Effect of Drop Height on Vertical Jumping Performance in Pre-, Circa-, and Post-Pubertal Boys and Girls

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Running head: Jumping performance in children

ABSTRACT

Purpose: To examine the effect of drop height on vertical jumping performance in children with respect to sex and maturity status.

Methods: Thirty-seven prepubertal, 71 circapubertal and 69 postpubertal boys and girls performed, in a randomized order, 2 squat jumps (SJ), 2 countermovement jumps (CMJ) and 2 drop jumps (DJ) from heights of 20, 30, 40, 50, 60 and 70 cm. The trial with the best jump height in each test was used for analysis.

Results: No significant sex × maturity status × jump type interaction for jump height was observed. However, on average, the children jumped higher in the CMJ than in SJ and DJs (+1.2 and +1.6 cm, $P<0.001$, respectively), with no significant differences between DJs and SJ or between DJs when increasing drop heights. Regarding DJs, 59.3% of the participants jumped higher from drop heights of 20 – 40 cm.

Conclusions: Children, independent of sex and maturity status, performed best in the CMJ, and no performance gain was obtained by dropping from heights of 20 to 70 cm. During maturation the use of drop heights between 20 and 40 cm may be considered for use in plyometric training, but the optimum height must be obtained individually.

Key-words: Children, Maturation, Sex, Plyometric, Reactive strength.

INTRODUCTION

Plyometric training is a popular form of physical conditioning in athletes owing to the utilization of stretch-shortening cycle (SSC) to produce muscle power (23). This form of work is based on the storage of elastic energy in the muscle-tendon unit during the eccentric phase and on its restitution during the subsequent concentric action. The SSC is present in common human movements such as walking, running, and jumping. Concerning jumping, the SSC mainly appears in the countermovement and drop jumps (13). Plyometric training including jumping has been shown to be beneficial for decreasing injury risk (13, 30). However, if the SSC is used too frequently and in high volume, it may predispose young athletes to injury because of the strain that the musculotendinous, musculoarticular and skeletal systems experience at each impact (24), as for instance during the landing phase of a jump. The onset of adolescence (i.e. around the peak height velocity) is a particularly critical period for injuries because of (i) imbalances within muscle-tendon units of young athletes, (ii) strength imbalances between the hamstrings and quadriceps, particularly in postpubertal girls, (iii) between-limb asymmetries which are high before puberty, and (iv) the relatively immature bone structure (25). Furthermore, there is evidence for differences in neuromuscular activation and technique between children and adults during jumping (14, 15). Thus, in early adolescence, conditioning coaches, physical educators and teachers should pay particular attention to the dosage of jump-type activities, particularly the number and intensity of take-off and landing phases in order to reduce the risk of developing problems such as patellofemoral pain, tendinosis/tendonitis, or osteochondrosis [e.g. Osgood-Schlatter’s (knee) or Sever’s (heel) disease] (5).

As with any form of exercise program, the variables of intensity, volume, frequency, repetition velocity and recovery should be carefully monitored to ensure optimal athletic development of children and adolescents while minimizing injury risk (23). During plyometric training, exercise intensity is influenced by the loading (ground reaction force rate and magnitude) achieved in the eccentric (braking) phase as the agonist muscle-tendon units are actively stretched. In contrast to the squat jump, which is largely considered to be a measure of concentric muscle performance, countermovement and drop jump performances involve both eccentric and concentric phases. Countermovement and drop jumps are typically examined in research, since the former is very common task in sports and the latter is frequently used in lower-body plyometric training (23). Regarding the drop jump, the stretch load is strongly influenced by the drop height of the body's centre of mass prior to landing in the jump, which has been suggested to be set in the region of 20 to 70 cm in adults (3). However, optimal drop height has not yet been determined according to age, maturity status, sex or training background. In prepubertal children, an optimal drop height has not been identified. This is partly a result of data showing no difference in jumping performance when landing from different heights during drop jumps (e.g. drop heights of 10 – 50 cm in 9- to 11-year-old boys and girls) (2, 19). This lack of effect of drop height on performance could partly result from prepubertal children not using stored elastic energy as effectively as young adults in SSC tasks, owing to their higher tendon compliance and lesser ability to recruit fully motor units (6, 7, 10, 29). In contrast, in young untrained adults, jumping height appears to increase up to an optimal drop height (~ 30-40 cm) and then decrease from heights of 40 – 50 cm (20). This decrement from heights > 40 cm was speculatively attributed to biomechanical inefficiency (SSC power output) and stiffness differences (3, 28). During adolescence, only Prieske et al. (21) studied jumping performance in postpubertal male and female elite handball players over a reduced range of drop heights (e.g. 20, 35 and 50 cm) and no information is yet available regarding the acute effect of drop height on jumping performance in circa- and post-pubertal recreationally active boys and girls. Yet, maturation could strongly influence the interaction between drop height and jumping performance as there is a gradual enhancement in the rapid force-producing potential and utilization of the underpinning mechanisms of the SSC over this maturational period (10, 22). This effect could be more significant in boys than girls since recent research has demonstrated that males would have greater adaptations in the mechanical (elastic) properties of the muscle and tendon than females during maturation (22). However, direct scientific evidence showing this result is still lacking.

