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

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4 **Effect of drop height on vertical jumping performance in pre-, circa- and post-**  
5 **pubertal boys and girls**

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12 **Running head:** Jumping performance in children

13

14 **ABSTRACT**

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

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

21 **Results:** No significant sex  $\times$  maturity status  $\times$  jump type interaction for jump height  
22 was observed. However, on average, the children jumped higher in the CMJ than in SJ  
23 and DJs (+1.2 and +1.6 cm,  $P < 0.001$ , respectively), with no significant differences  
24 between DJs and SJ or between DJs when increasing drop heights. Regarding DJs,  
25 59.3% of the participants jumped higher from drop heights of 20 – 40 cm.

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

30

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

## 32 INTRODUCTION

33 Plyometric training is a popular form of physical conditioning in athletes owing to the  
34 utilization of stretch-shortening cycle (SSC) to produce muscle power (23). This form  
35 of work is based on the storage of elastic energy in the muscle-tendon unit during the  
36 eccentric phase and on its restitution during the subsequent concentric action. The SSC  
37 is present in common human movements such as walking, running, and jumping.

38 Concerning jumping, the SSC mainly appears in the countermovement and drop jumps  
39 (13). Plyometric training including jumping has been shown to be beneficial for  
40 decreasing injury risk (13, 30). However, if the SSC is used too frequently and in high  
41 volume, it may predispose young athletes to injury because of the strain that the  
42 musculotendinous, musculoarticular and skeletal systems experience at each impact  
43 (24), as for instance during the landing phase of a jump. The onset of adolescence (i.e.  
44 around the peak height velocity) is a particularly critical period for injuries because of  
45 (i) imbalances within muscle-tendon units of young athletes, (ii) strength imbalances  
46 between the hamstrings and quadriceps, particularly in postpubertal girls, (iii) between-  
47 limb asymmetries which are high before puberty, and (iv) the relatively immature bone  
48 structure (25). Furthermore, there is evidence for differences in neuromuscular  
49 activation and technique between children and adults during jumping (14, 15). Thus, in  
50 early adolescence, conditioning coaches, physical educators and teachers should pay  
51 particular attention to the dosage of jump-type activities, particularly the number and  
52 intensity of take-off and landing phases in order to reduce the risk of developing  
53 problems such as patellofemoral pain, tendinosis/tendonitis, or osteochondrosis [e.g.  
54 Osgood-Schlatter's (knee) or Sever's (heel) disease] (5).

55 As with any form of exercise program, the variables of intensity, volume, frequency,  
56 repetition velocity and recovery should be carefully monitored to ensure optimal athletic  
57 development of children and adolescents while minimizing injury risk (23). During  
58 plyometric training, exercise intensity is influenced by the loading (ground reaction  
59 force rate and magnitude) achieved in the eccentric (braking) phase as the agonist  
60 muscle-tendon units are actively stretched. In contrast to the squat jump, which is  
61 largely considered to be a measure of concentric muscle performance,  
62 countermovement and drop jump performances involve both eccentric and concentric  
63 phases. Countermovement and drop jumps are typically examined in research, since the  
64 former is very common task in sports and the latter is frequently used in lower-body  
65 plyometric training (23). Regarding the drop jump, the stretch load is strongly  
66 influenced by the drop height of the body's centre of mass prior to landing in the jump,  
67 which has been suggested to be set in the region of 20 to 70 cm in adults (3). However,  
68 optimal drop height has not yet been determined according to age, maturity status, sex  
69 or training background. In prepubertal children, an optimal drop height has not been  
70 identified. This is partly a result of data showing no difference in jumping performance  
71 when landing from different heights during drop jumps (e.g. drop heights of 10 – 50 cm  
72 in 9- to 11-year-old boys and girls) (2, 19). This lack of effect of drop height on  
73 performance could partly result from prepubertal children not using stored elastic  
74 energy as effectively as young adults in SSC tasks, owing to their higher tendon  
75 compliance and lesser ability to recruit fully motor units (6, 7, 10, 29). In contrast, in  
76 young untrained adults, jumping height appears to increase up to an optimal drop height  
77 (~ 30-40 cm) and then decrease from heights of 40 – 50 cm (20). This decrement from  
78 heights > 40 cm was speculatively attributed to biomechanical inefficiency (SSC power

79 output) and stiffness differences (3, 28). During adolescence, only Prieske et al. (21)  
80 studied jumping performance in postpubertal male and female elite handball players  
81 over a reduced range of drop heights (e.g. 20, 35 and 50 cm) and no information is yet  
82 available regarding the acute effect of drop height on jumping performance in circa- and  
83 post-pubertal recreationally active boys and girls. Yet, maturation could strongly  
84 influence the interaction between drop height and jumping performance as there is a  
85 gradual enhancement in the rapid force-producing potential and utilization of the  
86 underpinning mechanisms of the SSC over this maturational period (10, 22). This effect  
87 could be more significant in boys than girls since recent research has demonstrated that  
88 males would have greater adaptations in the mechanical (elastic) properties of the  
89 muscle and tendon than females during maturation (22). However, direct scientific  
90 evidence showing this result is still lacking.

