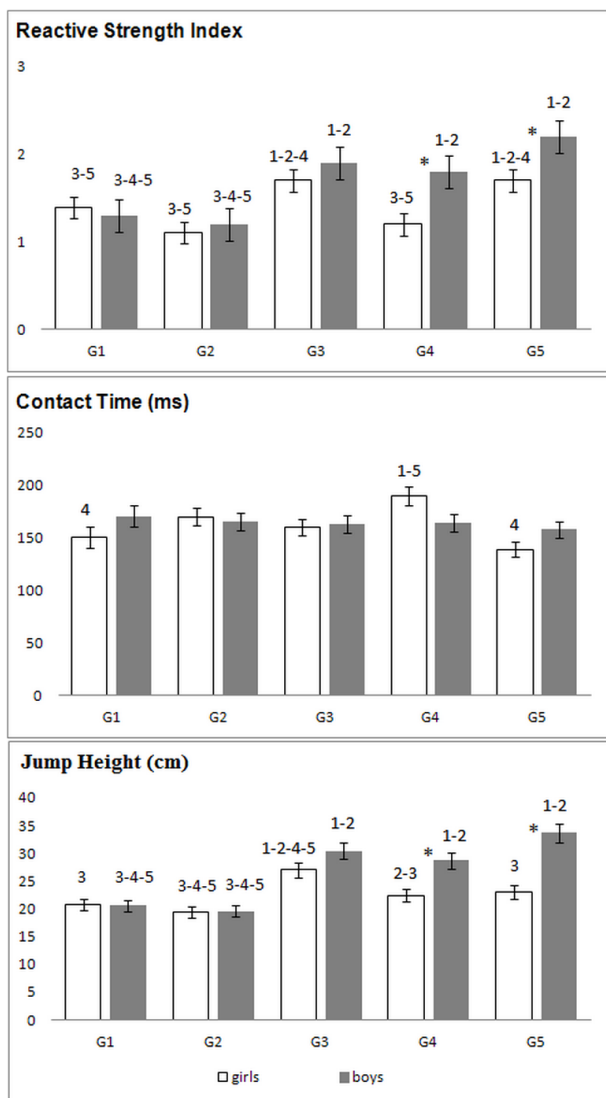


FIG. 3. Variation of reactive strength index, contact time and jumping height according to age and gender.

$p < 0.0001$, $\eta^2 = 0.28$], and there was a significant age \times gender interaction [$F(4,285) = 8.91$, $p < 0.001$, $\eta^2 = 0.07$]. H increased significantly between 13-14 and 15-16 by 66.3%, and between 17-18 and 19-20 by 13.2% in boys. It also increased significantly by 44.6% between 13-14 and 15-16, while it decreased by 16% at 17-18 in girls. Gender differences for hopping height were observed at the age of 17-18 years, with higher values in boys (Figure 3).

DISCUSSION

Leg stiffness. One of the major findings of the present study is that the spring-mass model is applicable to all the groups in this study with high r^2 levels (Figure 1). This is revealed by the linearity of the force/centre of mass slope. The correlation between this curve and the theoretical straight line due to the spring mass constant is about $r^2 = 0.73$ at the age of 12 and increases to $r^2 = 0.89$ at 17-18 years, which is not far from a perfect mechanical spring-mass model ($r^2 = 1$). This shows that the participants in the younger group tested in this