Therefore, the aim of the present study was to investigate the effect of drop height on jumping performance in pre-, circa- and post-pubertal boys and girls. We hypothesized that, unlike prepubertal children, circa- and post-pubertal children would exhibit a decrement in jump height when landing from high drop heights (i.e. above some optimal height), as is observed in young untrained adults. However, this could be more significant in boys than girls.

MATERIALS AND METHODS

Experimental approach to the problem

Our experimental approach was to assess drop jump performance over a series of heights in pre-, circa- and post-pubertal children, and determine whether it is differentially influenced by sex according to maturity status. The subjects were divided into six groups (prepubertal girls, prepubertal boys, circapubertal girls, circapubertal boys, postpubertal girls, postpubertal boys). Squat jump (SJ) was used as a reference for jumping ability (2). To check the effect of countermovement jump (CMJ) and drop jumps (DJ) from various heights (20, 30, 40, 50, 60 and 70 cm) on children's jumping performances, we compared CMJ and DJ scores to SJ performance using a within-subject design with jump height randomized between subjects.

Subjects

Thirty-seven healthy prepubertal boys and girls (n = 21/16), 71 circapubertal boys and girls (n = 49/22) and 69 postpubertal boys and girls (n = 15/54) volunteered to participate in the present study (descriptive characteristics are reported in Table 1). To be included, children had to perform recreational physical activity for ≤ 4 h per week and to be free of any medical contra-indication to physical activity. None were involved in any vigorous physical activity or engaged in a specific training program. Children were not athletes who might commonly perform high-intensity plyometric exercises, and were not historically experienced with drop jumps. They naturally practised recreational activities such as jumping in playgrounds in (and out of) school. Children were recruited from primary and secondary schools.

This study was approved by an Institutional Ethics Review Board (CERSTAPS #*2019-09-04*) and conformed to the standards of use of human subjects in research as outlined in the sixth *Declaration of Helsinki*. The children were informed of the experimental procedures and gave their written assent before any testing was conducted. In addition, the written informed consent was obtained from the parents or legal guardians of the children.

Anthropometric measurements and maturation assessment

A digital weight scale (TANITA, BC-545N, Japan) was used to measure body mass to the nearest 0.1 kg and barefoot standing height was assessed to the nearest 0.1 cm with a wall-mounted stadiometer (TANITA, HR001, Japan). Body mass index (BMI) was calculated as body mass (kg) divided by height squared (m^2). Age from peak height velocity (PHV) was used to assess somatic maturity and determined using standing height, sitting height and body mass. Its calculation was based on sex-specific regression equations according to the method proposed by Mirwald et al. (18). Children were grouped by their maturity status (pre-, circa- or post-PHV) into discrete bands based on their maturational offset (pre-PHV = < -1, circa-PHV = - 1 to +1, post-PHV = >1).

Testing

All subjects were tested in two experimental sessions separated by at least 48 h. During the first experimental session, anthropometric characteristics and maturity status were evaluated. All subjects were then familiarized with the testing procedures with the help of their physical education teacher and researchers. No subjects felt fear when jumping from the highest boxes; they were both confident and competent in performing the tests. During the second session, the subjects performed 2 SJs, 2 CMJs, and 2 DJs from heights of 20, 30, 40, 50, 60 and 70 cm. The two trials for each type of jump were performed sequentially while the different types of jump were done in a randomized order. There was at least 2 min of rest between trials. This rest interval was provided in order to minimize fatigue, as proposed by Bassa et al. (2). Before any exercise, the subjects completed a progressive warm-up that included 5 min of jogging followed by dynamic lower-limb exercises. Afterwards, the subjects performed submaximal and maximal SJs and CMJs; a single DJ was also performed from each DJ height. All the tests were performed indoors between 14:00 and 18:00 o'clock, and with the temperature kept between 22 and 27°C. The session duration lasted about one hour for each subject.