91

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

98

## 99 **MATERIALS AND METHODS**

### 100 **Experimental approach to the problem**

101 Our experimental approach was to assess drop jump performance over a series of  
102 heights in pre-, circa- and post-pubertal children, and determine whether it is

103 differentially influenced by sex according to maturity status. The subjects were divided  
104 into six groups (prepubertal girls, prepubertal boys, circapubertal girls, circapubertal  
105 boys, postpubertal girls, postpubertal boys). Squat jump (SJ) was used as a reference for  
106 jumping ability (2). To check the effect of countermovement jump (CMJ) and drop  
107 jumps (DJ) from various heights (20, 30, 40, 50, 60 and 70 cm) on children's jumping  
108 performances, we compared CMJ and DJ scores to SJ performance using a within-  
109 subject design with jump height randomized between subjects.

110

### 111 **Subjects**

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

122

123 This study was approved by an Institutional Ethics Review Board (CERSTAPS #2019-  
124 09-04) and conformed to the standards of use of human subjects in research as outlined  
125 in the sixth *Declaration of Helsinki*. The children were informed of the experimental  
126 procedures and gave their written assent before any testing was conducted. In addition,

127 the written informed consent was obtained from the parents or legal guardians of the  
128 children.

129

### 130 **Anthropometric measurements and maturation assessment**

131 A digital weight scale (TANITA, BC-545N, Japan) was used to measure body mass to  
132 the nearest 0.1 kg and barefoot standing height was assessed to the nearest 0.1 cm with  
133 a wall-mounted stadiometer (TANITA, HR001, Japan). Body mass index (BMI) was  
134 calculated as body mass (kg) divided by height squared ( $m^2$ ). Age from peak height  
135 velocity (PHV) was used to assess somatic maturity and determined using standing  
136 height, sitting height and body mass. Its calculation was based on sex-specific  
137 regression equations according to the method proposed by Mirwald et al. (18). Children  
138 were grouped by their maturity status (pre-, circa- or post-PHV) into discrete bands  
139 based on their maturational offset (pre-PHV =  $< -1$ , circa-PHV =  $-1$  to  $+1$ , post-PHV =  
140  $>1$ ).

141

### 142 **Testing**

143 All subjects were tested in two experimental sessions separated by at least 48 h. During  
144 the first experimental session, anthropometric characteristics and maturity status were  
145 evaluated. All subjects were then familiarized with the testing procedures with the help  
146 of their physical education teacher and researchers. No subjects felt fear when jumping  
147 from the highest boxes; they were both confident and competent in performing the tests.  
148 During the second session, the subjects performed 2 SJs, 2 CMJs, and 2 DJs from  
149 heights of 20, 30, 40, 50, 60 and 70 cm. The two trials for each type of jump were  
150 performed sequentially while the different types of jump were done in a randomized



151 order. There was at least 2 min of rest between trials. This rest interval was provided in  
152 order to minimize fatigue, as proposed by Bassa et al. (2). Before any exercise, the  
153 subjects completed a progressive warm-up that included 5 min of jogging followed by  
154 dynamic lower-limb exercises. Afterwards, the subjects performed submaximal and  
155 maximal SJs and CMJs; a single DJ was also performed from each DJ height. All the  
156 tests were performed indoors between 14:00 and 18:00 o'clock, and with the  
157 temperature kept between 22 and 27°C. The session duration lasted about one hour for  
158 each subject.

159

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

169

170 Jumping tests were performed with the following instructions:

171 *Squat Jump (SJ)*. From a standing position, the subjects flexed their knees to 90° to  
172 lower their centre of mass (i.e. to a squatting position). This position was held for 3 s  
173 before a maximal vertical jump was performed without countermovement. Jumps were

174 repeated if the researcher could clearly, visually detect a countermovement prior to the  
175 upward (jump) phase.

