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Skeletal Maturation, Body Size, and Motor Coordination in Youth 11–14 Years

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Abstract

Purpose: To estimate the relative contribution of biological maturation to variance in the motor coordination (MC) among youth and to explore gender differences in the associations. **Methods:** Skeletal maturation (Tanner-Whitehouse 3), stature, body mass and MC

(*Körperkoordinationstest für Kinder*) were assessed in 613 youth, 284 boys and 329 girls 11-14 years of age. Standardised residuals of skeletal age on chronological age were used as the estimate of skeletal maturity status independent of chronological age. Hierarchical multiple regression analyses were used to analyse associations between skeletal maturity status and MC.

Results: Skeletal maturity status by itself, i.e., standardised residuals of skeletal age on chronological age (step 3) explained a maximum of 8.1% of the variance in MC in boys (ΔR^2_3 in the range of 0.0% - 8.1%) and 2.8% of the variance in girls (ΔR^2_3 in the range of 0.0% - 2.8%), after controlling for stature, body mass and interactions of the standardised residuals of skeletal age on chronological age with stature and body mass. Corresponding percentages for the interactions of the standardised residuals of skeletal age and stature and body mass, after adjusting for stature and body mass (step 2) were 8.7% in boys (ΔR^2_2 in the range of 0.3% - 8.7%) and 7.1% in girls (ΔR^2_2 in the range of 0.1% - 7.1%). Chow tests suggested structural changes in β -coefficients in the four MC tests among boys and girls, 12-13 years. **Conclusion:** The percentage of variance in the four MC tests explained by skeletal maturation was relatively small, but the relationships differed between boys and girls. By inference, other factors, e.g., neuromuscular maturation, specific instruction and practice, sport participation, and others may influence MC at these ages.

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Abstract

Purpose: To estimate the relative contribution of biological maturation to variance in the motor coordination (MC) among youth and to explore gender differences in the associations. **Methods:** Skeletal maturation (Tanner-Whitehouse 3), stature, body mass and MC (*Körperkoordinationstest für Kinder*) were assessed in 613 youth, 284 boys and 329 girls 11-14 years of age. Standardised residuals of skeletal age on chronological age were used as the estimate of skeletal maturity status independent of chronological age. Hierarchical multiple regression analyses were used to analyse associations between skeletal maturity status and MC. **Results:** Skeletal maturity status by itself, i.e., standardised residuals of skeletal age on chronological age (step 3) explained a maximum of 8.1% of the variance in MC in boys (ΔR^2_3 in the range of 0.0% - 8.1%) and 2.8% of the variance in girls (ΔR^2_3 in the range of 0.0% - 2.8%), after controlling for stature, body mass and interactions of the standardised residuals of skeletal age on chronological age with stature and body mass. Corresponding percentages for the interactions of the standardised residuals of skeletal age and stature and body mass, after adjusting for stature and body mass (step 2) were 8.7% in boys (ΔR^2_2 in the range of 0.3% - 8.7%) and 7.1% in girls (ΔR^2_2 in the range of 0.1% - 7.1%). Chow tests suggested structural changes in β -coefficients in the four MC tests among boys and girls, 12-13 years. **Conclusion:** The percentage of variance in the four MC tests explained by skeletal maturation was relatively small, but the relationships differed between boys and girls. By inference, other factors, e.g., neuromuscular maturation, specific instruction and practice, sport participation, and others may influence MC at these ages. **Key words:** growth, maturation, motor development, youth

2 Introduction

3 Motor coordination (MC) plays an important role in the day to day activities of youth. In general,
4 well-coordinated youth show higher levels of physical activity (14) and physical fitness (11, 16)
5 than less-coordinated peers, whereas poorer levels of MC are associated with obesity in youth (2,
6 10). MC is also central to speed, jumping and agility and associated skills which are central to
7 participation in games and sports (23). More recently, MC has been associated with emotional
8 function and academic achievement/skills among youth (15, 20).

9 Several motor performances are influenced by individual differences in maturity status, although
10 the influence is more marked during adolescence than in childhood (4, 3). Earlier studies were
11 correlational, whereas more recent approaches have addressed potential interactions between
12 maturity status and body size as factors affecting performance. In two earlier studies, skeletal age
13 alone or as interaction terms with chronological age, stature or body mass accounted for a
14 maximum of 17% of variance in motor fitness in boys (3) and were not predictors of the
15 Flamingo balance, plate tapping and vertical jump in girls (4). Another approach used
16 standardised residuals of the regression of skeletal age on chronological age as the indicator of
17 maturity status to account for the relationship between skeletal and chronological ages (18). The
18 interactions terms of the standardised residuals of skeletal age on chronological age with stature
19 and body mass explained between 2% and 9% of variance in the standing long jump, dash and
20 ball throw for distance in children 7-12 years of age.