The jumping tests were performed using an optical measurement system (OptoJump, Microgate, Bolzano, Italy); this system has previously been validated for the collection and analysis of jump performance (1). In all jumping tests, the hands were placed on the hips with the elbows bowed outward (akimbo position). The best performance in each jump type was retained for further analysis. For all jumps, the jump height was derived from the flight time of the subjects. Ground contact time was also retained from drop jumps, and the reactive strength index (RSI), considered as a measurement of "explosive strength" (26), was calculated by dividing jump height by ground contact time during the drop jumps.

Jumping tests were performed with the following instructions:

Squat Jump (SJ). From a standing position, the subjects flexed their knees to 90° to lower their centre of mass (i.e. to a squatting position). This position was held for 3 s before a maximal vertical jump was performed without countermovement. Jumps were repeated if the researcher could clearly, visually detect a countermovement prior to the upward (jump) phase.

Countermovement Jump (CMJ). From a standing position, the subjects were instructed to dip and immediately jump with the aim of reaching the maximum height. The jump was visually inspected to ensure that a continuous movement was used with no observable interruption between downward and upward phases. Countermovement jumps were repeated if the researcher could clearly, visually detect an interruption between the downward and upward phases.

Drop Jump (DJ). Boxes of variable heights (20, 30, 40, 50, 60 and 70 cm) were placed in front of the OptoJump system. From a standing position close to the front edge of the box, the subjects extended one foot out in front of themselves to allow their body to move forward over the edge of the box before letting their body fall vertically without pushing upwards or outwards, jumping or flexing their support leg from the box. When done properly, the subjects landed close to the box (heel < 25 cm from the front of the box). Upon landing with both feet, they immediately jumped as high as possible. In their native French language, the instruction to the children was to “push as strong as possible and reduce the ground contact time”. The drop jumps from 20, 30, 40, 50, 60 and 70 cm were referenced as DJ20, DJ30, DJ40, DJ50, DJ60 and DJ70, respectively. In previous studies, the effect of drop height on jumping performance was investigated over a series of heights ranging from 10 to 50 cm in prepubertal children (2). However, we have chosen to test 60 and 70 cm to check the hypothesis that such heights could reduce jumping performance, possibly by spinal inhibitory neural mechanisms (27).

Statistical analysis

Data were screened for distribution normality and homogeneity using Shapiro-Wilk and Bartlett tests, respectively. Age and anthropometric characteristics (height, body mass and BMI) were compared between groups using a two-way (sex, maturity status) analysis of variance (ANOVA). A three-way multivariate ANOVA (sex, maturity status and jump type) with repeated measures was used for the statistical analysis of jump height, ground contact time or reactive strength index. When ANOVA revealed significant main or interaction effects, a Tukey HSD *post hoc* test was applied to test the discrimination between means. The effect size and statistical power were also reported when significant main or interaction effects were detected. The effect size was assessed using the partial eta-squared (η^2) and ranked as follows: ~ 0.01 = small effect, ~ 0.06 = moderate effect, ≥ 0.14 = large effect (4). 95% confidence intervals (CI 95%) were also indicated. The sample size required to obtain a high statistical power (90%) and a large effect size (Cohen's d = 0.9) was estimated at 15 participants per group. However, to reduce any possible errors relating to the effect size, the number of participants per group (i.e. per sex and maturity status) was ≥ 15 when the recruitment was possible. Statistical significance was set at $P<0.05$. Statistical procedures were performed using Statistica 8.0 software (StatSoft, Inc, USA). Results are presented as mean ± standard deviation (SD) in text and tables. Intraclass correlation coefficients (ICC) were calculated to check the reliability of the two measurements for each jump type using SPSS 1.0 software (IBM, Inc, USA). ICC scores were ranked as follows: < 0.50 (poor), between 0.50 and 0.75 (moderate), between 0.75 and 0.90 (good) and > 0.90 (excellent) (9).

RESULTS

Subjects' physical characteristics

The subjects' physical characteristics are displayed in Table 1. Regarding body mass, ANOVA revealed significant main effects for sex [F(1;171) = 74.1, P<0.001, η^2 = 0.30, power = 1.0] and maturity status [F(2;171) = 88.2, P<0.001, η^2 = 0.51, power = 1.0]; however, no significant sex × maturity status interaction effect was observed. On average, boys were heavier than girls (P<0.001) and body mass significantly increased with maturation (Pre < Circa < Post; P<0.01). ANOVA showed a significant sex × maturity status interaction effect [F(2;171) = 3.9, P<0.05, η^2 = 0.04, power = 0.70] for height, with boys being taller than girls regardless of the maturity level (P<0.001); however, the differences between sexes tended to decrease with maturation.

- Please insert Table 1 near here –

Jump height

Intraclass correlation coefficients for jump height measurements ranged 0.945 to 0.965. Jumping heights during the squat jump (SJ), countermovement jump (CMJ) and drop jumps (DJ) from 20, 30, 40, 50, 60 and 70 cm (DJ20, DJ30, DJ40, DJ50, DJ60 and DJ70, respectively) in pre-, circa- and post-pubertal girls and boys are displayed in Figure 1.

