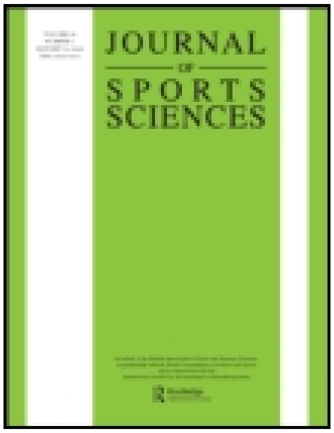

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Skeletal maturation, fundamental motor skills and motor coordination in children 7–10 years

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Abstract
Relationships between skeletal maturation and fundamental motor skills and gross motor coordination were evaluated in 429 children (213 boys and 216 girls) 7–10 years. Skeletal age was assessed (Tanner-Whitehouse 2 method), and stature, body mass, motor coordination (Körperkoordinations Test für Kinder, KTK) and fundamental motor skills (Test of Gross Motor Development, TGMD-2) were measured. Relationships among chronological age, skeletal age (expressed as the standardised residual of skeletal age on chronological age) and body size and fundamental motor skills and motor coordination were analysed with hierarchical multiple regression. Standardised residual of skeletal age on chronological age interacting with stature and body mass explained a maximum of 7.0% of the variance in fundamental motor skills and motor coordination over that attributed to body size per se. Standardised residual of skeletal age on chronological age alone accounted for a maximum of 9.0% of variance in fundamental motor skills, and motor coordination over that attributed to body size per se and interactions between standardised residual of skeletal age on chronological age and body size. In conclusion, skeletal age alone or interacting with body size has a negligible influence on fundamental motor skills and motor coordination in children 7–10 years.

Keywords: *bone age, motor development, growth, maturation*

Introduction

Interrelationships among growth, biological maturation and motor performance among children and adolescents are of interest to the physical activity and sport sciences. Two indicators of biological maturation have been traditionally used in studies of motor performance: skeletal age and stage of puberty. The former can be used from childhood through adolescence, while the latter is limited to the pubertal years (Malina, Bouchard, & Bar-Or, 2004). Early studies of skeletal age and motor performance were correlational (Clarke, 1971; Espenschade, 1940; Rajic et al., 1979; Rarick & Oyster, 1964; Seils, 1951), whereas more recent analyses have incorporated interactions among skeletal age, chronological age and body size (Beunen et al., 1997; Beunen, Ostyn, Simons, Renson, & van Gerven, 1981; Katzmarzyk, Malina, & Beunen, 1997). Motor items were limited to dashes (speed), vertical and standing long jumps and ball throws (power) and several fitness tests. Skeletal age influenced performance mainly through interactions with stature and body mass, although explained variances ranged from low to moderate.

The development of fundamental motor skills and motor coordination has received less attention in the context of growth and maturation. Correlations between skeletal age and outcome-based tests of striking, catching and balance were low to moderate in primary grade children (Seils, 1951), while a serial tapping task (motor control) was not related to skeletal age in children 5–9 years (Kerr, 1975). More specific measures of motor coordination and fundamental motor skills have not, to our knowledge, been considered relative to skeletal age. In this context, two

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questions were addressed in Portuguese children 7–10 years of age: (1) controlling for potential effects of body size per se, what is the contribution of the interaction of skeletal age and body size to the variance in fundamental motor skills and motor coordination? (2) controlling for the potential effects of body size per se and interactions with skeletal age, what is the contribution of skeletal age to the variance in fundamental motor skills and motor coordination? It was hypothesised that interactions of skeletal age and body size would contribute negligibly to the variation in fundamental motor skills and motor coordination over and above body size per se (H_1) and that skeletal age alone would contribute negligibly to the variation in fundamental motor skills and motor coordination over and above body size and interactions of skeletal age with body size (H_2).

Methods

Sample

The cross-sectional sample of 213 boys and 216 girls (n = 429) 7–10 years was part of the Healthy Growth of Madeira Study. The study was approved by the Scientific Committee of the University of Madeira and Ethics Committee of the Hospital of Funchal. Parents/legal guardians provided informed consent and participation was voluntary.

Proportional stratified random sampling was used. The number of the participants was proportional to the number of school children by age and sex in 40 schools randomly selected from the 11 districts of Madeira and Porto Santo. Children at each school were selected randomly until the required number of boys and girls was obtained (about 50 boys and 50 girls at each age from 7–10 years). Children with known disabilities were excluded.

Anthropometry

Stature (nearest mm) was measured with a portable stadiometer (Siber-Hegner, GPM). Body mass (100 g) was measured with a balance-beam scale (Seca Optima 760, Germany). Children wore swimming attire (two-piece for females) without shoes.

Skeletal maturation

Radiographs of the left hand and wrist were taken with a portable X-ray apparatus (Top 25, For you, Belgian) using Kodak films (OMAT MA, Ready Pack). Skeletal age was assessed with the Tanner-Whitehouse (TW2) 20 bone method (Tanner et al., 1983). The radius, ulna, seven carpals (excluding the pisiform) and metacarpals and phalanges of the 1st, 3rd and 5th rays were compared to written criteria for each bone; maturity scores were summed and converted to skeletal age. The TW2, 20-bone method was selected because maturation of both the carpals and radius-ulna-short bones characterises childhood and the transition into adolescence. During puberty and the growth spurt, on the other hand, carpals approach the mature state, while changes in long bones leading to epiphyseal union are dominant (Malina et al., 2004). A 20 bone maturity score/skeletal age was not available in the TW3 revision (Tanner, Healy, Goldstein, & Cameron, 2001).