21 The literature addressing the influence of maturity status on MC is less extensive. Using a
22 specific MC battery (*Körperkoordinationstest für Kinder* [KTK]; 19) with children 7-10 years of
23 age, standardised residuals of skeletal age on chronological age alone accounted for a maximum

of 9.0% of variance in MC tasks over that attributed to body size per se and to the interactions between standardised residuals of skeletal age on chronological age and body size.

The present paper extends the preceding analysis to youth 11-14 years of age. Changes in size, proportions, body composition and strength associated with the transition into puberty and with puberty per se may influence specific measures of MC. To this end, the purpose of this study was to evaluate the relationships among skeletal maturity status, body size and MC in single year age groups of boys and girls 11 through 14 years of age and to explore gender differences within each age group. It was hypothesized that skeletal maturation per se or interacting with body size has a negligible influence on the explained variance in MC, over and beyond body size, and that this relationship is different among boys and girls.

Methods

Participants

Data were from the 'Healthy Growth of Madeira Study', a cross-sectional study with 12 birth cohorts, assessed/measured in 2005/2006. The sample and sampling procedures, study design, organizational aspects, and protocols have been previously described (12). Briefly, all participants (n = 1637, 801 boys and 836 girls, aged 3 to 15 years) attended 40 public and/or private schools from the 11 districts of Madeira and Porto Santo Islands, Portugal. A proportional stratified sampling procedure was carried out by a member of Statistics Portugal. The number of participants enrolled in each school was proportional to the number of children living in this district. In each district, at least 1 kindergarten, 1 primary school and 1 high school

participated in the study. Children of specific ages and sex were randomly selected within each school. The current analysis was limited to 613 healthy youth, 284 boys and 329 girls, 11 through 14 years of age (Table 1). Procedures were explained to each participant and written informed consent was granted from parents or legal guardians prior to testing. The Scientific Board of the University of Madeira and the Regional Ethics Committee for Health approved the study.

Field Team

Six teachers of physical education were trained by members of the research team and collected the data. The field team completed a 3 month training program, 2-hours per day, at the University of Madeira. The program included theoretical and practical sessions. First, instructions and demonstrations for anthropometry and MC testing were given to the field team. Second, the field team members practiced on each other. Third, protocols were tested in 10 children (6 boys and 4 girls, 8 to 12 years). And fourth, the field team participated in a pilot study of anthropometry in 46 primary school children, 3-10 years of age and of MC in 30 children, 6-10 years. The children were assessed twice with an interval of 1 week.

Anthropometry

Measurements were taken in the gymnasium or unused classroom. Stature and body mass were measured using a standardised protocol (7). Stature was measured with a portable stadiometer (Siber-Hegner, GPM) to the nearest 0.1 cm and body mass was measured on a balance-beam

scale accurate to 0.1 kg (Seca Optima 760, Germany). Children wore a swimming costume (two-piece for females), without shoes and jewellery removed. In the pilot study, absolute and relative intra-observer technical errors of measurement were, respectively, 0.31 cm and 0.26% for stature, and 0.66 kg and 2.56% for body mass. Test-retest reliability via ANOVA-based intraclass correlations ranged from 0.98 to 0.99 for stature and body mass.

Motor coordination

The four tests of the ‘Körperkoordinationstest für Kinder’ (KTK) motor coordination test battery (19) were administered to all youth:

- Balancing backwards. The child walked backward on three balance beams of 3 m in length and 5 cm in height, but of different widths: 6.0, 4.5 and 3.0 cm, respectively. Three trials were administered and scored for each beam, for a total of 9 trials. The assessor awarded the first point when the second foot left the starting board placed in front of the beam ($25 \times 25 \times 5.7$ cm) and touched the first beam. One point was given for each successful step; a maximum of 8 points could be achieved per trial on each beam. The maximum score was $3 \times 3 \times 8 = 72$.
- Hopping on one leg. The test required the child to jump over one or more superposed foam-based panels ($60 \text{ cm} \times 20 \text{ cm} \times 5 \text{ cm}$, each). The starting height depended on the child’s age and on the outcome of the practice trials (1 or 2 per leg). For children over 6, the test had a minimum height of 5 cm (one foam-panel) for each leg. If the child failed this jump, then he/she started the first scored attempt at a height of 0 cm; if the child succeeded, then he/she began the first scored attempt with the recommended starting height

