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Modeling children's development in gross motor coordination reveals key modifiable determinants. An allometric approach

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Children change their body size, shape, and gross motor coordination (GMC) as they grow. Further, GMC is expected to link to changes in children's body size, physical activity (PA), and physical fitness (PF). The objective was to model GMC changes in children followed longitudinally and to investigate associations between these changes and PA and PF levels. A total of 245 children (122 girls) were observed at 6 years of age and followed annually until 9 years. A sequence of allometric models was fitted, that is, 1. body mass, stature, and PA; 2. addition of four PF tests; 3. addition of four more PF tests. In Model 1, changes in GMC are nonlinear, and body mass (-0.60 ± 0.07, $P < .001$) and stature (2.91 ± 0.35, $P < .001$) parameter estimates were significant suggesting children with a more linear body size/shape showed higher GMC performances. Girls tend to outperform boys across time, and PA was not associated with GMC changes. Model 2 fitted the data better, and the PF tests (handgrip, standing long jump, 50-yard dash, and shuttle run) were significantly linked to GMC change. In Model 3, adding the remaining PF tests did not change the order of any factors importance. The greatest GMC changes were achieved by children whose body size/shape has an ectomorphic dominance across the years. Considering that leaner and physically fitter children tended to be more coordinated, physical education should also focus on PF development in components related to muscular strength, speed, agility, and aerobic capacity, along with nutritional education to reduce fat mass.

KEYWORDS
allometric body size, children coordination, longitudinal growth, physical fitness

1 | INTRODUCTION

Children change their body size and composition as well as their body proportions and overall shape as they grow. Similarly, their motor performance (MP) and gross motor coordination (GMC) also increases with age.[1-3] Whilst a number of correlates have potential to influence GMC, a recent systematic review established that child-level variables such as age, sex (boys), physical activity, fitness, and weight status are all important.[3] These child-level factors were considered in the model developed by Stodden, Goodway, Langendorfer, Roberton, Rudisill, Garcia, et al[4] In this model, it is proposed that as children engage in physical activity (PA), they develop their gross motor skills further, enabling them to engage in more PA over time. Physical fitness (PF) was proposed as a mediator in this relationship, with the positive spiral of engagement resulting in a healthier weight status.

A subsequent recent narrative review has summarized the aspects of the model tested in the 5 years since it was proposed.[5] This review found evidence in childhood for a positive relationship between motor skill and PA, an increasing association between motor skill and cardiorespiratory endurance and muscular strength/endurance and that weight status (inverse) was both a precursor and a consequence of motor skill. Further support for the importance of these variables in Portuguese children has been found by Chaves, Baxter-Jones, Gomes, Souza, Pereira, and Maia,[6] who reported that child-level variables (sex, physical fitness, and body fat) explained 90% of the total variance in GMC, whilst the school-level correlates only explained 10%. Additionally, De Souza, Chaves, Lopes, Malina, Garganta, Seabra, et al[1] showed that children who were both fit and active at 10 years of age had a more favorable physical activity and fitness profile and better GMC at 6 years when compared to unfit and sedentary children.

As differences in body size and shape may confound MP,[7] the allometric approach provides an insightful methodology to interpret differences in children's MP that are associated with changes in their body size and shape.[8,9] This approach is a method of mathematically expressing the extent to which a variable (eg, physiologic, anatomic, or temporal) is related to a unit of body size, as size increases.[10] For example, Tsiotra, Nevill, Lane, and Koutedakis[11] using cross-sectional data in Greek children reported the most suitable body size/shape characteristics that best link to MP in a variety of traits (aerobic endurance, anaerobic speed, explosive power, flexibility, and static muscular strength). Additionally, a more satisfactory interpretation of child serial data in oxygen uptake[10,12] and aerobic power[9] has been achieved using ontogenetic allometry, namely adequate scaling linked to changes in body size and shape due to physical growth.