Fundamental motor skills

The Test of Gross Motor Development (TGMD-2, Ulrich, 2000) included six locomotor skills (run, gallop, hop, leap, jump horizontally and slide from side to side) and six object control skills (strike a stationary ball with a bat held by both hands, dribble a basketball while standing stationary, catch a plastic ball that was tossed underhand, kick a stationary ball with the preferred foot, throw a ball overhand and roll a ball underhand using the preferred hand). Performance criteria were described for each fundamental motor skill (3, 4 or 5 criteria depending on the task, Ulrich, 2000). A score of 1 was assigned if the child's performance met the respective criteria for each skill; otherwise 0 was assigned. Each skill was performed twice; the sum of individual scores for the two trials represented the score. Raw scores were summed to provide overall scores for locomotor and object control skills, respectively (Ulrich, 2000). The maximum score for each subset was 48.

Motor coordination

The "Körperkoordinations Test für Kinder" (KTK) (Kiphard & Schilling, 1974; Schilling & Kiphard, 1976) included four specific tasks: (1) balance while moving backwards on balance beams – number of successful steps; (2) 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); (3) jumping laterally as rapidly as possible from side to side over a small beam – number of correct jumps in 15 s; (4) shifting platforms – with the child standing with both feet on one platform and holding a second identical platform, he/she was required to place the second platform alongside the first and to step on to it; the first platform was then lifted and placed alongside the second and the child stepped on to it and so on – number of successful transfers (two points per transfer) in 20 s. Raw scores for each test were retained for analysis to reflect variation and specific components of motor coordination.

Field procedures

Data were collected between February and July 2006 by a team of six physical education teachers who completed a 3-month theoretical and practical training program on anthropometry and motor assessment. Equipment, measurement procedures, performance criteria, administration and scoring were studied in detail using demonstration, discussion, DVDs and videos. The lead author and teachers also scored sample motor performances. A pilot study was then conducted with 46 school children, 3–10 years (30, 6–10 years for motor coordination), who were measured and completed the test batteries twice within an 8-day period. 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 mass. Test–retest reliability via ANOVA-based intraclass correlations ranged from 0.98 to 0.99 for stature and body mass and 0.56 to 0.85 for the KTK. Mean test–retest reliability coefficients for TGMD-2 ratings were 0.90 (locomotor) and 0.85 (object control).

Field staff worked in pairs. Testing was done in the morning. Children started at different stations and did not follow the same sequence. Stature and body mass were measured in the gymnasium or unused classroom. Motor tests were conducted outdoors (school playground). Children were given a verbal description followed by a visual demonstration of each skill/test. About 20 children completed the anthropometry and motor assessments in the same day. Children appeared highly motivated and did not show overt signs of fatigue.

Hand-wrist radiographs were also taken at each school by a local hospital technician with the assistance of a field team member. Skeletal age ratings were done by the lead author. Inter-observer agreement between the author and an experienced assessor was 85.3%; intra-observer agreement was 91.8% (Freitas et al., 2004).

Analysis

Data were initially screened for entry errors and checked for outliers. Descriptive statistics were calculated for sex-specific single year age groups. Two-way ANOVAs were used to simultaneously test the effects of sex and age group on each variable and to verify interaction effects.

Hierarchical multiple regression analyses were used to estimate the contribution of skeletal age alone or interacting with stature and/or mass to the unique variance in fundamental motor skills and motor coordination over and above that explained by covariates. An advantage of hierarchical analysis is that once the order of the independent variables is specified, a unique partition of the total variance of the dependent variable accounted for by the independent variables may be made (Cohen, Cohen, West, & Aiken, 2003). Hierarchical analysis is also suitable when models include interactions terms and when independent variables are correlated with each other (Aiken & West, 1991; Pedhazur, 1997).

Given the lack of normality in distributions, body mass and locomotor subtest scores were either log-transformed or squared. Skeletal age was regressed on chronological age within each sex and age group; the standardised residuals were retained for analysis (Katzmarzyk et al., 1997). To reduce collinearity, stature and mass were z-standardised within each sex and age group before entry into the models. First- and second-order interactions (standardised residuals × stature, standardised residuals × mass, stature × mass, and standardised residuals × stature × mass) were computed from the standardised values. In almost all models, correlations (Pearson *r*) between independent variables and dependent variables were less than 0.30. Correlations among independent variables ranged from −0.21 to 0.80. In 14 of 78 regression models, correlations between some independent variables were >0.80 and were thus removed (Cohen et al., 2003). Variance inflation factors ranged from 1.29 to 3.75 (<10); variables with high variance inflation factors were control variables or interactions terms. Assumptions of linearity and homoscedasticity were also met.

Locomotor and object control fundamental motor skills subscale scores and the four motor coordination tests were entered separately as dependent variables. Stature and mass were entered as covariates in the first block. First- and second-order interactions between standardised residuals of skeletal age and body size were entered as variables of interest in the second block, while standardised residuals of skeletal age alone was entered in the third block. Accordingly, the effects of stature, mass and/or interactions of skeletal age with body size would be taken into account before the variable of interest, standardised residuals of skeletal age, was explored. Changes in explained variance (R^2 change) across blocks were estimated using *F*-tests. Allowing for sample sizes, hierarchical analyses were performed for 2-year age groups by sex: 7–8 and 9–10 years. All analyses were completed with STATA, version 11 (StataCorp, 2009) and SPSS, version 19.0. Significance was set at $P < 0.05$.