for age. When hopping over the foam-panels, the assessor ensured that the child started to hop at an adequate distance from the foam-panels (about 1.50 m). After hopping over the foam-panels, the child continued to hop on the same foot for at least two more hops. During the trial, the other foot may not touch the ground. The child had three attempts at each height which were scored in the following manner: valid 1st attempt = 3 points; valid 2nd attempt = 2 points; valid 3rd attempt = 1 point. For starting heights of 5cm or higher, if the first attempt was successful, the assessor awarded three points for all the underlying heights. If, at any given height, the child failed all three attempts, the next height was conducted only if the sum of the two lower heights was at least five points. With 12 foam-panels (total height of 60 cm) plus the 0 cm height (with no foam-panel), a maximum of 39 points could be achieved per leg for a total of 78 points.

- Jumping side-to-side. The child was required to jump laterally with both feet over a wooden platform (100 × 60 × 2 cm) as many times as possible in 15 seconds. A wooden slat (60 × 4 × 2 cm) was attached in the middle of the platform. The child was instructed to jump laterally over the wooden slat with both feet simultaneously; both feet had to leave and land on the floor at the same time. A total of two attempts were given and the number of correct jumps was summed.

- Shifting platforms. The child was required to move sideways on wooden boxes (25 × 25 × 2 cm with four supports of 3.7 cm height attached at each corner), placed side-to-side on the floor as many time as possible in 20 s. A free space of 3 or 4 m in the direction to which the transposition would take place was required. The boxes should not be placed too far away or too near, and the child should not spend too much time trying to align the boxes. The assessor stood facing the child (at a maximum distance of 2 m) and moved

111 along with the child as he/she transposed the boxes. Each successful transfer from one
112 platform to the other was given two points, one for shifting the platform and one for
113 transfer of the body; the number of points in 20 seconds was recorded. Two attempts of 20
114 seconds each were performed with a break of minimally 10 seconds. The score of the two
115 attempts was recorded and summed.

116 Raw scores for each MC test were used in the analysis. Intraclass correlation coefficients in the
117 pilot study indicated good test-retest reliability. Correlations ranged from 0.64 (hopping on one
118 leg; 95% confidence interval [CI] 0.25-0.83) to 0.90 (balancing backwards; 95% CI 0.80-0.95).

120 Skeletal age

121 Radiographs of the left hand-wrist were taken to each child with a portable unit [Model TOP 25
122 (140 kvp; 25 mA); For You Company, Belgium]. A local hospital technician, with the assistance
123 of a field team member, completed this task at the school. Radiographs were assessed with the
124 Tanner-Whitehouse [TW3] method (25). The radius, ulna, and metacarpals and phalanges of the
125 1st, 3rd and 5th rays and seven carpals (excluding the pisiform) were compared to written criteria
126 and a stage and associated maturity score was assigned to each bone. The summed maturity
127 scores were converted to radius-ulna-short bone [RUS] and carpal skeletal ages. All readings
128 were made by the first author who was trained by an experienced assessor [Gaston Beunen
129 (GB)]. There was high agreement between independent ratings of the same observer (91.8%) and
130 between his ratings and those of GB (85.3%) (1).

RUS skeletal ages were used in the present analysis as the carpal bones are near maturity and/or already mature during puberty and the growth spurt, while changes in long bones leading to epiphyseal union are the dominant activities in skeletal maturation at these ages (21). Nevertheless, 25 youth (4 boys 14 years, 2 girls 13 years and 19 girls 14 years of age) were excluded from the analysis because they were already skeletally mature, i.e., a maturity score of 1000 in RUS. A skeletal age is not assigned to skeletally mature individuals. Consequently, the total sample (n = 613) included youth with full data and who had not reached skeletal maturity as assigned by the TW3 RUS method.

Statistics

Statistics analyses were performed using STATA, version 13 (24) and SPSS 22.0 (17). Means and standard deviations were calculated by sex within each age group for chronological age, skeletal age, height, body mass and each MC test. A two-way ANOVA was used to test for the effect of chronological age (four levels: 11, 12, 13 and 14) and sex (two levels: boys and girls) on each MC test and to explore interaction effects. Effect size is given by the partial eta squared (η^2_p). Multiple comparisons were performed by means of Tukey HSD tests.