study were able to perform complex inter-muscular coordination of the lower limb, like a spring does. This type of behaviour was previously observed at the age of 12 years [30]. Consequently, neural control seems efficient early in childhood, but our study did not identify the key moment for this control. The findings of Wang et al. [28] revealed that six year-old children are not able to fully extend the lower extremities during the push-off phase of the jump [28], showing inefficient motor control during this complex jumping task. Consequently, the switch likely occurs between the ages of 6 and 11 years. When focusing on the evolution of leg stiffness, it seems that the main increase occurs after 14 years, especially when we remove the body mass effect. This is similar to previous results. Indeed, during running, Schepens et al. [46] found that relative stiffness remains constant after the age of 12 years. More precisely, the present study shows that the value of leg stiffness increases about 1.62-fold between G1 and G5. This increase is similar to that found by Wang et al. [28], who reported that 18-year-old boys were 2.1 times stiffer than 6-year-old boys. According to these authors, this was due primarily to the contribution of knee stiffness, which was 11.3 times greater in adults, whereas ankle and hip stiffness was 3.2 and 3.4 times higher, respectively. Furthermore, musculotendinous stiffness increased with age between 7 and 10 years [29], due to the maturation of elastic tissues, and notably due to a higher degree of tibialis anterior coactivation, which reduces neuromuscular efficiency, found in the youngest children. Adolescents (16-18 years) show higher values of k_{leg} than pre-adolescents (11-13 years). Furthermore, these authors found that at the age of 12 years, pre-adolescents coordinate their lower limbs appropriately in order to behave like a spring mass [30]. Another study showed greater values of leg stiffness with age in sub-maximal hopping tasks, when comparing 9-, 12- and 15-year-old children. A surface electromyogram reveals greater background muscle activity and short-latency stretch reflex activity in the soleus and vastus lateralis, suggesting that as children mature, they become more reliant on supra-spinal feed forward input and short latency stretch reflexes to regulate greater levels of leg stiffness and RSI when hopping. The age of 15-16 years is a threshold of maturity for lower limb behaviour in untrained adolescents, probably due to morphological transformations due to testosterone in males [47], allowing a significant increase in reactive strength which could be explained by neuromuscular maturation in the capacities of motor unit synchronization. This process has been reported to increase the capacity of maximal contraction [29, 47-48-49-50].

However, when removing the mass effect, the increase found in our study is reduced to just 1.15 times, showing that a large part of leg stiffness is produced to compensate for heavier mass during growth. Similar results have been observed previously when studying the effect of age [30].

Reactive strength index and contact time

The RSI increases from $1.39 \text{ m}\cdot\text{s}^{-1}$ for boys vs $1.07 \text{ m}\cdot\text{s}^{-1}$ for girls at 11-12 years to $2.22 \text{ m}\cdot\text{s}^{-1}$ for boys vs $1.67 \text{ m}\cdot\text{s}^{-1}$ for girls at 19-20

years, revealing significantly higher values in boys in the 17-18 and 19-20 year-old groups (+42 % and +27.2 %, respectively). This is consistent with a previous study [31] that found greater RSI during the maximal hopping task in 12- and 15-year-olds ($1.15 \text{ m}\cdot\text{s}^{-1}$ and $1.22 \text{ m}\cdot\text{s}^{-1}$ respectively) than in 9-year-olds ($0.74 \text{ m}\cdot\text{s}^{-1}$). The values found here are slightly higher in the present study than those found in the literature in similar conditions (Lloyd *et al.* [51] found $1.27 \text{ m}\cdot\text{s}^{-1}$ while we found $1.9 \text{ m}\cdot\text{s}^{-1}$ in this study). This could be explained by the difference of research design, with a natural hopping frequency in our study, whereas the afore-mentioned study imposed a hopping frequency of 2-2.5 Hz. Furthermore, the RSI increases during adolescence while contact time duration in boys did not change after 13-14 years old, implying that jumping performance increases with age for the same contact time. This means that during the same contact time, boys produce greater acceleration of their body mass than girls in order to take off at higher velocity. This suggests that the ability to increase force in a short amount of time increased from the age of 15-16 years in boys, allowing them to jump higher (+34.4%) than girls with higher RSI (+27.2%) at the beginning of adulthood (at 19-20 years).