Results

Descriptive characteristics are presented by sex and age group in Table I. Older youth were taller [F (3, 421 = 148.33, P < 0.001)] and heavier [F (3, 421 = 51.99, P < 0.001)] than younger children.

Table I. Descriptive statistics (mean, *s*) for all variables by age group and sex.

	Age intervals (years)			
	7	8	9	10
Variables	x̄ ± *s*	x̄ ± *s*	x̄ ± *s*	x̄ ± *s*
Boys	(*n* = 48)	(*n* = 51)	(*n* = 45)	(*n* = 69)
Chronological age (years)	7.5 ± 0.3	8.5 ± 0.3	9.5 ± 0.3	10.6 ± 0.3
Skeletal age (years)	7.6 ± 0.9	8.3 ± 1.0	9.2 ± 1.0	10.5 ± 1.4
Anthropometry				
Stature (cm)	126.8 ± 5.5	131.6 ± 6.3	135.7 ± 5.8	143.4 ± 6.6
Body mass (kg)	27.1 ± 4.7	30.9 ± 6.6	32.4 ± 7.1	40.6 ± 10.0
Fundamental motor skills				
Locomotor, total score	34.7 ± 5.1	37.5 ± 3.8	39.2 ± 5.6	39.3 ± 4.7
Run	7.0 ± 1.6	7.3 ± 1.1	7.3 ± 1.3	7.3 ± 1.2
Gallop	6.0 ± 2.3	7.0 ± 1.8	7.6 ± 1.4	7.4 ± 1.3
Hop	6.7 ± 1.4	7.1 ± 1.6	7.7 ± 2.0	8.0 ± 1.7
Leap	2.2 ± 1.3	2.4 ± 1.0	2.6 ± 1.4	3.1 ± 1.7
Horizontal jump	5.4 ± 2.3	5.7 ± 1.8	6.2 ± 1.5	5.6 ± 1.6
Slide	7.5 ± 1.2	8.0 ± 0.1	7.8 ± 0.8	7.9 ± 0.5
Object control, total score	31.7 ± 5.8	35.9 ± 4.1	37.0 ± 5.8	39.9 ± 4.6
Striking a stationary ball	6.1 ± 1.7	7.1 ± 1.6	7.2 ± 2.7	7.7 ± 1.9
Stationary dribble	6.0 ± 2.2	7.2 ± 1.4	7.4 ± 1.2	7.4 ± 1.1
Catch	4.3 ± 1.4	4.6 ± 1.3	5.2 ± 0.9	5.5 ± 0.9
Kick	4.5 ± 1.6	5.1 ± 1.1	5.2 ± 1.6	6.2 ± 1.8
Overhand throw	4.9 ± 2.1	5.7 ± 1.5	5.9 ± 1.5	6.2 ± 1.3
Underhand roll	6.0 ± 1.5	6.3 ± 1.3	6.0 ± 1.9	6.9 ± 1.4
Motor coordination†				
Balancing backwards	42.0 ± 11.0	48.4 ± 11.7	53.2 ± 11.4	50.4 ± 11.8
Hopping on one leg	26.7 ± 12.2	35.3 ± 9.1	37.9 ± 11.2	42.7 ± 16.6
Jumping side-to-side	33.6 ± 9.2	44.1 ± 9.9	47.1 ± 11.4	50.5 ± 14.1
Shifting platforms	33.1 ± 5.0	37.2 ± 4.9	40.1 ± 6.5	42.4 ± 6.3
Girls	(*n* = 45)	(*n* = 41)	(*n* = 52)	(*n* = 78)
Chronological age (years)	7.5 ± 0.3	8.5 ± 0.3	9.4 ± 0.3	10.6 ± 0.3
Skeletal age (years)	7.3 ± 1.0	8.6 ± 1.1	9.5 ± 1.1	11.0 ± 1.4
Anthropometry				
Stature (cm)	125.7 ± 5.2	131.6 ± 5.7	136.4 ± 6.2	141.9 ± 6.9
Body mass (kg)	26.4 ± 5.9	29.7 ± 6.6	34.5 ± 8.6	36.6 ± 7.8
Fundamental motor skills				
Locomotor, total score	36.0 ± 4.1	37.8 ± 4.0	38.2 ± 3.9	40.0 ± 4.1
Run	7.0 ± 1.1	7.0 ± 1.2	6.9 ± 1.4	7.4 ± 1.2
Gallop	6.4 ± 2.4	7.2 ± 1.6	7.4 ± 1.6	7.6 ± 1.0
Hop	6.9 ± 2.0	7.3 ± 1.6	7.4 ± 1.5	8.4 ± 1.5
Leap	2.4 ± 1.3	2.9 ± 1.4	2.7 ± 1.2	2.8 ± 1.7
Horizontal jump	5.4 ± 1.7	5.4 ± 1.9	5.9 ± 1.6	5.9 ± 1.7
Slide	7.9 ± 0.7	8.0 ± 0.2	7.9 ± 0.6	7.9 ± 0.5
Object control, total score	28.6 ± 6.2	29.0 ± 5.3	32.3 ± 4.7	34.7 ± 5.8
Striking a stationary ball	5.4 ± 2.2	5.3 ± 1.6	5.9 ± 1.8	6.2 ± 2.4
Stationary dribble	5.6 ± 2.2	6.1 ± 2.1	7.0 ± 1.4	7.1 ± 1.3
Catch	4.1 ± 1.4	4.3 ± 1.2	4.9 ± 1.1	5.6 ± 0.8
Kick	3.8 ± 1.6	3.9 ± 1.3	4.4 ± 1.0	4.9 ± 2.1
Overhand throw	4.1 ± 2.0	4.0 ± 2.4	4.2 ± 1.8	4.9 ± 1.9
Underhand roll	5.6 ± 1.8	5.4 ± 1.6	6.0 ± 1.7	6.1 ± 1.8
Motor coordination†				
Balancing backwards	43.6 ± 11.6	47.9 ± 14.2	50.7 ± 11.0	50.9 ± 11.1
Hopping on one leg	28.9 ± 10.9	32.7 ± 13.1	35.7 ± 11.9	41.4 ± 13.9
Jumping side-to-side	38.3 ± 13.7	45.4 ± 12.0	48.2 ± 9.5	54.6 ± 14.5
Shifting platforms	32.8 ± 4.9	35.7 ± 5.4	38.5 ± 5.2	40.7 ± 7.6