Skeletal age was regressed on chronological age and the standardised residuals of skeletal age on chronological age (SAsr) were retained for analysis. The residuals represented the effects of skeletal age, independent of chronological age (18). The associations between each MC test (dependent variables [DV]) and the SAsr alone or interacting with stature and/or body mass (independent variables [IV]) were analysed with sex-specific hierarchical multiple regressions within each age group. To reduce collinearity, stature and body mass (log transformed) were z-

standardised within each age and sex, and first- and second-order interactions were computed from the standardised values before being modelled. $\text{SAsr} \times \text{stature}$ and $\text{SAsr} \times \text{stature} \times \text{body mass}$ interactions were excluded in some models due to collinearity ($r > 0.76$) (9). Correlations between each MC test and SAsr ranged from -0.31 and 0.19. Variance inflation factors (VIF) ranged from 1.398 to 3.919. Assumptions of linearity and homoscedasticity were also met.

Stature, body mass, and $\text{stature} \times \text{body mass}$ were entered as covariates in the first block. The second block included $\text{SAsr} \times \text{stature}$, $\text{SAsr} \times \text{body mass}$, and $\text{SAsr} \times \text{stature} \times \text{body mass}$. SAsr s were entered alone in the third block. Changes in explained variance (R^2 change) across blocks were estimated using F -tests. The effect size was defined as: $f^2 = (R^2_{AB} - R^2_A)/(1 - R^2_{AB})$, where R^2_A is the variance accounted for a block of independent variables A and R^2_{AB} is the combined variance accounted for the block of independent variables A and another block of independent variables B (8). Structural change tests [Chow test; (6)] were used to test the equality between sets of coefficients (intercept and/or slopes) in boys and girls; i.e., whether relationships between biological maturation and MC were the same among boys and girls. This was conducted only at 12 and 13 years of age, steps 2 and 3, where the regression models presented the same number of parameters. The residual sums of squares obtained in each of the three ANOVAs (boys, girls, and sexes pooled) were used in the computations. The level of significance was set at $p < 0.05$, unless otherwise stated.

Results

Sample sizes and means and standard deviations for all variables are summarized in Table 1 by sex and age group. Several comparisons are significant. The interaction between chronological

age and sex is significant for stature ($F_{3, 605} = 8.83, p < 0.001, \eta^2_p = 0.04$). Older children are heavier ($F_{3, 605} = 39.59, p < 0.001, \eta^2_p = 0.16$) and perform better on three tests: balancing backwards ($F_{3, 605} = 3.18, p = 0.024, \eta^2_p = 0.02$), hopping on one leg ($F_{3, 605} = 41.65, p < 0.001, \eta^2_p = 0.17$), JS ($F_{3, 605} = 30.89, p < 0.001, \eta^2_p = 0.13$), and shifting platforms ($F_{3, 605} = 40.10, p < 0.001, \eta^2_p = 0.17$). Boys perform better than girls in hopping on one leg ($F_{3, 605} = 33.87, p < 0.001, \eta^2_p = 0.05$) and shifting platforms ($F_{3, 605} = 19.08, p < 0.001, \eta^2_p = 0.03$). Other main and interaction effects for MC tests are not significant.

Insert Table 1

Estimated percentages of variance in each MC test explained by SAsr alone or interacting with body size derived from the hierarchical regression analyses are summarized by sex and age group in Table 2. Details of the regression analyses, specifically step 3 of the models are presented as Supplemental Digital Content (SDC) (Tables S1-S4) while the complete tables will be provided upon request.

For balancing backwards, step 2 of the model, entering SAsr $\times$ stature, SAsr $\times$ body mass, and SAsr $\times$ stature $\times$ body mass interactions, explains 1.0-3.7% and 0.3-7.1% of variance in boys and girls, respectively, over and above stature, body mass, and the stature $\times$ body mass interaction. The addition of SAsr in step 3 of the model accounts for an extra 0.0-1.5% (boys) and 0.0-2.5% (girls) of the variance in balance scores. Changes in R^2 from step 1 to step 2 and from step 2 to step 3 are not statistically significant in all age groups and for boys and girls (see Table S1, SDC

1, Results of the hierarchical multiple regression analyses of size and skeletal maturation on balancing backwards).