176

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

183

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

## 198 **Statistical analysis**

199 Data were screened for distribution normality and homogeneity using Shapiro-Wilk and  
200 Bartlett tests, respectively. Age and anthropometric characteristics (height, body mass  
201 and BMI) were compared between groups using a two-way (sex, maturity status)  
202 analysis of variance (ANOVA). A three-way multivariate ANOVA (sex, maturity status  
203 and jump type) with repeated measures was used for the statistical analysis of jump  
204 height, ground contact time or reactive strength index. When ANOVA revealed  
205 significant main or interaction effects, a Tukey HSD *post hoc* test was applied to test the  
206 discrimination between means. The effect size and statistical power were also reported  
207 when significant main or interaction effects were detected. The effect size was assessed  
208 using the partial eta-squared ( $\eta^2$ ) and ranked as follows:  $\sim 0.01$  = small effect,  $\sim 0.06$  =  
209 moderate effect,  $\geq 0.14$  = large effect (4). 95% confidence intervals (CI 95%) were also  
210 indicated. The sample size required to obtain a high statistical power (90%) and a large  
211 effect size (Cohen's  $d = 0.9$ ) was estimated at 15 participants per group. However, to  
212 reduce any possible errors relating to the effect size, the number of participants per  
213 group (i.e. per sex and maturity status) was  $\geq 15$  when the recruitment was possible.  
214 Statistical significance was set at  $P < 0.05$ . Statistical procedures were performed using  
215 Statistica 8.0 software (StatSoft, Inc, USA). Results are presented as mean  $\pm$  standard  
216 deviation (SD) in text and tables. Intraclass correlation coefficients (ICC) were  
217 calculated to check the reliability of the two measurements for each jump type using  
218 SPSS 1.0 software (IBM, Inc, USA). ICC scores were ranked as follows:  $< 0.50$  (poor),  
219 between 0.50 and 0.75 (moderate), between 0.75 and 0.90 (good) and  $> 0.90$  (excellent)  
220 (9).

221

## 222 RESULTS

### 223 Subjects' physical characteristics

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

233

234 - Please insert Table 1 near here -

235

### 236 Jump height

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

242 - Please insert Figure 1 near here -

243

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

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

259

### 260 **Contact time**

261 Ground contact times obtained during the drop jumps are presented in Table 2. ANOVA  
262 showed a significant sex  $\times$  maturity status  $\times$  drop height interaction [ $F(10;855) = 2.0$ ,  
263  $P < 0.05$ ,  $\eta^2 = 0.02$ , power = 0.89]. While boys displayed no significant difference  
264 between maturity levels, postpubertal girls exhibited a significantly higher contact time  
265 than their prepubertal counterparts during drop jumps from 30, 40, 50 and 60 cm (Table  
266 2).

267

268

- Please insert Table 2 near here -

269

**270 Reactive strength index**

271 Reactive strength indices obtained during DJs from heights of 20 – 70 cm are presented  
272 in Table 3. ANOVA showed no significant sex × maturity status × drop height  
273 interaction effect; however there was a significant sex × maturity status interaction  
274 effect for RSI [ $F(2;171) = 19.6, P < 0.001, \eta^2 = 0.19, \text{power} = 0.99$ ]. In girls, RSI was  
275 not significantly different between pre- ( $0.401 \pm 0.030$  [CI 95% = 0.342-0.459]), circa-  
276 ( $0.463 \pm 0.025$  [CI 95% = 0.413-0.513]) and post- ( $0.390 \pm 0.017$  [CI 95% = 0.359-  
277 0.422]) pubertal groups, however it was significantly greater in postpubertal than circa-  
278 and pre-pubertal boys (pre:  $0.440 \pm 0.026$  [CI 95% = 0.389-0.491], circa:  $0.473 \pm 0.017$   
279 [CI 95% = 0.440-0.506], post:  $0.674 \pm 0.031$  [CI 95% = 0.613-0.734];  $P < 0.001$ ).

280 Furthermore, ANOVA revealed a significant main effect for drop height [ $F(5;855) =$   
281  $9.3, P < 0.001, \eta^2 = 0.05, \text{power} = 0.99$ ] with RSI decreasing from DJ20 to DJ70,  
282 although this decrement was statistically different from DJ60 ( $P < 0.001$ ; DJ20:  $0.496 \pm$   
283  $0.014$  [CI 95% = 0.467-0.524], DJ30:  $0.495 \pm 0.012$  [CI 95% = 0.472-0.518], DJ40:  
284  $0.472 \pm 0.011$  [CI 95% = 0.451-0.493], DJ50:  $0.476 \pm 0.012$  [CI 95% = 0.453-0.499],  
285 DJ60:  $0.459 \pm 0.012$  [CI 95% = 0.435-0.482], DJ70:  $0.443 \pm 0.010$  [CI 95% = 0.422-  
286 0.463]).