Notes: †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 s; shifting platforms – number of successful transfers (two points per transfer) in 20 s.

Scores on the locomotor [F (3, 420 = 19.01, $P < 0.001$)] and object control [F (3, 420 = 37.39, $P < 0.001$)] subscales improved with age. Boys performed better than girls on the object control subscale [F (1, 420 = 89.12, $P < 0.001$)]. Significant interactions between sex and age group were not evident for fundamental motor skills subtests.

A significant main effect of age was noted for each motor coordination test: balancing backwards [F (3, 421 = 11.78, $P < 0.001$)], hopping on one leg [F (3, 421 = 24.09, $P < 0.001$)], jumping side-to-side [F (3, 421 = 35.80, $P < 0.001$)] and shifting platforms [F (3, 421 = 42.64, $P < 0.001$)]. Girls scored significantly better than boys on jumping side-to-side [F (1, 421 = 5.40, $P < 0.001$)] and boys scored significantly better than girls on shifting platforms [F (1, 421 = 4.85, $P < 0.001$)].

Results of hierarchical multiple regression analyses of fundamental motor skills are summarised in Table II. Standardised residuals of skeletal age × stature, standardised residuals of skeletal age × mass,

Table II. Results of hierarchical multiple regression analyses of body size and skeletal maturation on locomotor and object control fundamental motor skills (TGMD-2).

	Locomotor subtest†			Object control subtest		
	Step 3			Step 3		
Variable	*B*	*SE B*	*β*	*B*	*SE B*	*β*
Boys, 7–8 years						
Stature	140.96	53.41	0.43*	1.59	0.95	0.30
Body mass‡	−130.62	52.84	−0.38*	−0.86	0.94	−0.16
Stature × body mass	−8.93	37.18	−0.03	−0.21	0.63	−0.05
SAsr × ST	−14.43	50.27	−0.04	−1.55	0.93	−0.29
SAsr × BM	−22.97	59.80	−0.06	0.99	0.93	0.20
SAsr × ST × BM	5.42	43.33	0.02	−0.16	0.52	−0.06
SAsr	−69.01	44.44	−0.21	−0.81	0.79	−0.15
R^2		0.11			0.06	
ΔR^2		0.02			0.01	
Boys, 9–10 years						
Stature	72.65	55.02	0.20	1.06	0.80	0.20
Body mass	−135.32	55.42	−0.39*	−0.87	0.81	−0.17
Stature × body mass	−9.17	36.96	−0.03	−0.98	0.55	−0.19
SAsr × ST	(*a*)	(*a*)	(*a*)	−0.20	0.65	−0.03
SAsr × BM	−67.22	40.73	−0.19	(*a*)	(*a*)	(*a*)
SAsr × ST × BM	45.48	36.59	0.18	1.01	0.58	0.25
SAsr	−30.72	43.58	−0.09	−1.92	0.65	−0.36**
R^2		0.11			0.14*	
ΔR^2		0.00			0.07**	
Girls, 7–8 years						
Stature	49.21	49.67	0.16	0.20	1.02	0.03
Body mass	−87.80	48.69	−0.28	−0.92	0.99	−0.16
Stature × body mass	−171.43	48.48	−0.54**	−1.55	0.94	−0.29
SAsr × ST	46.42	47.73	0.19	−0.56	0.87	−0.12
SAsr × BM	2.51	50.50	0.01	1.30	0.95	0.27
SAsr × ST × BM	2.25	30.28	0.01	0.49	0.56	0.17
SAsr	7.22	46.38	0.02	−1.31	0.94	−0.23
R^2		0.18*			0.09	
ΔR^2		0.00			0.02	
Girls, 9–10 years						
Stature	96.41	46.64	0.30*	2.13	0.80	0.40**
Body mass	−104.16	44.79	−0.33*	−0.32	0.76	−0.06
Stature × body mass	−9.04	42.54	−0.03	0.67	0.72	0.13
SAsr × ST	15.01	41.23	0.05	−0.38	0.70	−0.08
SAsr × BM	−17.94	41.35	−0.06	0.37	0.70	0.07
SAsr × ST × BM	7.34	26.18	0.04	−0.53	0.44	−0.17
SAsr	−58.08	38.66	−0.18	−1.40	0.66	−0.26*
R^2		0.10			0.10	
ΔR^2		0.02			0.03*	