- Please insert Figure 1 near here -

ANOVA did not reveal a significant sex × maturity status × jump type interaction for jump height. However, significant main effects were observed for sex [F(1;171) = 96.4,

$P<0.001$, $\eta^2 = 0.36$, power = 1.0], maturity status [$F(2;171) = 23.2$, $P<0.001$, $\eta^2 = 0.21$, power = 0.99] and jump type [$F(7;1197) = 7.5$, $P<0.001$, $\eta^2 = 0.04$, power = 0.99]. Girls achieved lower jump heights than boys regardless of jump type ($P<0.001$). Furthermore, while no significant difference was observed between circa- and post-pubertal children, jump height was significantly lower in prepubertal children than circa- and post-pubertal children ($P<0.001$). Jump height was greater during CMJ than SJ and all DJs ($P<0.001$); no significant difference was observed between SJ and DJ heights. However, when counting how many subjects produced their best performance at each drop height, jump heights were found to be higher for DJ30 and DJ40 in girls, DJ20 in pre- and circa-pubertal boys and DJ40 in postpubertal boys. When expressing the drop height at which best performance was achieved as a percentage of standing height, the values were respectively 34.7, 26.1, 24.6, 26.7, 25.7 and 24.8% in prepubertal girls, pubertal girls, postpubertal girls, prepubertal boys, pubertal boys and postpubertal boys.

Contact time

Ground contact times obtained during the drop jumps are presented in Table 2. ANOVA showed a significant sex × maturity status × drop height interaction [$F(10;855) = 2.0$, $P<0.05$, $\eta^2 = 0.02$, power = 0.89]. While boys displayed no significant difference between maturity levels, postpubertal girls exhibited a significantly higher contact time than their prepubertal counterparts during drop jumps from 30, 40, 50 and 60 cm (Table 2).

- Please insert Table 2 near here -

Reactive strength index

Reactive strength indices obtained during DJs from heights of 20 – 70 cm are presented in Table 3. ANOVA showed no significant sex × maturity status × drop height interaction effect; however there was a significant sex × maturity status interaction effect for RSI [$F(2;171) = 19.6$, $P<0.001$, $\eta^2 = 0.19$, power = 0.99]. In girls, RSI was not significantly different between pre- (0.401 ± 0.030 [CI 95% = 0.342-0.459]), circa- (0.463 ± 0.025 [CI 95% = 0.413-0.513]) and post- (0.390 ± 0.017 [CI 95% = 0.359-0.422]) pubertal groups, however it was significantly greater in postpubertal than circa- and pre-pubertal boys (pre: 0.440 ± 0.026 [CI 95% = 0.389-0.491], circa: 0.473 ± 0.017 [CI 95% = 0.440-0.506], post: 0.674 ± 0.031 [CI 95% = 0.613-0.734]; $P<0.001$). Furthermore, ANOVA revealed a significant main effect for drop height [$F(5;855) = 9.3$, $P<0.001$, $\eta^2 = 0.05$, power = 0.99] with RSI decreasing from DJ20 to DJ70, although this decrement was statistically different from DJ60 ($P<0.001$; DJ20: 0.496 ± 0.014 [CI 95% = 0.467-0.524], DJ30: 0.495 ± 0.012 [CI 95% = 0.472-0.518], DJ40: 0.472 ± 0.011 [CI 95% = 0.451-0.493], DJ50: 0.476 ± 0.012 [CI 95% = 0.453-0.499], DJ60: 0.459 ± 0.012 [CI 95% = 0.435-0.482], DJ70: 0.443 ± 0.010 [CI 95% = 0.422-0.463]).

- Please insert Table 3 near here -

DISCUSSION

The aim of the present study was to determine the effect of drop height on vertical jumping performance in relation to maturity status and sex in children. We hypothesized that, unlike prepubertal children, circa- and post-pubertal children would exhibit a decrement in jump height when the drop height exceeded a certain value (i.e. optimal height), and this could be more significant in boys than girls. The results of the present study do not confirm our hypotheses. They show that although the greatest jump heights were achieved in CMJ, the increase in DJ drop height had no significant effect on jumping performance and provided no further gain compared to the squat jump. Furthermore, while boys generally jumped higher than girls irrespective of maturity status, there was no effect of sex on the drop height-dependence of jump height. Nonetheless, a count of the number of subjects who produced their best performance at each drop height revealed that greater jump heights were obtained for drop heights between 20 and 40 cm in both girls and boys.