287

288

289

- Please insert Table 3 near here -

290

291

292

293

## 294 **DISCUSSION**

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

308

309 Previous studies in adults have shown that DJ performance is greater than for CMJ,  
310 with performances increasing to a drop height of 20 and 40 cm in adults who use stiff  
311 versus compliant lower-limb landing strategies, respectively, but declining thereafter  
312 (28). These critical drop heights are dependent at least partially on sex and training  
313 background (8) as well as musculotendinous stiffness (28). In the present study, a  
314 consistent (i.e. group-level) gain in jump height was not observed during DJs in any of  
315 the examined biological age or sex groups when compared to SJ. This is in agreement  
316 with previous studies showing no improvement in DJ40 compared to SJ in pre- and  
317 post-pubertal boys (19) or DJs with a range of drop heights (10-50 cm) compared to SJ

318 in untrained prepubertal boys and girls (2). This implies that untrained children, even  
319 during postpubertal ages, are not able to benefit strongly from the function of the SSC  
320 during DJ as adults do (29). The exact mechanisms for this phenomenon are still  
321 unknown, but there are indications that the lower tendon stiffness in children (11, 12)  
322 may result in longer contact time (14) and challenge the efficacy of the SSC. In  
323 addition, this lack of gain in jump height could be associated with an impaired  
324 coordination and balance during the awkward stage of adolescence (i.e. around the peak  
325 height velocity) (22). Finally, children have a lower strength-to-body mass ratio than  
326 adults (17), and might therefore not be able to generate sufficient ground reaction force  
327 to utilise the greater kinetic energy provided by landing from a height prior to the jump.  
328 Nevertheless, the lack of difference in jump height between DJs performed from  
329 different heights in all age and sex groups may reflect the significant inter-individual  
330 variability in optimal drop height within each group, as shown by the fact that most girls  
331 jumped higher from 30 and 40 cm, most of the pre- and circa-pubertal boys were better  
332 in DJ20, and most of the post-pubertal boys reached their peak jumping height in DJ40.  
333

334 As mentioned above, further increases in drop height may result in decrements in jump  
335 height. The relationship between jump height and drop height is related to the capacity  
336 of the neuromuscular system not only to use the SSC efficiently but also to protect the  
337 muscle-tendon unit from potential injury when drop height increases (16, 27). This  
338 regulation is achieved possibly by spinal inhibitory neural mechanisms (16, 27), and  
339 according to the presented data it seems that such an inhibitory mechanism exists in  
340 both sexes, particularly when drop height is increased above 60 cm, independently of  
341 maturity level. It is worth noting that the decreased jumping performance in adults (men



342 and women) also appears when increasing the drop height above 20-40 cm (28) or 60  
343 cm (8). However, it is still unknown whether these heights are comparable between  
344 children and adults since differences in body mass result in significant differences in the  
345 impact force (energy) during contact with the ground, which has to be absorbed or  
346 dissipated from the passive and active components of the musculoskeletal system.

347

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

362

363 Several considerations should be mentioned in this study. It has been reported that  
364 photocell devices such as the Optojump present small, systematic measurement errors  
365 when assessing jump height through the flight time method in comparison with jump

366 height measured from a force plate (1). However, these systematic errors should not  
367 affect the conclusions of the present study since the Optojump photoelectric cells have  
368 an excellent inter-trial reliability for the assessment of jump height (1). Thus, they can  
369 be used with confidence to detect between-group differences in cross-sectional  
370 comparisons. Furthermore, it is well known that intra-session reliability of jump height  
371 performance is critically important to ensure that observed differences between jump  
372 types do not result from systematic bias, such as a learning effect, muscle/body  
373 temperature or fatigue. In the present study, this systematic bias was reduced as much as  
374 possible since all the children performed the same warm-up and were fully familiarized  
375 with the tests prior to the experimental measurements. Also, all tests were performed  
376 under similar conditions, i.e. in indoor rooms between 14:00 and 18:00 o'clock, with  
377 the temperature ranging 22 to 27°C. This low systematic bias is evidenced by the high  
378 intraclass correlation coefficients obtained for each jump type in the current study (from  
379 0.945 to 0.965). Another point of consideration is that children had to push as forcefully  
380 as possible and reduce the ground contact time, which may have resulted in sub-  
381 optimum jumping performance. However, this instruction was used to standardize the  
382 drop jumps and thus better quantify the effect of drop height on jumping performance  
383 with respect to maturity status and sex, as previously done by Prieske et al. (21).