Notes: †Square-transformed; ‡log-transformed; *B*, unstandardised coefficients; *SE B*, standard error of *B*; *β*, standardised coefficients; ΔR^2, R^2 change; stature and body mass are standardised estimates; SAsr, standardised residuals of skeletal age on chronological age; SAsr × ST, interaction of SAsr with stature; SAsr × BM, interaction of SAsr with body mass; (*a*) excluded from the model due to a strong linear relationship with other predictor(s); *$P < 0.05$; **$P < 0.01$. N = 97 for locomotor subtest, boys, 7–8 years; N = 111 for locomotor subtest, boys, 9–10 years; N = 97 for object control subtest, boys, 7–8 years; N = 110 for object control subtest, boys, 9–10 years; N = 85 for locomotor subtest, girls, 7–8 years; N = 130 for locomotor subtest, girls, 9–10 years; N = 86 for object control subtest, girls, 7–8 years; N = 129 for object control subtest, girls, 9–10 years.

and standardised residuals of skeletal age × stature × mass interactions explained 0.0–3.0% of the total variance in the locomotor subscale over and above stature, mass and stature × mass interaction (change in R^2 [ΔR^2] from step 1 to 2). Standardised residuals of skeletal age alone contributed 0.0–2.0% to the total variance over and above body size (block 1) and interactions of standardised residuals of skeletal age with body size (block 2) in step 3. Interactions terms for standardised residuals of skeletal age and body size, and standardised residuals of skeletal age alone did not reach significance. Standardised beta coefficients (β) for standardised residuals of skeletal age × stature, standardised residuals of skeletal age × mass, standardised residuals of skeletal age × stature × mass interactions and standardised residuals of skeletal age alone were negative in some models.

Adding the interactions of standardised residuals of skeletal age with body size to the first block of variables explained a maximum of 4.0% of total variance in object control tasks (ΔR^2 ranged from 0.0% to 4.0%), and did not lead to a significant improvement. Standardised residuals of skeletal age alone accounted for an additional 7.0% of the variance in boys 9–10 years [F change (1, 103) = 8.78, $P < 0.01$] and an additional 3% in girls 9–10 years [F change (1, 121) = 8.78, $P < 0.05$] over and above body size and interactions of standardised residuals of skeletal age with body size (ΔR^2 ranged from 1.0% to 7.0%). Again, β coefficients for standardised residuals of skeletal age × body size interactions and standardised residuals of skeletal age alone were negative in some regression models.

Corresponding analyses of motor coordination are summarised in Tables III (balance, hopping) and IV (jumping, shifting platforms). For balancing backwards, step 2 accounted for an additional 1.0–7.0% of the total variance over and above block 1 and was significant in girls 9–10 years [F change (3, 123) = 8.78, $P < 0.05$]. Standardised residuals of skeletal age entered in step 3, resulting in ΔR^2 from 0.0% to 1.0%, and did not contribute to predicting balancing backwards over and above steps 1 and 2. The interaction between standardised residuals of skeletal age and stature reached significance for girls 7–8 years ($\beta = -0.40$, $P < 0.05$) and 9–10 years ($\beta = 0.38$, $P < 0.01$). For hopping on one leg, the explained variance of standardised residuals of skeletal age × stature, standardised residuals of skeletal age × mass and standardised residuals of skeletal age × stature × mass interactions ranged from 1.0% to 6.0% over and above the variance accounted for by stature, mass and stature × mass interaction. When standardised residuals of skeletal age alone entered the model, R^2 changed from 0.0% to 9.0% and was significant in boys 7–8 years [F change (1, 90) = 12.29, $P < 0.01$]. In the final models, β coefficients for standardised residuals of skeletal age (boys 7–8 years, $\beta = -0.41$) and standardised residuals of skeletal age × stature (boys 7–8 years, $\beta = -0.30$; girls 9–10 years, $\beta = 0.31$) reached significance.

For the jumping side-to-side task, interactions between standardised residuals of skeletal age and body size did not explain a large percentage of total variance after controlling for body size (ΔR^2 ranged from 1.0% to 5.0%) and did not result in a significant increase in explained variance. In the final models, standardised residuals of skeletal age contributed a maximum of 2.0% to the explained variance (ΔR^2 ranged from 0.0% to 2.0%) after controlling for body size and interactions between standardised residuals of skeletal age and body size. β coefficients for the interactions of standardised residuals of skeletal age with body size and standardised residuals of skeletal age alone were negative in some models. For shifting platforms, addition of standardised residuals of skeletal age × stature, standardised residuals of skeletal age × mass and standardised residuals of skeletal age × stature × mass interactions to the hierarchical process (step 2) contributed an additional 0.0–7.0% of the total variance over and above body size. When standardised residuals of skeletal age were entered in step 3, the model explained an additional 0.0–1.0% of the total variance over and above body size and interactions between standardised residuals of skeletal age and body size. β coefficients for the interactions of standardised residuals of skeletal age and body size and standardised residuals of skeletal age alone were negative is some models.

Discussion

Relationships between skeletal maturation and fundamental motor skills and motor coordination were considered in Portuguese children 7–10 years. Overall, a relatively limited amount of the variance in fundamental motor skills and motor coordination was explained by the interactions of standardised residuals of skeletal age × stature, and of skeletal age × mass over and above body size per se or by standardised residuals of skeletal age alone (Tables II–IV) (Full tables [steps 1, 2 and 3] can be provided by the corresponding author upon request). Although not directly comparable, correlation studies of skeletal age and outcome-based locomotor and object-control skills indicated somewhat stronger though variable relationships in children of approximately the same age (Rarick & Oyster, 1964; Seils, 1951) and adolescents (Clarke, 1971; Espenschade, 1940). Controlling for chronological age, stature and body mass did not markedly alter the correlations.