Insert Table 2

For hopping on one leg, the addition of $\text{SAsr} \times \text{stature}$, $\text{SAsr} \times \text{body mass}$, and $\text{SAsr} \times \text{stature} \times \text{body mass}$ interactions in the second model explains 0.3-7.5% and 0.1-3.6% of variance in boys and girls, respectively, after accounting for the variance in hopping on one leg explained by step 1 (see Table S2, SDC 2, Results of the hierarchical multiple regression analyses of size and skeletal maturation on hopping on one leg). Step 2 adds significantly to the explained variance in boys at 14 years ($\Delta R^2_2 = 0.08$, F change $_{1, 53} = 5.07$, $p = 0.029$, $f^2 = 0.10$). In the third model (step 3), the percentage of variance explained by SAsr beyond that explained by steps 1 and 2 is 0.0-5.0% in boys and 0.1-2.8% in girls. The third model adds significantly to explained variance in boys at 12 years ($\Delta R^2_3 = 0.05$, F change $_{1, 67} = 4.03$, $p = 0.049$, $f^2 = 0.06$).

The second step of hierarchical multiple regression analysis for jumping side-to-side (see Table S3, SDC 3, Results of the hierarchical multiple regression analyses of size and skeletal maturation on jumping side-to-side) in which the interactions of SAsr and body size are entered, accounts for 0.3-7.5% (boys) and 2.4-5.3% (girls) of the variance over and above the variance explained by stature, body mass, and $\text{stature} \times \text{body mass}$. In the third step of the model, stature, body mass and $\text{stature} \times \text{body mass}$ (block 1) was entered followed by $\text{SAsr} \times \text{stature}$, $\text{SAsr} \times \text{body mass}$, and $\text{SAsr} \times \text{stature} \times \text{body mass}$ (block 2). The variance explained in jumping side-

to-side increased 0.4-3.6% in boys and 0.0-1.3% in girls. In steps 2 and 3, however, the addition of the variables did not significantly increase R^2 .

Results of the corresponding analysis for shifting platforms (see Table S4, SDC 4, Results of the hierarchical multiple regression analyses of size and skeletal maturation on shifting platforms) indicate that over and above the variance accounted for by stature, body mass, and stature $\times$ body mass, the variance explained by block 2 variables, i.e., interactions of SAsr with stature, body mass and stature and body mass, ranged from 0.5-8.7% in boys and from 0.3-2.5% in girls. Corresponding estimates for step 3, over and beyond the variance accounted for blocks 1 and 2, were 0.0-8.1% in boys and 0.4-2.0% in girls. The F change in R^2 (ΔR^2_3) was significant in boys at 14 years ($\Delta R^2_3 = 0.08$, F change $_{1, 52} = 5.09$, $p = 0.028$, $f^2 = 0.10$).

Results of the Chow tests are summarized in Table 3. With the exception of balancing backwards at 13 years, results of all other F tests are higher than the critical value indicating structural differences in the regression coefficients for all MC test performances of boys and girls. For balancing backwards, step 2 at 13 years, indicates no structural differences between boys and girls (Chow test $F = 0.98 < F_{7,126} = 2.08$, $\alpha = 0.05$), i.e., the relationship between balancing backwards and IVs is the same in boys and girls.

Insert Table 3

237 Discussion

238 The estimated contribution of skeletal maturation expressed at the standardized residual of
239 skeletal age on chronological age (SAsr) to performances on four MC tests was considered in a
240 sample of largely adolescent youth 11-14 years. The amount of variance in each of the four MC
241 tests explained by SAsr or by SAsr interacting with body size was small and overlapped
242 considerably between boys and girls. In addition, age-related trends in the percentage of variance
243 explained in each of the four MC tests were largely inconsistent with perhaps three exceptions:
244 the variance explained by skeletal age alone increased with age in boys from 11 to 14 years for
245 jumping side-to-side and shifting platforms, while the variance explained by skeletal age
246 interacting with body size increased with age in girls for balancing backwards.

247 A previous analysis of relationships among skeletal maturation, body size and MC in Portuguese
248 children, 7-10 years noted that SAsr alone explained a maximum of 9.0% of variance in MC in
249 boys but only 1.0% in girls (13). This was generally consistent with the variance explained in the
250 current study among youth 11-14 years. The specific percentages of variance explained in motor
251 coordination tests in boys 7-10 years (13) and 11-14 years (this study), respectively, were as
252 follows: balancing backwards, 1.5% and 1.0%; hopping on one leg, 5.0% and 9.0%; jumping
253 side-to-side, 3.6% and 2.0%; and shifting platforms, 8.1% and 1.0%. Corresponding percentages
254 of variance in girls 7-10 years and 11-14 years, respectively, were as follows: balancing
255 backwards, 2.5% and 0.0%; hopping on one leg, 2.8% and 1.0%; jumping side-to-side, 1.3% and
256 0.0%; and shifting platforms, 2.0% and 1.0%. Although the percentages of explained variance
257 were not high, the results suggested a tendency for SAsr by itself to account for a higher share of
258 the variance in MC tests in boys compared to girls. By inference, the possibility that the
259 influence of skeletal maturation on MC may be sex-specific at these ages merits further study.