When dealing with longitudinal data on children`s growth and MP, ontogenetic allometry has been most successfully framed within multilevel statistical models to interpret changes in strength and aerobic power in children.[13] This has never been carried out using GMC longitudinal data during childhood, even though children change in size, shape, and body proportions. This means that parts of the model by Stodden, Goodway, Langendorfer, Roberton, Rudisill, Garcia, et al[4] can be tested longitudinally, if we consider the allometric perspective, appropriate statistical methods and use suitable data, that is, the inclusion of time-varying predictors of GMC changes. The aforementioned review[5] highlighted that there was a need for further longitudinal analysis to test the model by Stodden and colleagues. We hypothesize that (a) GMC changes are nonlinear with evident sex differences; (b) as children grow, changes in their body size and proportions expressing a tendency to linearity relative to body mass, that is, a more ectomorphic physique, will be positively associated better GMC across time; (c) more physically active children will also have greater GMC levels; (d) physical fitness levels will be systematically linked to GMC changes, although the contribution of fitness components will show different effect sizes and rankings, that is, they will be a function of the complexity of the task structure of each test, and the respective fitness component, that may be linked to GMC changes. Thus, the aims of this study were to (a) model GMC changes in children followed longitudinally from 6 to 9 years of age using an allometric approach and (b) investigate the associations between these changes and children's PA and physical fitness levels.

2 | METHODS

2.1 | Sample

The sample was selected from a mixed-longitudinal study on growth, physical activity, GMC, physical fitness, biological maturation, body composition, and motivation for sport in Azorean youth. Briefly, subjects were resident on the four main Azores Islands (between 36.5°-40° North latitude and 24.5°-31.5° West longitude), namely Faial, Pico, São Miguel, and Terceira, and represented about 99% of the total population of school children in the 9 islands. Sampling within each island was random, and no differences were noted across the 4 islands. All measurements were taken annually in the fall during September and October by trained physical education teachers of each participating school. All assessments were carried out in the schools using similar testing conditions and protocols. The objectives and procedures of the study were thoroughly explained to parents, and their informed consent was obtained. Written informed consent was obtained from parents or legal guardians, and the study was approved by the ethics committee of the Faculty of Sport, University of Porto.

The larger study started in 2002 and the last wave of data collection was in 2008. In this article, we only deal with children from the first cohort that remained in the study—a total of 245 children (122 girls). These children were observed initially at 6 years of age (ie, in 2002) and were followed annually until 9 years, with GMC data obtained from 6 to 9 years of age.

2.2 | Anthropometry

All measurements were made according to standardized procedures.[14] Body mass was measured to the nearest 0.1 kg on a Seca scale (Seca Optima 760, Germany) with children lightly dressed and barefoot; stature was measured to the nearest 0.5 cm using a portable stadiometer (Siber Hegner, Switzerland). Children were measured with their feet together and head in the Frankfurt plane.

2.3 | Physical fitness

Physical fitness (PF) was assessed using the Fitnessgram (health related)[15] and the American Alliance for Health, Physical Education, Recreation and Dance (performance related)[16] test batteries and includes (a) 1-mile run/walk (aerobic capacity), (b) curl-ups (strength and endurance of abdominal muscles), (c) push-ups (upper body strength and endurance), (d) trunk lift (trunk extensor strength and flexibility), (e) standing long jump (explosive power), (f) handgrip strength (static strength), (g) 50-yard dash (running speed), and the (h) shuttle run (agility).

For ease of interpretation, performance on the 1-mile run/walk was converted in meters per minute (m/min), and the 50-yard dash and the shuttle run in meters per second (m/s). Then, all physical fitness results were transformed to z-scores using the grand-mean centering as advocated.[17]

2.4 | Gross motor coordination

Gross motor coordination was assessed with a standardized test battery for children which was developed in Germany (*Körperkoordinationtest für Kinder* [KTK]) by Schilling and Kiphard.[18] The assessment comprises four tests: (a) balance—child walks backward on a balance beam 3 m in length, but of decreasing widths: 6 cm, 4.5 cm, 3 cm; (b) jumping laterally—child makes consecutive jumps from side to side over a small beam (60 cm × 4 cm x 2 cm) as fast as possible for 15 seconds; and (c) hopping on one leg over an obstacle—the child is instructed to hop on one foot at a time over a stack of foam squares. After a successful hop with each foot, the stature is increased by adding a square (50 cm × 20 cm × 5 cm); (d) shifting platforms—the child begins by standing with both feet on one platform (25 cm × 25 cm × 2 cm supported on four legs 3.7 cm high), places the second platform alongside the first and steps on to it. The first platform is then placed alongside the second and the child steps on to it and the sequence continues for 20 seconds. The sum of scores for each test was used to expresses the overall GMC score which is different from the normalized Motor Quotient score. Our approach was advocated by Schilling.[19]