Results of regression analyses including age, weight, height and skeletal age provide more variable

Table III. Results of hierarchical multiple regression analyses of body size and skeletal maturation on motor coordination (KTK): balance and hopping.

	Balancing backwards			Hopping on one leg		
	Step 3			Step 3		
Variable	*B*	*SE B*	*β*	*B*	*SE B*	*β*
Boys, 7–8 years						
Stature	1.22	2.02	0.10	8.19	1.55	0.74***
Body mass[†]	−2.12	2.02	−0.17	−7.22	1.58	−0.65***
Stature × body mass	1.29	1.60	0.10	1.82	1.08	0.19
SAsr × ST	0.61	1.90	0.05	−3.15	1.49	−0.30*
SAsr × BM	0.16	2.30	0.01	0.44	1.55	0.04
SAsr × ST × BM	0.21	2.02	0.02	0.40	0.89	0.07
SAsr	−1.93	1.75	−0.16	−4.52	1.29	−0.41**
R^2		0.05			0.34***	
ΔR^2		0.01			0.09*	
Boys, 9–10 years						
Stature	2.02	1.53	0.18	11.66	1.93	0.77***
Body mass	−6.21	1.59	−0.58***	−12.31	2.01	−0.82***
Stature × body mass	0.50	1.07	0.05	−2.44	1.31	−0.17
SAsr × ST	−1.03	1.27	−0.09	(*a*)	(*a*)	(*a*)
SAsr × BM	(*a*)	(*a*)	(*a*)	1.27	1.53	0.08
SAsr × ST × BM	0.30	1.05	0.04	−0.25	1.33	−0.02
SAsr	−0.56	1.28	−0.05	−2.09	1.59	−0.14
R^2		0.22***			0.37***	
ΔR^2		0.00			0.01	
Girls, 7–8 years						
Stature	4.74	2.14	0.36*	8.53	1.60	0.73***
Body mass	−6.52	2.09	−0.50**	−10.16	1.56	−0.87***
Stature × body mass	−1.80	1.99	−0.15	−2.63	1.48	−0.24
SAsr × ST	−4.10	1.83	−0.40*	1.47	1.36	0.16
SAsr × BM	3.28	2.01	0.31	0.42	1.49	0.04
SAsr × ST × BM	−0.47	1.19	−0.07	0.54	0.88	0.10
SAsr	0.68	1.98	0.05	−1.58	1.48	−0.14
R^2		0.20*			0.46***	
ΔR^2		0.00			0.01	
Girls, 9–10 years						
Stature	2.05	1.55	0.19	5.93	1.85	0.42**
Body mass	−3.45	1.49	−0.31*	−6.81	1.80	−0.52***
Stature × body mass	−0.34	1.41	−0.03	−0.91	1.70	−0.07
SAsr × ST	3.78	1.37	0.38**	4.55	2.11	0.31*
SAsr × BM	−1.62	1.37	−0.15	−0.90	1.81	−0.07
SAsr × ST × BM	−1.02	0.87	−0.16	0.65	1.20	0.08
SAsr	0.81	1.28	0.07	−0.67	1.55	−0.05
R^2		0.18**			0.19***	
ΔR^2		0.00			0.00	

Notes: [†]log-transformed; *B*, unstandardised coefficients; *SE B*, standard error of *B; β*, standardised coefficients; ΔR^2, R^2 change; stature and body mass are standardised estimates; SAsr, standardised residuals of skeletal age on chronological age; SAsr × ST, interaction of SAsr with stature; SAsr × BM, interaction of SAsr with body mass; (*a*) excluded from the model due to a strong linear relationship with other predictor(s); $*P < 0.05$; $**P < 0.01$; $***P < 0.001$.
$N = 95$ for balancing backwards, boys, 7–8 years; $N = 111$ for balancing backwards, boys, 9–10 years; $N = 98$ for hopping on one leg, boys, 7–8 years; $N = 110$ for hopping on one leg, boys, 9–10 years; $N = 86$ for balancing backwards, girls, 7–8 years; $N = 130$ for balancing backwards, girls, 9–10 years; $N = 85$ for hopping on one leg, girls, 7–8 years; $N = 127$ for hopping on one leg, girls, 9–10 years.

results. Coefficients of determination approximated zero for the dash, jump and agility shuttle run in children 7–11 years (Rajic et al., 1979), while the variance explained in the dash, standing long jump and distance throw varied by age group among boys (4–30%) and girls (7–27%) 7–12 years (Katzmarzyk et al., 1997). Skeletal age separately or in combination with chronological age, stature or mass were not significant predictors of the standing long and vertical jumps and shuttle run among girls 6–16 years (Beunen et al., 1997), but accounted for only a small percentage of the variance in the vertical jump (6–13%) in boys 13–17 years and the shuttle run (1–3%) in boys 12–16 years (Beunen et al., 1981).

The preceding studies used skeletal age as the indicator of maturity status. More recently,

Table IV. Results of hierarchical multiple regression analyses of body size and skeletal maturation on motor coordination (KTK): jumping and shifting platforms.