Previous studies in adults have shown that DJ performance is greater than for CMJ, with performances increasing to a drop height of 20 and 40 cm in adults who use stiff versus compliant lower-limb landing strategies, respectively, but declining thereafter (28). These critical drop heights are dependent at least partially on sex and training background (8) as well as musculotendinous stiffness (28). In the present study, a consistent (i.e. group-level) gain in jump height was not observed during DJs in any of the examined biological age or sex groups when compared to SJ. This is in agreement with previous studies showing no improvement in DJ40 compared to SJ in pre- and post-pubertal boys (19) or DJs with a range of drop heights (10-50 cm) compared to SJ in untrained prepubertal boys and girls (2). This implies that untrained children, even during postpubertal ages, are not able to benefit strongly from the function of the SSC during DJ as adults do (29). The exact mechanisms for this phenomenon are still unknown, but there are indications that the lower tendon stiffness in children (11, 12) may result in longer contact time (14) and challenge the efficacy of the SSC. In addition, this lack of gain in jump height could be associated with an impaired coordination and balance during the awkward stage of adolescence (i.e. around the peak height velocity) (22). Finally, children have a lower strength-to-body mass ratio than adults (17), and might therefore not be able to generate sufficient ground reaction force to utilise the greater kinetic energy provided by landing from a height prior to the jump. Nevertheless, the lack of difference in jump height between DJs performed from different heights in all age and sex groups may reflect the significant inter-individual variability in optimal drop height within each group, as shown by the fact that most girls jumped higher from 30 and 40 cm, most of the pre- and circa-pubertal boys were better in DJ20, and most of the post-pubertal boys reached their peak jumping height in DJ40.

As mentioned above, further increases in drop height may result in decrements in jump height. The relationship between jump height and drop height is related to the capacity of the neuromuscular system not only to use the SSC efficiently but also to protect the muscle-tendon unit from potential injury when drop height increases (16, 27). This regulation is achieved possibly by spinal inhibitory neural mechanisms (16, 27), and according to the presented data it seems that such an inhibitory mechanism exists in both sexes, particularly when drop height is increased above 60 cm, independently of maturity level. It is worth noting that the decreased jumping performance in adults (men and women) also appears when increasing the drop height above 20-40 cm (28) or 60 cm (8). However, it is still unknown whether these heights are comparable between children and adults since differences in body mass result in significant differences in the impact force (energy) during contact with the ground, which has to be absorbed or dissipated from the passive and active components of the musculoskeletal system.

Taking into account the results presented in Figure 1 and Tables 2 – 3 it could be argued that, at least for drop heights of 30 – 60 cm, postpubertal girls jumped higher than prepubertal girls by proportionally increasing their contact time, as shown by their unchanged RSI. In contrast, postpubertal boys achieved better jump height improvements for the same jump types than their younger counterparts without increasing their contact time, resulting in an increase RSI. This indicates different between-sex strategies to improve performance, possibly to compensate for the anthropometric changes that occur during growth and/or maturation (see Table 1). Interestingly, in the examined subgroups, between-sex differences in standing height tended to decrease as maturation proceeded whereas body mass differences remained consistent. Considering the above, it could be speculated that the lack of increase of RSI in girls, which is a measure of explosive strength, could be linked to the disproportionally smaller increase in body mass during maturation when compared to boys.

Several considerations should be mentioned in this study. It has been reported that photocell devices such as the Optojump present small, systematic measurement errors when assessing jump height through the flight time method in comparison with jump height measured from a force plate (1). However, these systematic errors should not affect the conclusions of the present study since the Optojump photoelectric cells have an excellent inter-trial reliability for the assessment of jump height (1). Thus, they can be used with confidence to detect between-group differences in cross-sectional comparisons. Furthermore, it is well known that intra-session reliability of jump height performance is critically important to ensure that observed differences between jump types do not result from systematic bias, such as a learning effect, muscle/body temperature or fatigue. In the present study, this systematic bias was reduced as much as possible since all the children performed the same warm-up and were fully familiarized with the tests prior to the experimental measurements. Also, all tests were performed under similar conditions, i.e. in indoor rooms between 14:00 and 18:00 o'clock, with the temperature ranging 22 to 27°C. This low systematic bias is evidenced by the high intraclass correlation coefficients obtained for each jump type in the current study (from 0.945 to 0.965). Another point of consideration is that children had to push as forcefully as possible and reduce the ground contact time, which may have resulted in sub-optimum jumping performance. However, this instruction was used to standardize the drop jumps and thus better quantify the effect of drop height on jumping performance with respect to maturity status and sex, as previously done by Prieske et al. (21).