2.5 | Physical activity

Physical activity was assessed by direct interview (one-to-one) with the Godin and Shephard questionnaire,[20] and all questions were placed in children's daily routine contexts. Previous validation studies reported moderate correlations ($0.40 \le r \le 0.62$) when comparing the Godin-Shephard questionnaire with accelerometry in children aged 7-10 years.[21] Furthermore, child responses to the questionnaire have been shown to be reliable in previous studies with Portuguese children with intraclass correlations ranging from 0.75 to 0.80.[6,22] Participants reported the number of times/week they spent in different activities for a period of at least 15 minutes, and three PA categories were considered in terms of the metabolic equivalent task (MET) method: light (3 METs), that is, activities such as easy walking or swimming; moderate (5 METs), that is, activities such as fast walking, leisurely bicycling, dance, and noncompetitive swimming; and vigorous (9 METs), that is, activities such as running, jogging, soccer, basketball, judo, roller skating, and vigorous swimming. A total PA score (TPA) was derived by multiplying the frequency of each category by its corresponding MET value. This time-varying predictor was grand-mean centered as advocated by Hox, 2010.[17]

2.6 | Data reliability

Data quality control was assessed 2 weeks apart using a random sample of 25 children (13 boys; 12 girls) from each of the four islands, and reliability was estimated via ANOVA-based intraclass correlation coefficients (*R*) using a test-retest protocol: *R* was .98 and .99 for stature and body mass, respectively, and .75 for TPA; in health-related PF tests was $0.65 \le R \le 0.97$, in performance-related tests was $0.64 \le R \le 0.87$, whereas in GMC was $0.79 \le R \le 0.98$. Furthermore, we also estimated the physical fitness tests′ stability across time for boys and girls using the intraclass correlation coefficient based on the one-way random effects model. Results were as follows: boys between .45 for standing long jump and .80 for push-ups, and for girls, between .52 for standing long jump and .75 for push-ups.

2.7 | Statistical analyses

Descriptive statistics (means and SDs) for anthropometric variables, PA, PF, and GMC, were computed per year of data collection. An appropriate method of analyzing longitudinal (repeated measures) data is to adopt a multilevel modeling approach which is an extension of ordinary multiple regression where the data have a hierarchical or clustered structure. A hierarchy consists of units or measurements grouped at different levels. One example is repeated measure data where individuals are measured on more than one occasion. As such, in our study, children, assumed to be a random sample, represent the level-2 units, with the children′s repeated measurements recorded at each visit occasion, being the level-1 units. Note that, in contrast to traditional repeated measures analyses, the visit occasions are also assumed to be a random variable over time. The two levels of random variation take account of the fact that GMC characteristics of individual children, such as their average GMC growth rate, vary around a population mean and also that each child's observed measurements vary around his or her own GMC growth trajectory. Further, in this study, sex is treated as a fixed factor, and all other variables are time-varying covariates because they change in time. Using the ontogenetic multiplicative model suggested by Nevill, Holder, Baxter-Jones, Round, and Jones,[23] where $y = \text{body mass}^{k1} \bullet \text{stature}^{k2} \bullet$

exp ($a_i + b_i$•age + c•age^2) ε_{ij}, a modified stepwise approach was used to match our purposes and hypotheses. Hence, our first model (M_1) only considers body mass, stature, age, sex (girls are the reference category, girls=0), and TPA. It is a log-linear multilevel regression model and is expressed as follows,

$$\begin{aligned}\text{Log}_e\,\text{GMC} = {} & k_1 \cdot \log_e(\text{body mass}) + k_2 \cdot \log_e(\text{stature}) \\ & + a_i + b_i \cdot \text{age} + c_i \cdot \text{age}^2 + d_i \cdot \text{sex} \\ & + e_i(\text{age}-\text{by}-\text{sex interaction}) \\ & + f_i \cdot \text{TPA} + \log_e(\varepsilon_{ij})\end{aligned}$$

where k_1 and k_2 are the ontogenetic allometric coefficients; a_i, and b_i are allowed to vary randomly from child to child (*level-2*); and log$_e$ (ε_{ij}) is assumed to have a constant error variance between visit occasions (*level-1*). The constant a_i is also allowed to vary for different populations, in this case the fixed factor sex. Further, age^2 models the nonlinearity of GMC changes, in fact a quadratic component, and age-by-sex expresses differences in boys and girls mean GMC trajectories across age.