	Jumping side-to-side			Shifting platforms		
	Step 3			Step 3		
Variable	*B*	*SE B*	*β*	*B*	*SE B*	*β*
Boys, 7–8 years						
Stature	4.64	1.83	0.41*	2.69	0.79	0.53**
Body mass†	−1.49	2.07	−0.12	−1.38	0.81	0.27
Stature × body mass	3.74	1.78	0.34*	0.74	0.56	0.17
SAsr × ST	0.25	1.69	0.02	0.24	0.76	0.05
SAsr × BM	−2.69	2.29	−0.22	−0.93	0.79	−0.20
SAsr × ST × BM	−1.94	1.16	−0.28	−0.55	0.45	−0.20
SAsr	−2.22	1.49	−0.20	−0.57	0.66	−0.11
R^2		0.12			0.17*	
ΔR^2		0.02			0.01	
Boys, 9–10 years						
Stature	5.84	2.06	0.43**	2.73	0.85	0.48**
Body mass	−5.30	2.14	−0.39	−2.85	0.88	−0.50**
Stature × body mass	−0.26	1.41	−0.02	−0.54	0.58	−0.14
SAsr × ST	(*a*)	(*a*)	(*a*)	(*a*)	(*a*)	(*a*)
SAsr × BM	0.25	1.58	0.02	0.02	0.57	0.01
SAsr × ST × BM	−0.50	1.43	−0.05	(*a*)	(*a*)	(*a*)
SAsr	−1.49	1.71	−0.11	−0.43	0.63	−0.08
R^2		0.11			0.15**	
ΔR^2		0.01			0.00	
Girls, 7–8 years						
Stature	6.07	2.26	0.46**	3.24	0.75	0.67***
Body mass	−5.63	2.20	−0.42*	−3.38	0.73	−0.70***
Stature × body mass	1.08	2.10	0.09	−0.92	0.69	−0.21
SAsr × ST	−3.05	1.93	−0.29	−1.21	0.64	−0.32
SAsr × BM	1.13	2.12	0.10	0.84	0.70	0.21
SAsr × ST × BM	−1.16	1.25	−0.18	0.19	0.41	0.08
SAsr	0.60	2.08	0.05	−0.67	0.69	−0.14
R^2		0.15			0.30**	
ΔR^2		0.00			0.01	
Girls, 9–10 years						
Stature	5.61	1.77	0.46**	2.62	0.79	0.47**
Body mass	−3.36	1.70	−0.27	−3.27	0.75	−0.59***
Stature × body mass	−2.55	1.62	−0.22	−0.78	0.71	−0.15
SAsr × ST	1.38	1.57	0.13	−0.19	0.69	−0.04
SAsr × BM	2.63	1.57	0.22	1.25	0.69	0.23
SAsr × ST × BM	−1.50	1.00	−0.21	−0.13	0.44	−0.04
SAsr	−0.94	1.47	−0.08	0.15	0.65	0.03
R^2		0.14*			0.19**	
ΔR^2		0.00			0.00	

Notes: †log-transformed; *B*, unstandardised coefficients; *SE B*, standard error of *B*; *β*, standardised coefficients; ΔR^2, R^2 change; stature and body mass are standardised estimates; SAsr, standardised residuals of skeletal age on chronological age; SAsr × ST, interaction of SAsr with stature; SAsr × BM, interaction of SAsr with body mass; (*a*) excluded from the model due to a strong linear relationship with other predictor(s); *$P < 0.05$; **$P < 0.01$; ***$P < 0.001$.
N = 95 for jumping side-to-side, boys, 7–8 years; *N* = 113 for jumping side-to-side, boys, 9–10 years; *N* = 98 for shifting platforms, boys, 7–8 years; *N* = 112 for shifting platforms, boys, 9–10 years; *N* = 86 for jumping side-to-side, girls, 7–8 years; *N* = 129 for jumping side-to-side, girls, 9–10 years; *N* = 84 for shifting platforms, girls, 7–8 years; *N* = 127 for shifting platforms, girls, 9–10 years.

predicted age at PHV, that is future maturity timing, was used as the indicator of maturity status in a comparison of motor coordination in normal weight and overweight/obese children 6–10 years of age (D'Hondt et al., 2013). Predicted age at PHV did not enter in the stepwise multiple linear regression (r = −0.06), and BMI was a negative predictor of total KTK MQ (β = −0.61) over a 2-years interval. These results need to be critically evaluated within the limitations of the equations for predicting age at PHV, especially at young ages (Malina & Koziel, 2014a, 2014b), and small sample sizes of the two groups compared. The present study, in contrast, used standardised residuals of skeletal age on chronological age as the maturity indicator in a larger sample spanning a broad range of weight-for-height. The standardise residuals of skeletal age explained a maximum of 9% of variance in fundamental motor skills and motor coordination over that attributed to body size per se and interactions between the residuals and body size.

Several recent studies have addressed fundamental motor skills and motor coordination in normal weight and overweight/obese children (D'Hondt et al., 2011; Gentier et al., 2013; Krombholz, 2013; Lopes, Stodden, Bianchi, Maia, & Rodrigues, 2012) and noted similar results highlighting the negative influence of elevated BMI. This reflects current concern for the increasing prevalence of overweight/obesity among youth. It would seemingly make more sense to consider relationships between motor proficiency across the broad spectrum of the BMI as it is entirely possible that low weight-for-height may have a negative influence on fundamental motor skills and motor coordination as suggested in several studies relating the BMI to indicators of fitness (Bovet, Auguste, & Burdette, 2007; Huang & Malina, 2010, 2007; Malina, Katzmarzyk, & Siegel, 1998).

With several exceptions, the explained variances for the different outcome-based measures overlapped the variances in fundamental motor skills observed with hierarchical analyses (Table II). Variation in results reflected, in part, the tests, sampling, age, method of maturity assessment and analytical strategies. Moreover, skeletal age per se or interacting with body size is probably more relevant in outcome-based tests requiring a maximal effort as in dashes, jumps and distance throws. The TGMD-2 tests of locomotor and object control skills, in contrast, emphasise specific components of movement patterns rather than outcomes.