384

## 385 **CONCLUSIONS**

386 The main results of the present study indicate that children, independent of sex and  
387 maturity status, did not improve performance as drop heights were increased from 20 to  
388 70 cm compared to the squat jump, and that explosive strength capacities (measured as  
389 the reactive strength index) were significantly reduced when drop heights were 60 cm or

390 higher. However, a count of the number of subjects who produced their best  
391 performance at each drop height revealed that jump heights were greatest for drop  
392 heights between 20 and 40 cm. When expressing the drop height at which best  
393 performance was achieved as a percentage of standing height, the values were  
394 respectively 34.7, 26.1, 24.6, 26.7, 25.7 and 24.8% in prepubertal girls, pubertal girls,  
395 postpubertal girls, prepubertal boys, pubertal boys and postpubertal boys. Therefore, the  
396 use of drop heights between 20 and 40 cm can be recommended in children during  
397 testing, or during training with the aim of improving explosive strength capacities with  
398 plyometric training.

399

#### 400 **PRACTICAL APPLICATIONS**

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

408

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413

**414 AUTHORS' CONTRIBUTIONS**

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

425

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428

**429 CONFLICT OF INTEREST**

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

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522 **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 (7.6-11.6)	12.2 ± 1.0 <sup>***</sup> (11.1-13.6)	14.6 ± 0.6 <sup>***,\$\$\$</sup> (12.7-15.3)	12.7 ± 0.9 (11.7-14.3)	14.5 ± 0.7 <sup>***</sup> (13.4-15.9)	15.7 ± 1.2 <sup>***,\$\$\$</sup> (15.1-16.0)
Years to (from) APHV	-2.4 ± 0.8	-0.1 ± 0.6 <sup>***</sup>	2.0 ± 0.5 <sup>***,\$\$\$</sup>	-1.7 ± 0.7	0.1 ± 0.6 <sup>***</sup>	1.7 ± 0.9 <sup>***,\$\$\$</sup>
Height (cm)	136.4 ± 8.9	154.9 ± 5.0 <sup>***</sup>	163.9 ± 5.2 <sup>***,\$\$\$</sup>	154.1 ± 6.5	169.6 ± 6.4 <sup>***</sup>	174.6 ± 9.4 <sup>***,\$\$</sup>
Body mass (kg)	31.9 ± 6.1	43.2 ± 6.8 <sup>***</sup>	53.1 ± 7.8 <sup>***,\$\$\$</sup>	40.8 ± 6.1	56.0 ± 9.0 <sup>***</sup>	66.9 ± 14.8 <sup>***,\$\$\$</sup>
BMI (kg/m <sup>2</sup> )	17.1 ± 2.1	18.0 ± 2.8	19.8 ± 2.5 <sup>***,\$\$</sup>	17.1 ± 1.9	19.4 ± 2.2 <sup>***</sup>	21.9 ± 3.7 <sup>***,\$\$\$</sup>

523 Mean ± SD. BMI: body mass index; APHV: age at peak height velocity. \*\*, \*\*\*: significantly different from prepubertal children (Pre) at

524 P < 0.01 and P < 0.001, respectively; \$\$, \$\$\$: significantly different from circapubertal children (Circa) at P < 0.01 and P < 0.001,

525 respectively. Post: postpubertal children.

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527

528 **Table 2.** Ground contact times (seconds) obtained during drop jumps from drop heights of 20, 30, 40, 50, 60, and 70 cm (DJ20, DJ30,  
529 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 <sup>\$</sup>	0.512 ± 0.168	0.551 ± 0.165	0.516 ± 0.155 <sup>\$</sup>	0.554 ± 0.169	0.557 ± 0.191
	Post	54	0.590 ± 0.107	0.609 ± 0.130 <sup>***</sup>	0.609 ± 0.114 <sup>**</sup>	0.622 ± 0.105 <sup>**</sup>	0.619 ± 0.105 <sup>*</sup>	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

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

533



534 **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,  
535 DJ60, and DJ70, respectively). Refer to text for between-group and between-condition difference information.

	n	DJ20	DJ30	DJ40	DJ50	DJ60	DJ70	
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	
Girls	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
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	
Boys	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

536 Mean ± SD. Pre: prepubertal children. Circa: circapubertal children. Post: postpubertal children. DJ: drop jump. Reactive strength index =

537 jump height / ground contact time.

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539

540 **Figure legends**

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