The second model (M_2) builds on the previous one and adds the first set of time-varying physical fitness predictors, namely standing long jump (SLJ), 50-yard dash (50yrd), and shuttle run (SR); the addition of handgrip strength (HG) is from Nevill et al[8] suggestions. The log-linear multilevel regression model is now

$$\begin{aligned}\text{Log}_e\text{GMC} = {} & k_1 \cdot \log_e(\text{body mass}) + k_2 \cdot \log_e(\text{stature}) \\ & + a_i + b_i \cdot \text{age} + c_i \cdot \text{age}^2 \\ & + d_i \cdot \text{sex} + e_i(\text{age}-\text{by}-\text{sex interaction}) \\ & + f_i \cdot \text{TPA} + g_i \cdot \text{SLJ} + h_i \cdot \text{50yrd} \\ & + i_i \cdot \text{SR} + j_i \cdot \text{HG} + \log_e(\varepsilon_{ij})\end{aligned}$$

The third and last model (M_3) adds the remaining PF tests [1-mile run/walk (1MRW), curl-ups (CUPS), push-ups (PUSH), and trunk lift (TLIFT)], and the log-linear multilevel regression model is

$$\begin{aligned}\text{Log}_e\text{GMC} = {} & k_1 \cdot \log_e(\text{body mass}) + k_2 \cdot \log_e(\text{stature}) \\ & + a_i + b_i \cdot \text{age} + c_i \cdot \text{age}^2 \\ & + d_i \cdot \text{sex} + e_i(\text{age}-\text{by}-\text{sex interaction}) \\ & + f_i \cdot \text{TPA} + g_i \cdot \text{SLJ} + h_i \cdot \text{50yrds} \\ & + i_i \cdot \text{SR} + j_i \cdot \text{HG} + l_i \cdot \text{1MRW} \\ & + m_i \cdot \text{CUPS} + n_i \cdot \text{PUSH} \\ & + p_i \cdot \text{TLIFT} + \log_e(\varepsilon_{ij})\end{aligned}$$

All parameters of each model were simultaneously estimated using full maximum likelihood procedures implemented in the SuperMix v1 software.[24] These procedures are robust, efficient, and consistent, and the optimization of the maximum likelihood would stop if multicollinearity was present (Hedeker, Gibbons).[25] Yet, no such problems were detected because all models converged to proper solutions. Further, residuals were inspected as advocated by Hox,[17] and no special problems were encountered.

As is current practice,[17] the Deviance is the measure of model goodness of fit, and it is expected that if a new model fits the data better than the previous one, the deviance is expected to drop significantly. Further, the change in deviances (Δ_D) follow a chi-square distribution whose degrees of freedom are calculated from the difference (Δ_P) between the numbers of the estimated parameters in each model assuming they are nested within each other. Statistical significance was set at 5%.

3 | RESULTS

Descriptive statistics across the study years are summarized in Table 1. Boys and girls consistently become taller and heavier from 6 to 9 years old. On average, girls show a systematic decrease in TPA with age, but this is not apparent in boys. Further, across the years, on average, boys and girls show better GMC and fitness.

Multilevel modeling results are in Table 2. In Model 1, boys outperform girls at 6 years of age (the anchoring age of the analysis). The interaction age-by-sex is negative suggesting that the trajectory of the boys′ GMC (with increasing age) is significantly lower than that of the girls. There is a nonlinear trend in GMC across the study years. Further, this model "sets the scene" for the ontogenetic scaling factors that best describe children body size/shape and their GMC development from 6 to 9 years of age. Body mass (-0.60 ± 0.07, $P < .001$) and stature (2.92 ± 0.35, $P < .001$) parameter estimates (negative and positive, respectively) are statistically significant suggesting that more linear children (ectomorphic) in their overall physique, and less heavy, show the best GMC development across time. Contrary to our hypothesis, TPA was not significantly associated with GMC changes from 6 to 9 years of age. The variance components show significant intraindividual differences in GMC changes across the years, that is, different individual growth rates. Further, the higher a child's GMC level at 6 years, the lower the growth rate over the time (covariance=-0.0058 ± 0.0014, $P = .003$).