Interactions between standardised residuals of skeletal age and body size accounted for a maximum of 7.0% of variance in the four KTK tests over and above body size alone, while standardised residuals of skeletal age alone explained a maximum of 9% of the variance over and above the influence body size and standardised residuals of skeletal age × size interactions (Tables III and IV). Many of the β coefficients were negative, suggesting that later maturation was associated with better performances on the motor coordination tests. Several studies have considered different balance tests. Skeletal age was not correlated with standing on a stick lengthwise) in primary grade children (Seils, 1951) and was poorly correlated with the Brace test (composite score based on a series of stunts requiring coordination and balance) in adolescents ~13–16 years (Espenschade, 1940). Skeletal age alone or in combination with chronological age, stature and/or mass was not a significant predictor of the flamingo stand in girls 6–16 years (Beunen et al., 1997) and a stick balance test in adolescent boys (Beunen et al., 1981).

Allowing for the relatively small increments in the total explained variance in fundamental motor skills and motor coordination (7–9%), one can inquire about their relevance. This can be addressed through the effect size statistic (Cohen, 1988). In hierarchical multiple regression, effect size is 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. Effect sizes of increments from steps 1 to 2 and from steps 2 to 3 were small in both fundamental motor skills (f^2 0.00 to 0.03) and KTK (f^2 0.00 to 0.09). In light of the small effect sizes, it may be postulated that skeletal maturation alone or interacting with body size has a relatively small influence on the development of fundamental motor skills and motor coordination in this sample of children 7–10 years.

Fundamental motor skills and motor coordination are probably more dependent upon neuromuscular maturation independent of body size and skeletal maturity status. It is also likely that a certain level of motor coordination is a component of fundamental motor skills, so that children deficient in motor coordination may not perform well in fundamental motor skills. It would seemingly make sense to control for motor coordination while evaluating the relationship between skeletal age and fundamental motor skills, and vice versa. There is also a need to expand the skills assessed in each domain and view their interrelationships.

The interaction between standardised residuals of skeletal age and stature reached significance for balancing backwards and hopping on one leg (Table III) implying that skeletal age affected these tests to some extent through stature. Following suggestions of Dawson (2014), two-way interaction effects for standardised variables were plotted and visually inspected by calculating predicted values of the balancing tests under different conditions (high and low values of standard residuals of skeletal age and high and low values of stature). For balancing backwards, taller 7–8 year old girls scored better than shorter peers at low values of the residuals of skeletal age; at high values of the residuals, the short and tall groups had similar scores. Taller 9–10 year old girls also scored better than shorter girls at high values of skeletal age standardised residuals, while scores on balancing backwards overlapped considerably between stature groups with low skeletal age residuals. The relationship between standardised residuals of skeletal age and hopping on one leg (boys, 7–8 years) was consistently negative for tall and short children. The high stature group scored better than the low stature group at high and low values of standard residuals. For boys 9–10 years, taller boys had better scores at high values of standardised residuals of skeletal age.

Although limited, relationships between standardised residuals of skeletal age and motor coordination may differ as a function of stature among children 7–10 years. Given the potential role of stature, it may be worthwhile to consider percentage of predicted mature height attained at the time of study as a maturity indicator (Malina, 2014). For example, a negative relationship between percentage of predicted mature height and activity level was noted in children 5–9 years of age (Eaton & Yu, 1989); other applications of the method have been largely limited to adolescents and youth athletes (Malina, 2014).

Although fundamental motor skills and motor coordination were largely independent of skeletal age in Portuguese children 7–10 years, the results were generally consistent with previous studies, allowing for different analytical approaches. There is a need to extend the research to younger and older children. Future research with more children within single year age groups would provide a more robust analysis and more specific insights. A longitudinal design with appropriate statistical analyses would better capture changes over time and allow for inter-individual variation in rates of motor development and growth.

The results imply a limited role for skeletal maturation per se or interacting with body size in the development of fundamental motor skills and motor coordination among children 7–10 years of age. Skeletal age may not be a sufficiently sensitive indicator of maturity status at these ages. Tests of fundamental motor skills and motor coordination may be more reflective of neuromuscular maturation per se, which may be not strongly related with skeletal maturation and body size. Indeed, development of fundamental movement skills is often described in terms of stages, leading to mature movement patterns (Haubenstricker & Seefeldt, 1986).

The results have several implications for those working with children. The negligible contribution of skeletal age per se and interacting with body size to variance in fundamental motor skills and motor coordination implies an important role for other factors affecting movement development and proficiency. These likely involve neuromuscular maturation per se; differential growth in body proportions and composition; environmental conditions related to home, school and neighbourhood; habits of outdoor play and physical activity; and/or specific instruction and practice as in physical education and sport (Malina, 2012, 2014).

In summary, skeletal maturation expressed as the standardised residual of the regression of skeletal age on chronological age was not strongly associated with fundamental motor skills and motor coordination. Standardised residuals of skeletal age interacting with stature and/or body mass or of skeletal age by itself explained only 0.0–9.0% of total variance in fundamental motor skills and motor coordination. Many of the β coefficients were negative, suggesting that later maturation was associated with better performances on fundamental motor skills and motor coordination. The results support the hypotheses that skeletal age per se or interacting with body size has a negligible influence on tests of fundamental motor skills and motor coordination in children. By inference, individual differences in neuromuscular maturation interacting with environmental conditions, habits of play and physical activity and specific instruction and practice may be primary factors influencing fundamental motor skills and motor coordination among children.

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