CONCLUSIONS

The main results of the present study indicate that children, independent of sex and maturity status, did not improve performance as drop heights were increased from 20 to 70 cm compared to the squat jump, and that explosive strength capacities (measured as the reactive strength index) were significantly reduced when drop heights were 60 cm or higher. However, a count of the number of subjects who produced their best performance at each drop height revealed that jump heights were greatest for drop heights between 20 and 40 cm. When expressing the drop height at which best performance was achieved as a percentage of standing height, the values were respectively 34.7, 26.1, 24.6, 26.7, 25.7 and 24.8% in prepubertal girls, pubertal girls, postpubertal girls, prepubertal boys, pubertal boys and postpubertal boys. Therefore, the use of drop heights between 20 and 40 cm can be recommended in children during testing, or during training with the aim of improving explosive strength capacities with plyometric training.

PRACTICAL APPLICATIONS

Although no assessment of injury risk was done in relation to drop heights in the present study, we do not recommend the use of drop heights greater than 60 cm in order to limit the risk of developing problems such as patellofemoral pain, tendinosis/tendonitis, or osteochondrosis [e.g. Osgood-Schlatter's (knee) or Sever's (heel) disease] in young untrained children. In accordance with previous studies (23), children should use different types of jumps during training programmes to optimize performance adaptations.

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AUTHORS' CONTRIBUTIONS

This study was conducted in the laboratory of metabolic adaptations during exercise in physiological and pathological conditions (AME2P, EA 3533) at the Clermont Auvergne University, France. DS and SR designed the research; AB, DS, ED and PD collected data and performed research; AJB, DP and SR analysed data; SR supervised research; AJB, DP and SR wrote the manuscript and all authors provided critical revisions important for intellectual content of the finished manuscript. All authors approved the final version of the manuscript and agree to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved. All persons designated as authors qualify for authorship, and all those who qualify for authorship are listed.

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CONFLICT OF INTEREST

The authors declare no competing interests. The results of the study are presented clearly, honestly and without fabrication, falsification or inappropriate data manipulation.

REFERENCES

1. Attia A, Dhahbi W, Chaouachi A, Padulo J, Wong DP, Chamari K. Measurement errors when estimating the vertical jump height with flight time using photocell devices: the example of Optojump. Biol Sport. 2017;34(1):63-70.
2. Bassa EI, Patikas DA, Panagiotidou AI, Papadopoulou SD, Pylianidis TC, Kotzamanidis CM. The effect of dropping height on jumping performance in trained and untrained prepubertal boys and girls. J Strength Cond Res. 2012;26(8):2258-64.
3. Bobbert MF, Huijing PA, van Ingen Schenau GJ. Drop jumping. II. The influence of dropping height on the biomechanics of drop jumping. Med Sci Sports Exerc. 1987;19(4):339-46.
4. Cohen J. Statistical power analysis for Behavioral sciences. Cambridge: Academic Press; 1969.
5. Difiori JP. Overuse injuries in children and adolescents. Phys Sportsmed. 1999;27(1):75-89.
6. Kluka V, Martin V, Vicencio SG, et al. Effect of muscle length on voluntary activation of the plantar flexors in boys and men. Eur J Appl Physiol. 2016;116(5):1043-51.
7. Kluka V, Martin V, Vicencio SG, et al. Effect of muscle length on voluntary activation level in children and adults. Med Sci Sports Exerc. 2015;47(4):718-24.
8. Komi PV, Bosco C. Utilization of stored elastic energy in leg extensor muscles by men and women. Med Sci Sports. 1978;10(4):261-5.
9. Koo TK, Li MY. A Guideline of Selecting and Reporting Intraclass Correlation Coefficients for Reliability Research. J Chiropr Med. 2016;15(2):155-63.
10. Korff T, Horne SL, Cullen SJ, Blazevich AJ. Development of lower limb stiffness and its contribution to maximum vertical jumping power during adolescence. J Exp Biol. 2009;212(Pt 22):3737-42.
11. Kubo K, Kanehisa H, Kawakami Y, Fukanaga T. Growth changes in the elastic properties of human tendon structures. Int J Sports Med. 2001;22(2):138-43.
12. Lambertz D, Mora I, Grosset JF, Perot C. Evaluation of musculotendinous stiffness in prepubertal children and adults, taking into account muscle activity. J Appl Physiol (1985). 2003;95(1):64-72.
13. Latorre Roman PA, Villar Macias FJ, Garcia Pinillos F. Effects of a contrast training programme on jumping, sprinting and agility performance of prepubertal basketball players. J Sports Sci. 2018;36(7):802-8.
14. Lazaridis S, Bassa E, Patikas D, Giakas G, Gollhofer A, Kotzamanidis C. Neuromuscular differences between prepubescents boys and adult men during drop jump. Eur J Appl Physiol. 2010;110(1):67-74.
15. Lazaridis SN, Bassa EI, Patikas D, Hatzikotoulas K, Lazaridis FK, Kotzamanidis CM. Biomechanical comparison in different jumping tasks between untrained boys and men. Pediatr Exerc Sci. 2013;25(1):101-13.
16. Leukel C, Gollhofer A, Keller M, Taube W. Phase- and task-specific modulation of soleus H-reflexes during drop-jumps and landings. Exp Brain Res. 2008;190(1):71-9.
17. Martin RJ, Dore E, Hautier CA, Van Praagh E, Bedu M. Short-term peak power changes in adolescents of similar anthropometric characteristics. Med Sci Sports Exerc. 2003;35(8):1436-40.