Model 2 fits the data significantly better than Model 1 [deviance in $M_1 = -529.0166$ and in $M_2 = -641.9411$; $\Delta_D = -112.92$, $\Delta_{P=}4$, $P < .001$]. With the inclusion of four PF tests, boys′ GMC do not differ from girls at 6 years of age, that is, at baseline. The negative interaction is still significant, meaning that boys' GMC development (trajectory over age) remains lower than the girls, that is, the GMC trajectories are diverging. The first set of PF tests showed significant results in the expected direction: that is, faster children in the 50-yard dash and in the shuttle run, and stronger children in the standing long jump and in the handgrip are those who

TABLE 1 Descriptive statistics (mean ± SD) for girls and boys across the study years

Tests	Girls Year 1	Girls Years 2	Girls Year 3	Girls Year 4	Boys Year 1	Boys Year 2	Boys Year 3	Boys Year 4
Stature (cm)	117.6 ± 5.6	122.6 ± 5.9	128.2 ± 6.4	133.2 ± 6.5	118.9 ± 5.1	123.9 ± 5.5	129.5 ± 5.8	134.5 ± 6.3
Body Mass (kg)	24.0 ± 4.6	26.1 ± 5.6	29.8 ± 6.6	33.5 ± 7.7	24.6 ± 5.2	26.9 ± 6.3	30.2 ± 7.5	34.2 ± .1
Gross motor coordination (Sum of points)	99.5 ± 27.2	130.9 ± 30.7	157.78 ± 34.2	174 ± 38.6	111.0 ± 31.1	140.5 ± 36.6	164.6 ± 37.0	182.1 ± 39.8
Total physical activity	41.2 ± 32.9	37.8 ± 23.3	34.8 ± 3.3	33.3 ± 19.8	51.4 ± 31.8	42.1 ± 24.0	47.7 ± 22.8	49.3 ± 23.3
Fitness items								
1-mile run/walk (min)	14.2 ± 2.7	14.6 ± 3.5	14.3 ± 3.1	13.7 ± 2.4	13.1 ± 2.7	13.8 ± 4.0	13.4 ± 3.6	12.3 ± 2.7
Push-up (reps)	6.8 ± 7.1	9.0 ± 7.3	13.4 ± 12.2	10.2 ± 8.9	9.3 ± 8.8	10.9 ± 8.8	16.0 ± 11.0	16.0 ± 13.3
Curl-up (reps)	12.3 ± 15.2	11.5 ± 14.1	20.2 ± 21.7	21.0 ± 21.7	12.9 ± 18.8	12.6 ± 15.3	25.7 ± 33.5	26.7 ± 2.6
Trunk lift (cm)	27.2 ± 6.6	28.3 ± 6.3	31.0 ± 5.6	33.8 ± 7.8	26.3 ± 8.3	26.8 ± 6.0	29.3 ± 5.4	26.7 ± 25.6
50-yard dash (s)	12.6 ± 1.5	11.6 ± 1.2	11.0 ± 1.1	10.4 ± 1.1	11.7 ± 1.3	11.0 ± .1.1	10.3 ± 1.0	9.7 ± 1.0
Standing long jump (cm)	88.6 ± .15.1	102.3 ± 21.5	105.8 ± 20.0	104.7 ± 38.5	95.9 ± 18.5	107.0 ± 22.1	111.1 ± 23.7	116.3 ± 38.4
Handgrip (kgf)	8.2 ± 1.7	10.2 ± 2.1	11.6 ± 2.7	13.4 ± 2.9	9.9 ± 2.1	12.1 ± 2.7	13.5 ± 3.0	15.7 ± 3.3
Shuttle run (s)	15.0 ± 1.6	14.6 ± 1.6	13.8 ± 1.3	13.5 ± 1.7	14.4 ± 1.4	14.0 ± .1.6	13.4 ± 1.4	12.7 ± 1.4

consistently show better GMC results across the years. As all tests are expressed in z-scores, it is possible to compare their relevance (based on their parameter estimates) in terms of their association with GMC changes: handgrip strength and 50-yard dash are the most important followed by shuttle run and standing long jump.