Jump height

The boys' jumping performance was characterized by a sharp increase in height after 15-16 years, whereas the girls' jump height increased until 15-16 years, then decreased at 17-18 years. This suggests that 15-16 years is a threshold where jump height increases for both genders and also a threshold of gender differentiation, since differences between boys and girls were observed only after 15-16 years, +22% at 17-18 and +31.8% at 19-20. The decrease in the height value observed in girls aged 17 to 20 years compared to the 15-16 years group could be explained by the difference in body mass, which is 16.25% greater at 17-18 years compared to 15-16 years, with a dramatically higher fat percentage value (+21.9%). This type of evolution has been observed previously [52], with a slight increase

in body mass at the age of 15-16 years for girls and a decrease at the age of 18 years. Our results are quite similar but with a two-year forward shift.

CONCLUSIONS

This study revealed spring-mass behaviour in all groups ($r^2 = .73-.89$), meaning that by 12 years, children are able to perform complex inter-muscular coordination of the lower limb, revealing efficient neural control early during childhood. The unexpected result of this study was a threshold of evolution of leg stiffness at the age of 15-16 years, with higher values compared to younger ages. Additionally, two trends of evolution were observed for each gender, with constant leg stiffness in boys between mid-adolescence and adulthood and fluctuations in girls' stiffness. Based on the results of this large cross-sectional study, the reactive strength index is a determinant of the state of maturity that provides a threshold of maturity at 15-16 years old and gender differentiation thereafter. That suggests that coaches should propose a similar SSC task such as plyometric exercises for both genders until the age of 15. Plyometric training is a generic term describing quick, powerful movement, using a pre-stretch, or counter-movement that involves the SSC. This includes fast SSC movement, such as bounding, repeated hurdle hops and slow SSC movement such as the vertical jump and box jump. A high level of RSI requires from athletes the ability to develop maximal forces in minimal time. More practically, our study suggests that the same plyometric exercises can be proposed to both boys and girls until 15, but they should differ after this age. Indeed, as proposed by previous papers [31, 53], the RSI level could be used to choose for example the height of a box for drop jumping to avoid too long contact time (>250 ms). Indeed, a too great box height for girls would be too stressful for the muscle-tendon complex.

Conflict of interests: the authors declared no conflict of interests regarding the publication of this manuscript.

REFERENCES

- Mian OS, Thom JM, Ardigò LP, Narici MV, Minetti, AE. Metabolic cost, mechanical work, and efficiency during walking in young and older men. *Acta Physiol.* 2006;186(2):127-139.
- Thelen E. Developmental Origins of Motor Coordination: Leg Movements in Human Infants. *Dev Psychobiol.* 1985;18(1):1-22.
- Clark JE, Phillips SJ. The development of intralimb coordination in the first six months of walking. In J. Fagard & P. Wolff, Editors. *The development of timing control and temporal organization in coordinated action.* Amsterdam: Elsevier Science Publishers; 1991. p. 245-257
- Bates NA, Ford KR, Myer GD, Hewett TE. Timing differences in the generation of ground reaction forces between the initial and secondary landing phases of the drop vertical jump. *Clinic Biomech.* 2013;28(7):796-799.
- Temfemo A, Hugues J, Chardon K, Mandengue SH, Ahmaidi S. Relationship between vertical jumping performance and anthropometric characteristics during growth in boys and girls. *Eur J Pediatr.* 2009;168:457-564.
- Jensen JL, Phillips SJ, Clark JE. For young jumpers, differences are in the movement's control not its coordination. *Res Q Exerc Sport.* 1994;65:258-268.
- Phillips SJ, Clark JE. Temporal coordination and control in the development of the standing long jump. *Motor Development: Res and Reviews.* 1997;1:99-121.
- Aura O, Komi PV. The mechanical efficiency of locomotion in men and women with special emphasis on stretch-shortening cycle exercises. *Eur J Appl Physiol.* 1986;55(1):37-43.
- Bosco C, Ito A, Komi PV. Neuromuscular function and mechanical efficiency of human leg extensor muscles during jumping exercises. *Acta Physiol Scand.* 1982;114:543-550.
- Arampatzis A, Schade F, Walsh M, Brüggeman GP. Influence of leg stiffness and its effect on myodynamic jumping performance. *J Electromyogr Kinesiol.* 2001;11:355-364.
- Chelly MS, Denis C. Leg power and hopping stiffness: relationship with sprint running performance. *Med Sc Sports Exerc.* 2001;33:326-333.
- Dalleau G, Belli A, Viale F, Lacour JR,