18. Mirwald RL, Baxter-Jones AD, Bailey DA, Beunen GP. An assessment of maturity from anthropometric measurements. Med Sci Sports Exerc. 2002;34(4):689-94.
19. Pääsuke M, Ereline J, Gapeyeva H. Knee extensor muscle strength and vertical jumping performance characteristics in pre- and post-pubertal boys. Pediatr Exerc Sci. 2001;13:60-9.
20. Peng HT. Changes in biomechanical properties during drop jumps of incremental height. J Strength Cond Res. 2011;25(9):2510-8.
21. Prieske O, Chaabene H, Puta C, Behm DG, Busch D, Granacher U. Effects of Drop Height on Jump Performance in Male and Female Elite Adolescent Handball Players. Int J Sports Physiol Perform. 2019;14(5):674-80.
22. Radnor JM, Oliver JL, Waugh CM, Myer GD, Moore IS, Lloyd RS. The Influence of Growth and Maturation on Stretch-Shortening Cycle Function in Youth. Sports Med. 2018;48(1):57-71.
23. Ramirez-Campillo R, Burgos CH, Henriquez-Olguin C, et al. Effect of unilateral, bilateral, and combined plyometric training on explosive and endurance performance of young soccer players. J Strength Cond Res. 2015;29(5):1317-28.
24. Read PJ, Jimenez P, Oliver JL, Lloyd RS. Injury prevention in male youth soccer: Current practices and perceptions of practitioners working at elite English academies. J Sports Sci. 2018;36(12):1423-31.
25. Sayer TA, Hinman RS, Paterson KL, et al. Differences in Hip and Knee Landing Moments across Female Pubertal Development. Med Sci Sports Exerc. 2019;51(1):123-31.
26. Suchomel TJ, Bailey CA, Sole CJ, Grazer JL, Beckham GK. Using reactive strength index-modified as an explosive performance measurement tool in Division I athletes. J Strength Cond Res. 2015;29(4):899-904.
27. Taube W, Leukel C, Schubert M, Gruber M, Rantalainen T, Gollhofer A. Differential modulation of spinal and corticospinal excitability during drop jumps. J Neurophysiol. 2008;99(3):1243-52.
28. Walshe AD, Wilson GJ. The influence of musculotendinous stiffness on drop jump performance. Can J Appl Physiol. 1997;22(2):117-32.
29. Waugh CM, Korff T, Blazevich AJ. Developmental differences in dynamic muscle-tendon behaviour: implications for movement efficiency. J Exp Biol. 2017;220(Pt 7):1287-94.
30. Weber ML, Lam KC, McLeod TCV. The effectiveness of injury prevention programs for youth and adolescent athletes. International Journal of Athletic Therapy and Training. 2016;21(2):25-31.

Table 1. Subjects' physical characteristics

	Girls n = 92			Boys n = 85		
	Pre	Circa	Post	Pre	Circa	Post
n	16	22	54	21	49	15
Age (y)	9.2 ± 1.6	12.2 ± 1.0***	14.6 ± 0.6$^{***,\$\$\$}$	12.7 ± 0.9	14.5 ± 0.7***	15.7 ± 1.2$^{***,\$\$\$}$
	(7.6-11.6)	(11.1-13.6)	(12.7-15.3)	(11.7-14.3)	(13.4-15.9)	(15.1-16.0)
Years to (from) APHV	-2.4 ± 0.8	-0.1 ± 0.6***	2.0 ± 0.5$^{***,\$\$\$}$	-1.7 ± 0.7	0.1 ± 0.6***	1.7 ± 0.9$^{***,\$\$\$}$
Height (cm)	136.4 ± 8.9	154.9 ± 5.0***	163.9 ± 5.2$^{***,\$\$\$}$	154.1 ± 6.5	169.6 ± 6.4***	174.6 ± 9.4$^{***,\$\$}$
Body mass (kg)	31.9 ± 6.1	43.2 ± 6.8***	53.1 ± 7.8$^{***,\$\$\$}$	40.8 ± 6.1	56.0 ± 9.0***	66.9 ±14.8$^{***,\$\$\$}$
BMI (kg/m^2)	17.1 ± 2.1	18.0 ± 2.8	19.8 ± 2.5$^{***,\$\$}$	17.1 ± 1.9	19.4 ± 2.2***	21.9 ± 3.7$^{***,\$\$\$}$