The final Model 3 fitted the data better than Model 2 [deviance in $M_2 = -641.9411$ and in $M_3 = -666.5133$; $\Delta_D = -24.5722$, $\Delta_{P=} 4$, $P < .001$]. Whilst previous results remain similar in their interpretation in this new model as they were in M_2, the addition of four PF tests did not change the order of their importance. Note that the body mass and stature exponents in M_3 now becomes (-0.43 ± 0.06, $P < .001$) and (1.16 ± 0.31, $P = .002$), respectively. The body mass and stature exponents associated with GMC changes can be rearranged and expressed as a stature-to-mass ratio within a relatively linear power function relationship as follows: $\text{mass}^{-0.43} \cdot \text{stature}^{1.16} = (\text{stature} \cdot \text{mass}^{-0.37})^{1.16}$, since $\text{mass}^{-0.43} = (\text{mass}^{-0.37})^{1.16}$. This stature-to-body mass ratio is similar to the Reciprocal Ponderal Index ($\text{RPI} = \text{stature} \cdot \text{mass}^{-0.333}$), suggesting that more linear children (ectomorphic) in their overall physique, and less heavy, show the best GMC development across time. Further, curl-ups and push-ups were not significantly associated with children′s GMC changes across time, and the 1-mile run/walk and the trunk lift were ordered in 5th and 6th place in terms of their links to GMC development.

4 | DISCUSSION

To the best of our knowledge, this is perhaps the first study that used ontogenetic allometry with serial GMC data and identified the best scaling factors relating stature and body mass changes that are associated with superior GMC performance. Across the three models, we consistently showed two strong points: (a) children whose overall physique across the study years has a dominant ectomorphic component, that is, taller and less heavy, outperform their peers in their GMC changes across time; (b) girls consistently outperform boys over the observed age range having adjusted for body size/shape as well as differences in PF. In fact, the stature-by-body mass ratio in M_3 is almost perfectly the Reciprocal Ponderal Index ($\text{stature}/\text{body mass}^{0.333}$). Simplistically, we could infer that weight status (inverse) may be considered a precursor, as well as a consequence of GMC performance as well as motor skill. However, most previous evidence of this is cross-sectional, or when longitudinal, has not been modeled to take account of how changes in growth interact with changes in GMC and in motor skill.[26] Also, previous research has not identified how changes in body size and shape are important to understand GMC and most probably motor skill, as well as its implication in sex differences which in

TABLE 2 Multilevel results for the three consecutive gross motor coordination (GMC) models

	Model 1		Model 2		Model 3	
Parameters	**Estimate ± SE**	***P*-value**	**Estimate ± SE**	***P*-value**	**Estimate ± SE**	***P*-value**
Fixed effects						
Intercept	−7.4314 ± 1.5353	<.001	−0.2859 ± 1.4237	.840	0.5574 ± 1.3683	.683
Ln body mass	−0.6026 ± 0.0721	<.001	−0.4844 ± 0.0652	<.001	−0.4335 ± 0.0645	<.001
Ln Stature	2.9162 ± 0.3508	<.001	1.3649 ± 0.3231	<.001	1.1560 ± 0.3111	.002
Age (years)	0.2436 ± 0.0197	<.001	0.2361 ± 0.0184	<.001	0.2397 ± 0.0185	<.001
Age^2 (years)	−0.0343 ± 0.0044	<.001	−0.0363 ± 0.0044	<.001	−0.0394 ± 0.0045	<.001
Sex (boys)	0.0782 ± 0.0379	.039	0.03264 ± 0.0339	.323	0.0358 ± 0.0321	.265
Interaction (age-by-sex)	−0.0232 ± 0.0098	.018	−0.0328 ± 0.0093	.004	−0.0331 ± 0.0095	.005
Total physical activity	0.0002 ± 0.0002	.382	0.0002 ± 0.0002	.353	0.0006 ± 0.0002	.779
S Long jump (z-score)			0.0212 ± 0.0068	.001	0.0213 ± 0.0068	.001
50 yards (z-score)			0.0406 ± 0.0086	<.001	0.0347 ± 0.0087	.007
Shuttle run (z-score)			0.0293 ± 0.0072	.006	0.0302 ± 0.0072	.003
Handgrip (z-score)			0.0623 ± 0.0102	<.001	0.0581 ± 0.0102	<.001
1-mile run/walk (z-score)					0.0188 ± 0.0068	.005
Curl-up (z-score)					0.0076 ± 0.0062	.219
Push-up (z-score)					0.0042 ± 0.0069	.541
Trunk lift (z-score)					0.0082 ± 0.0070	.007
Variance components						
Intercept	0.0550 ± 0.0067	<.001	0.0388 ± 0.0050	.001	0.0358 ± 0.0047	.001
Age	0.0015 ± 0.0005	<.002	0.0011 ± 0.0004	.014	0.0013 ± 0.0004	.004
Covariance (Intercept/Age)	−0.0058 ± 0.0014	.003	−0.0052 ± 0.0126	.001	−0.0056 ± 0.0012	.001
Residual	0.0134 ± 0.0009	<.001	0.0133 ± 0.0098	<.001	0.0131 ± 0.0009	<.001
Deviance	− 529.0166		− 641.9411		− 666.5133	
Number of estimated parameters	12		16		20	
Change in deviance (Δ_D) and in number of estimated parameters (Δ_P)			$\Delta_D = -112.92$, $\Delta_P = 4$, $P < .001$		$\Delta_D = -24.5722$, $\Delta_P = 4$ $P < .001$	