Interestingly, none of the interactions terms of SAsr and body size reached statistical significance in youth 11-14 years (see Tables S1-S4, SDC 1-4). By inference, relationships between SAsr and MC tests did not differ as a function of stature and/or body mass in youth 11-14 years. However, it may be worth noting that step 2, interactions between SAsr and body size, added a relatively little to the explained variance in jumping side-to-side (7.5%) and shifting platforms (8.7%) at 13 years and in hopping on one leg (7.5%) at 14 years of age in boys (Table 2). And, in step 3, variance explained by SAsr alone, added a relatively large amount to the explained variance in shifting platform (8.1%) at 14 years in boys. These ages (13-14 years) approximate the timing of peak height velocity in European boys (21). Among girls, it was only at 14 years when there was an increased in the explained variance in balancing backwards (7.1%) by SAsr interacting with body size. This age is about two years later than mean age at peak height velocity in European girls (21). However, effect sizes of increments from step 1 to step 2 or from step 2 to step 3 were small ($f^2 = 0.06$ to 0.10). Among Portuguese children 7-10 years, SAsr influenced balancing backwards and hopping on one leg through its interaction with stature (13). Nevertheless, the results of both studies highlight the small increments in the total explained variance in specific MC tests.

Although the KTK test battery was described as a measure of motor coordination on the basis of a factor analysis in which the four tests loaded on a single factor (19), it is possible that other functional capacities are involved. For example, hopping on one leg and jumping side-to-side are both items which require projection of the body through space. As such, performance of the tests likely requires a combination of agility, speed and strength in addition to balance and coordination. On the other hand, balancing backwards and shifting platforms do not require

projection of the body through space, and as such are perhaps largely dependent upon balance and coordination per se.

The study of Portuguese children 7-10 years also considered fundamental movement skills in addition to MC (13). For locomotor skills (run, gallop, hop, leap, horizontal jump and slide), SASr alone contributed 0.0%–2.0% to the total variance over and above body size, and interactions of SASr with body size in boys and girls. For object control skills (strike a stationary ball, stationary dribble, catch, kick, overhand throw and underhand roll), the contributions of SASr alone were from 1.0% to 7.0% in boys and 2.0% to 3.0% in girls. Although earlier studies addressing the contribution of skeletal maturation to variation in motor performance have used different motor tasks and analytical strategies, the results were generally consistent with the hierarchical regression analyses, i.e., skeletal age alone or interacting with body size explained relatively small percentages of the variance in motor performances. With standardised residuals of skeletal age on chronological age as the indicator of maturity status, interrelationships among skeletal maturity, body size, and three motor performance tasks were addressed in American children, 7-12 years (18). Results of the stepwise regression analyses showed that standardised residuals of skeletal age on chronological age was the best predictor of the 35-yard dash, standing long jump, and softball throw for distance. The variance explained by the standardised residuals (partial R^2) was 7-14% in boys and 4% in girls, while the interactions terms (SASr $\times$ stature, SASr $\times$ body mass, and SASr $\times$ stature $\times$ body mass) explained 3-7% of the variance in boys and 2-9% in girls. Overall, the variance in the three motor performance tasks attributed to skeletal maturation overlapped the variance observed in MC in the present study.

Also using a regression approach, the contribution of skeletal age alone or in combination with chronological age and body size to variance in a variety of fitness tests was considered in