- Bourdin M. A simple method for field measurements of leg stiffness in hopping. *Int J Sports Med.* 2004;25:170-176.
13. Farley CT, Morgenroth DC. Leg stiffness primarily depends on ankle stiffness during human hopping. *J Biomech.* 1999;32:267-273.
 14. Markovic G. Does plyometric training improve vertical jump height? A meta-analytical review. *Br J Sports Med.* 2007;41:349-355.
 15. Padulo J, Laffaye G, Ardigò LP, Chamari K. Concentric and Eccentric: muscle contraction or exercise? *J Hum Kinet.* 2013;37:5-6.
 16. Lieber RL, Bodine-Fowler SC. Skeletal muscle mechanics: implications for rehabilitation. *Phys Ther.* 1993;73:844-856.
 17. Webb MR, Trendham D. Chemical mechanism of myosin-catalyzed ATP hydrolysis. In: Peachy LD, Adrian RH, Giger SR editors. *Handbook of Physiology.* Bethesda, MD. American Physiological Society; 1983. p. 237-255.
 18. Komi PV. Stretch-shortening cycle: a powerful model to study normal and fatigued muscle. *J Biomech.* 2000;33:1197-1206.
 19. Asmussen E, Bonde-Petersen F. Storage of elastic energy in skeletal muscles in man. *Acta Physiol Scand.* 1974;91:385-392.
 20. Hill AV. *First and last experiments in muscle mechanics.* Cambridge: University Press; 1970.
 21. McMahon TA, Valiant G, Frederick EC. Groucho running. *J Appl Physiol.* 1987;62:2326-2337.
 22. McMahon TA, Cheng GC. The mechanics of running - How does stiffness couple with speed. *J Biomech.* 1990;23:65-78.
 23. Walshe AD, Wilson GJ, Murphy A. The validity and reliability of a test of lower body musculotendinous stiffness. *Eur J Appl Physiol* 1996;73:332-339.
 24. Bret C, Rahmani A, Dufour AB, Messonnier L, Lacour JR. Leg strength and stiffness as ability factors in 100m sprint running. *J Sports Med Phys Fit.* 2002;42:274-281.
 25. Flanagan EP, Comyns TM. The use of contact time and the reactive strength index to optimize fast stretch-shortening cycle training. *Strength Cond J.* 2008;30:32-38.
 26. Young W. Laboratory strength assessment of athletes. *New Stud Athl* 1995;10:89-96.
 27. McClymont D, Hore A. Use of the reactive strength index (RSI) as an indicator of plyometric training conditions. *J Sports Sci.* 2004;22:495-496.
 28. Wang LI, Lin DC, Huang, C. Age effect on jumping techniques and lower limb stiffness during vertical jump. *Res Sports Med.* 2004;12:209-219.
 29. Lambertz D, Mora I, Grosset JF, Perrot C. Evaluation of musculotendinous stiffness in prepubertal children and adults, taking into account muscle activity. *J Appl Physiol.* 2003; 95:64-72.
 30. Korff T, Horne SL, Cullen SJ, Blazeovich AJ. Development of lower limb stiffness and its contribution to maximum vertical jumping power during adolescence. *J Exp Biol.* 2009;212:3737-3742.
 31. Lloyd RS, Oliver JL, Hugues MG, Williams CA. Age-related differences in the neural regulation of stretch-shortening cycle activities in male youths during maximal and sub-maximal hopping. *J Electromyogr Kinesiol.* 2012;22:37-43.
 32. Padua DA, Carcia CR, Arnold BL, Granata KP. Gender differences in leg stiffness and stiffness recruitment strategy during two-legged hopping. *J Mot Behav.* 2005;37(2):111-125.