all likelihood may favor girls with increasing age. Thus, our finding extends the previous literature in this area.

Scaling exponents for size during physical growth have been used as the most suitable denominators by which different variables (eg, aerobic power, muscle strength, Peak VO_2, and distance running) are adjusted for, and they provided elucidative interpretations of children performance across their chronological age.[8,9] Although there are reports with serial data using allometry with O_2 consumption in a variety of situations,[13,27] no previous GMC longitudinal data tried to identify how children change in their size, proportions, and shape, that is, how their overall physique affected, positively or negatively, their GMC performance. Notwithstanding this absence, evidence from GMC cross-sectional[28,29] and time-limited longitudinal studies[26] showed GMC-negative associations with increasing body mass, as well as a widening gap in children and adolescents with different BMI statuses. This inverse relationship may be partially explained by probable increases in fat mass which are detrimental to GMC performance when tasks require body mass to be projected.[30] Additionally, increased overall mass across the childhood years may also be linked to reduced inefficiency in movement patterns that inherently demand adequate segmental velocities as required by some of the KTK test battery tasks.[31] Thus, it may be possible that excess mass impedes stabilization and/or propulsion of the body, which decreases the likelihood of overweight/obese individuals to be more physically active,[26] and show lower levels of GMC.

It is well accepted that with the passage of time children express their fundamental motor skills (FMS) as well as their GMC development in higher levels of mature performance.[32] This can be explained by the interplay between child genetic endowments and their environmental factors.[33] Whilst children generally improve their GMC with age,[34] in the current study, a nonlinear trend in GMC across time was found suggesting a performance peak at 9 years of age, that is, the exponent of age square remains negative in all models. Yet, available reports on GMC centile charts in Portuguese children[35,36] do not clearly show a plateau around 9 years of age. Our finding is perhaps due to the fact that our serial data stop at 9 years. Nevertheless, and although measuring gross motor skills[37] rather than GMC, it has been shown that there is a plateauing of locomotor skills as children near the upper age limits for the test, that is, 10 years, which is also consistent with Portuguese children data using the same test battery (TGMD-2).[38] In addition, we also showed that girls consistently outperformed boys across the years (ie, the interaction age-by-sex was negative and significant) when changes in their body size and shape were considered in the analyses. This sex difference was maintained even when GMC changes were adjusted for the other time-varying covariates, that is, PF components. This sex difference is a new finding that contradicts what is available in the literature[3,39] and needs further exploration.