Belgian girls 6-16 years (4) and boys 12-19 years (3). Among girls, skeletal age alone or in combination with chronological age and body size did not explain any of the variance in balance (Flamingo stand), speed of limb movement (plate tapping), vertical and standing long jumps, and a shuttle run (speed, agility). Among boys, skeletal age alone or in combination with chronological age and body size did not explain any of the variance in a stick balance task, and explained variable amounts of the variance in the vertical jump (0-17%), shuttle run 0-10%) and plate tapping (0-13%). The highest estimated of explained variance occurred during the interval of the adolescent spurt in boys, 10% in the shuttle run at 14 years, 13% in plate tapping at 14 years and 12-17% in the jump at 14-16 years. It should be noted that estimated peak gains in the shuttle run and plate tapping occurred before age at peak height velocity, while estimated peak gain in the vertical jump occurred after age at peak height velocity in the longitudinal series of the Belgian boys (5). Although the MC tasks considered and analytical strategy used in this study were different, the maximum amounts of variance explained by skeletal age alone or in combination with body size (Table 2) occurred around the interval of the growth spurt in Portuguese boys, jumping side-to-side (7.5%, 13 years), hopping on one foot (7.5%, 14 years) and shifting platforms (8.7%, 13 years; 8.1%, 14 years). In contrast, there did not appear to be an association between explained variance and the interval of the growth spurt in Portuguese girls; the maximum amount of variance explained in balancing backwards (7.1%) was noted at 14 years, which is about two years after the average age at peak height velocity in European girls (21).

This study of the relationships among skeletal maturation, body size and MC assessed with the KTK test battery in youth 11-14 years is somewhat novel. Hierarchical analysis, which permits the estimation of unique and incremental contributions of independent variables, is an advantage

328 compared to other regression approaches. The large sample size, the representativeness of the
329 sample, and the reliability of the data also provide confidence in generalizing the results to other
330 samples. However, given the cross-sectional design, variation in potential associations over time
331 during adolescence cannot be ascertained. This would require a longitudinal research to capture
332 temporal changes and permit control of inter-individual variation in rates of growth and
333 maturation and also rates of development of MC.

334 Skeletal maturation was assessed with the most recent version of the Tanner-Whitehouse RUS
335 method (25). A number of 14 year old boys and 13 and 14 year old girls were already skeletally
336 mature and were excluded from the analysis. Nevertheless, performances on the four MC tests
337 did not statistically differ between the small samples of skeletally mature and larger samples of
338 non-skeletally mature boys and girls 14 years of age (Table available on request). The small
339 sample of skeletally mature boys was taller and heavier than non-mature boys (though not
340 significant), while the skeletally mature girls were significantly heavier though not taller. It
341 should also be noted that the criterion for the final stages of the radius and ulna is simply that
342 epiphyseal fusion has begun. The interval from beginning of epiphyseal fusion to complete union
343 is thus not considered. As such, it is likely that many of the mature boys and girls may not have
344 been skeletally mature if another assessment protocol was used.

345 Despite the above limitations, skeletal maturation per se or interacting with body size had a
346 limited role in explaining variation in MC in Portuguese youth 11-14 years of age. By inference,
347 other factors are involved including interactions among neuromuscular maturation, differential
348 rates of growth in body segments during the transition into adolescence, habits of outdoor play
349 and physical activity, and perhaps specific instruction and practice as in physical education and
350 sport, among others (13, 22).

351 In summary, standardised residuals of skeletal age on chronological age, alone or interacting
352 with body size, explained a maximum of 8.7% of total variance in four MC tests, over and above
353 body size in Portuguese youth 11-14 years of age. The estimated variances accounted for by
354 skeletal age alone or in interactions with body size overlapped considerably between boys and
355 girls and did not vary consistent among age groups 11-14 years.

356

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363

364 Conflicts of interest

365 The authors declare no conflict of interest. The results of the present study do not constitute
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367

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437

438 Listing of Supplemental Digit Content

439 Supplemental Digit Content 1, Table S1. pdf.. Table that summarizes the results of the
440 hierarchical multiple regression analyses of size and skeletal maturation on balancing backwards.

441 Supplemental Digit Content 2, Table S2. pdf. Table that summarizes the results of the
442 hierarchical multiple regression analyses of size and skeletal maturation on hopping on one leg.

443 Supplemental Digit Content 3, Table S3. pdf. Table that summarizes the results of the
444 hierarchical multiple regression analyses of size and skeletal maturation on jumping side-to-side.

445 Supplemental Digit Content 4, Table S4. pdf. Table that summarizes the results of the
446 hierarchical multiple regression analyses of size and skeletal maturation on shifting platforms.

Table 1. Descriptive statistics of study variables.