Mean ± SD. BMI: body mass index; APHV: age at peak height velocity. **, ***: significantly different from prepubertal children (Pre) at P < 0.01 and P < 0.001, respectively; $$, $$$: significantly different from circapubertal children (Circa) at P < 0.01 and P < 0.001, respectively. Post: postpubertal children.

Table 2. Ground contact times (seconds) obtained during drop jumps from drop heights of 20, 30, 40, 50, 60, and 70 cm (DJ20, DJ30, DJ40, DJ50, DJ60, and DJ70, respectively).

		n	DJ20	DJ30	DJ40	DJ50	DJ60	DJ70
	Pre	16	0.477 ± 0.152	0.433 ± 0.132	0.453 ± 0.114	0.466 ± 0.102	0.494 ± 0.108	0.567 ± 0.109
Girls	Circa	22	0.503 ± 0.134$^{\$}$	0.512 ± 0.168	0.551 ± 0.165	0.516 ± 0.155$^{\$}$	0.554 ± 0.169	0.557 ± 0.191
	Post	54	0.590 ± 0.107	0.609 ± 0.130***	0.609 ± 0.114**	0.622 ± 0.105**	0.619 ± 0.105*	0.610 ± 0.119
	Pre	21	0.539 ± 0.100	0.568 ± 0.085	0.581 ± 0.112	0.588 ± 0.069	0.608 ± 0.079	0.606 ± 0.077
Boys	Circa	49	0.621 ± 0.140	0.619 ± 0.114	0.623 ± 0.095	0.641 ± 0.103	0.648 ± 0.111	0.650 ± 0.119
	Post	15	0.504 ± 0.104	0.513 ± 0.105	0.528 ± 0.070	0.515 ± 0.082	0.524 ± 0.085	0.550 ± 0.079

Mean ± SD. Pre: prepubertal children. Circa: circapubertal children. Post: postpubertal children. DJ: drop jump. *, **, ***: significantly different from prepubertal children (Pre) at $P < 0.05$, $P < 0.01$ and $P < 0.001$, respectively. $: significantly different from boys with the same maturity status at $P < 0.05$.

Table 3. Reactive strength indices calculated for drop jumps from drop heights of 20, 30, 40, 50, 60, and 70 cm (DJ20, DJ30, DJ40, DJ50, DJ60, and DJ70, respectively). Refer to text for between-group and between-condition difference information.

		n	DJ20	DJ30	DJ40	DJ50	DJ60	DJ70
Girls	Pre	16	0.41 ± 0.18	0.44 ± 0.18	0.41 ± 0.16	0.42 ± 0.18	0.39 ± 0.14	0.34 ± 0.12
	Circa	22	0.47 ± 0.13	0.48 ± 0.15	0.44 ± 0.12	0.48 ± 0.15	0.46 ± 0.16	0.45 ± 0.14
	Post	54	0.40 ± 0.09	0.40 ± 0.11	0.39 ± 0.09	0.39 ± 0.09	0.38 ± 0.10	0.38 ± 0.11
Boys	Pre	21	0.49 ± 0.14	0.46 ± 0.13	0.44 ± 0.12	0.43 ± 0.09	0.41 ± 0.14	0.41 ± 0.11
	Circa	49	0.51 ± 0.24	0.49 ± 0.13	0.48 ± 0.14	0.46 ± 0.17	0.45 ± 0.16	0.45 ± 0.14
	Post	15	0.70 ± 0.19	0.70 ± 0.19	0.67 ± 0.15	0.68 ± 0.13	0.66 ± 0.13	0.63 ± 0.12

Mean ± SD. Pre: prepubertal children. Circa: circapubertal children. Post: postpubertal children. DJ: drop jump. Reactive strength index = jump height / ground contact time.

Figure legends

Figure 1. Jumping heights during squat jumps (SJ), countermovement jumps (CMJ) and drop jumps (DJ) from drop heights of 20, 30, 40, 50, 60 and 70 cm (DJ20, DJ30, DJ40, DJ50, DJ60 and DJ70, respectively) in pre-, circa- and post-pubertal girls and boys. Jump height was significantly lower in prepubertal children than in circa- and post-pubertal children at $P<0.001$ (***).