 33. Fukunaga T, Miyatani M, Tachi M, Kouzaki M, Kawakami Y, Kanehisa H. Muscle volume is a major determinant of joint torque in humans. *Acta Physiol Scand.* 2001; 172:249-255.
 34. Knuttgen HG. Force, work, power, and exercise. *Med Sc Sports.* 1978;10:227-228.
 35. Harriss DJ, Atkinson G. Ethical Standards in Sport and Exercise Science Research: *Int J Sports Med.* 2013;30:701-702.
 36. Ferris DP, Farley CT. Interaction of leg stiffness and surface stiffness during human hopping. *J Appl Physiol.* 1997;82:15-22.
 37. Atkinson G, Reilly T. Circadian variation in sports performance. *Sports Med.* 1996;21:292-312.
 38. Lees A, Vanrenterghem J, De Clercq D. Understanding how an arm swing enhances performance in the vertical jump. *J Biomech.* 2004;37:1929-1940.
 39. Choukou MA, Laffaye G, Tiair R. Reliability and validity of an accelerometric system for assessing vertical jumping performance. *Biol Sport.* 2014;31:55-62.
 40. Casartelli N, Muller R, Mafiuletti N. Validity and reliability of the Myotest accelerometric system for the assessment of vertical jump height. *J Strength Cond Res.* 2010;24:3186-3193.
 41. Nuzzo JL, Anning JH, Scharfenberg JM. The reliability of three devices used for measuring vertical jump height. *J Strength Cond Res.* 2011;25:2580-2590.
 42. Jaric S, Mikrov D, Markovic M. Normalizing physical performances tests for body size: a proposal for standardization. *J Strength Cond Res.* 2005;19:467-474.
 43. Nevill AM, Ramsbottom R, Williams C. Scaling physiological measurements for individuals of different body size. *Eur J Appl Physiol Occup Physiol.* 1992;6:110-117.
 44. Folland JP, McCauley TM, Williams AG. Allometric scaling of strength measurements to body size. *Eur J Appl Physiol.* 2008;102:739-745.
 45. Cohen J. *Statistical power analysis for the behavior sciences.* 2nd Ed. Lawrence Erlbaum Associates, Hillsdale; 1988.
 46. Schepens B, Willems PA, Cavagna GA. The mechanics of running in children. *J Physiol.* 1998;509(3):927-940.
 47. Belanger AY, McComas AJ. Contractile properties of human skeletal muscle in childhood and adolescence. *Eur J Appl Physiol.* 1989;58:563-567.
 48. Grosset JF, Mora I, Lambertz D, Perot C. Age-related changes in twitch properties of plantar flexor muscles in prepubertal children. *Pediatr Res.* 2005;58(5):966-970.
 49. Grosset JF, Mora I, Lambertz D, Perot C. Changes in stretch reflexes and muscle stiffness with age in prepubescent children. *J Appl Physiol.* 2007;102(6):2352-2360.
 50. Seger JY, Thorstensson A. Electrically evoked eccentric and concentric torque velocity relationships in human knee extensor muscles. *Acta Physiol Scand.* 2000;169:63-69.
 51. Lloyd R, Oliver J, Hugues M, Williams C. Reliability of field-based measures of leg stiffness and reactive strength index in youths. *J Sport Sci.* 2009;27(4):1565-73.
 52. Sempé M, Pédrón G, Roy-Pernot MP. *Auxologie méthode et séquences.* Paris: Théraplix; 1997.
 53. McClymont D. Use of the reactive strength index (RSI) as an indicator of plyometric training conditions. In *Science and Football V: The proceedings of the fifth World Congress on Sports Science and Football*, Lisbon, Portugal; 2003. p. 408-16.