Variables	Age intervals, years			
	11	12	13	14
	$\bar{x} \pm \text{sd}$	$\bar{x} \pm \text{sd}$	$\bar{x} \pm \text{sd}$	$\bar{x} \pm \text{sd}$
Boys	(n = 84)	(n = 75)	(n = 67)	(n = 58)
Chronological age (years)	11.5±0.30 [‡]	12.5±0.30	13.5±0.27	14.5±0.27
Skeletal age (years)	11.3±1.09	12.6±1.08	13.5±1.03	14.8±1.03
Anthropometry				
Stature (cm)	147.2±7.5	154.2±8.1	160.3±8.7	166.6±7.3
Body mass (kg)	42.5±9.9	48.9±12.1	52.4±11.8	56.6±11.0
Motor coordination [†]				
Balancing backwards	53.8±12.1	57.5±10.7	56.8±10.2	60.2±8.5
Hopping on one leg	47.1±14.2	54.7±13.1	58.9±15.7	66.9±8.3
Jumping side-to-side	53.9±12.3	60.0±13.2	64.8±14.1	68.8±11.9
Shifting platforms	43.7±6.1	46.5±5.9	48.7±6.2	52.2±6.8
Girls	(n = 97)	(n = 89)	(n = 73)	(n = 70)
Chronological age (years)	11.5±0.31	12.4±0.31	13.5±0.29	14.4±0.29
Skeletal age (years)	11.8±0.94	12.4±0.79	13.3±0.88	14.2±0.57
Anthropometry				
Stature (cm)	149.3±7.2	154.0±6.6	156.0±10.1	160.4±6.5
Body mass (kg)	43.9±9.8	46.4±10.2	51.8±10.4	54.4±8.8
Motor coordination [†]				
Balancing backwards	55.1±12.3	55.9±10.5	57.6±10.1	56.0±10.7
Hopping on one leg	44.1±14.1	47.8±14.1	52.6±12.9	57.5±11.6
Jumping side-to-side	55.6±10.8	60.2±12.0	62.6±10.9	66.0±11.1
Shifting platforms	42.4±5.2	45.4±5.8	45.5±6.9	49.1±6.2

[‡]Data are means and standard deviations; [†]raw scores. Units for each motor test: balancing backwards - number of successful steps; hopping on one leg over an obstacle - sum of successful attempts at each height (three points for the first, two points for the second and one point for the third attempt); jumping side-to-side - number of correct jumps in 15 seconds; shifting platforms - number of successful transfers (two points per transfer) in 20 s.

Table 2 Summary table of the percentages of variance explained by standardised residuals of skeletal age on chronological age (SAsr) interacting with body size (ΔR^2_2) and (SAsr alone (ΔR^2_3) for each motor coordination test by sex and age group 11 through 14 years.

Variable†	Balancing backwards				Hopping on one leg				Jumping side-to-side				Shifting platforms			
	11	12	13	14	11	12	13	14	11	12	13	14	11	12	13	14
Boys																
ΔR^2_2	3.7‡	1.7	1.0	2.7	2.0	1.5	0.3	7.5	0.5	2.4	7.5	0.3	0.5	5.1	8.7	4.3
ΔR^2_3	0.0	0.6	1.5	0.4	0.0	4.5	4.0	5.0	0.4	0.8	1.0	3.6	0.0	0.1	2.4	8.1
Girls																
ΔR^2_2	0.3	3.9	4.8	7.1	0.1	0.7	3.6	1.9	2.4	3.3	5.3	4.7	2.5	0.3	1.2	0.4
ΔR^2_3	2.5	2.3	2.3	0.0	0.1	1.6	2.8	2.4	0.2	0.3	1.3	0.0	0.8	0.7	0.4	2.0

†Block 1: stature, body mass and stature × body mass; block 2: SAsr × stature, SAsr × body mass, and SAsr × stature × body mass; block 3: SAsr.

‡Percentage.

ΔR^2_2 : changes in R^2 from step 1 to step 2; ΔR^2_3 changes in R^2 from step 2 to step 3.

Table 3 Structural changes among boys and girls.

Motor coordination	Regression models			
	Step 2		Step 3	
	Chow test (<i>F</i>)	Structural change	Chow test (<i>F</i>)	Structural change
Balancing backwards				
12 years	4.60***	Yes	5.93***	Yes
13 years	0.98	No	2.25*	Yes
Hopping on one leg				
12 years	10.16***	Yes	10.26***	Yes
13 years	4.13***	Yes	2.79**	Yes
Jumping side-to-side				
12 years	2.14*	Yes	2.07*	Yes
13 years	5.49***	Yes	6.26***	Yes
Shifting platforms				
12 years	5.11***	Yes	5.00***	Yes
13 years	7.41***	Yes	8.11***	Yes

* $p < .05$; ** $p < .01$; *** $p < .001$.

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