Previous literature supports a positive relationship between motor skill as well as GMC and physical activity.[4,5] However, the strength of associations across developmental time remains unclear.[5] Over time, there is some evidence which shows that children's TPA levels decrease with age[1] and that this condition may affect their GMC levels.[2] Similarly, Lopes, Rodrigues, Maia, and Malina[30] found that children's GMC influences their PA levels from 6 till 10 years of age, that is, less coordinated children decreased their PA with increasing age, whereas the opposite occurred with more coordinated children. In contrast, in our study, when we jointly modeled how PA and physical fitness items are associated over time with GMC changes, and how this relates to growth changes, TPA was not significantly associated with GMC changes. This appeared to be mostly because average TPA systematically declined with age in girls and had an "erratic" behavior in boys. Whilst systematic reviews have found a relationship between motor competence and PA, the relationship may not be straightforward.[40] Rather than simply examining the relationship between GMC and total duration of PA, the type and context of PA are likely to be of more importance. A systematic review found that PA was not a consistent correlate of all type of motor competence, although it was considered a consistent correlate of GMC and fundamental movement skill composites.[3] It is also plausible that a relationship between TPA and GMC was not found in the current study because children were not old enough to report reliably on their activity levels, even though previous studies have found moderate correlations with accelerometry in slightly older children.[20]

Previous research found associations between GMC and FMS with cardiorespiratory endurance and muscular strength/endurance.[5] Yet, in the current study, and based on our modeling strategy, we were not only able to estimate different effects sizes for fitness components on GMC, but also rank them in their importance (all are in the same metric, that is, a z-score) in terms of "impact" on GMC development. This is a novel finding. In the first set of fitness tests, the rank order was as follows: handgrip strength, 50-yard dash, shuttle run, and standing long jump. Because the motor tasks of these PF tests, as well as those from GMC, include multijoint movements with many degrees of freedom within the body, we speculate that the combination of isometric, concentric, and eccentric muscle activity requires a high degree of both inter- and intramuscular coordination and control. Further, in muscular strength development, the ability to effectively recruit motor units, to increase motor unit firing rates, and decrease levels of co-activation agonist and antagonist muscles (ie, coordinated muscle recruitment) are part of developmental neuromuscular adaptations that occur as children develop their fundamental motor skills and increase their GMC.[4,5]

Standing long jump and handgrip involves the integration of the central nervous system and the skeletal muscle system to arrange adequate strength for an intended motor task.[41] Interestingly, the exponents of body mass (−0.48 year 2; −0.43 year 3) and stature (1.36 year 2; 1.15 year 3) suggested, in line with previously published data, that handgrip and standing long jump increase in proportion to body size at a rate a little greater than the cross-sectional area of body size.[7,42] Besides, the stature exponents, standing long jump and handgrip, respectively, may simply mirror the mechanical advantages of being taller. For example, Tsiotra, Nevill, Lane, and Koutedakis[11] analyzed log-transformed handgrip strength using log-transformed body mass and stature, as well as age as covariates, and found significantly lower levels of strength in children suspected of developmental coordination disorder as compared to their typically developing peers. Both 50-yard dash and shuttle run indicate PF agility and velocity components which also partially reflect measures of motor coordination or a "skill" factor. Thus, the higher the skill factor in the test, the more likely that the coordination of agonistic, synergistic, and antagonistic muscle groups will also impact GMC to a higher degree.[42]

Finally, the inclusion of four more PF tests (Model 3) did not change the importance of the previous set. From these new ones, curl-ups and push-ups were not significantly associated with GMC, but the 1-mile run/walk and trunk lift were. As curl-ups and push-ups involve specific muscle groups such as the *pectoralis major*, *triceps brachii,* and *rectus abdominis*, we speculate that their actions may not be transferable to KTK tasks. When measured in absolute terms, maximal oxygen uptake progressively increases during childhood.[10] Our data expressed in m/min also showed increases with age. Relatively taller boys and girls who also have a linear physique tend to perform better on both tests and hence their link. The trunk lift test is assumed to simultaneously measure trunk extensor strength and flexibility. Although, hyperflexibility reduces stability around the joint and may make it difficult to control movements, and hypoflexibility limits the range of movement around joints and therefore restricts movement quality[43] we do not have a clear link between trunk lift performance and GMC.

This study is not without limitations. First, TPA was estimated via a questionnaire, which is prone to well-known limitations in children, especially in a young age. Financial and logistic aspects limited our choice to a questionnaire. However, direct interviews were used, and data were reliable and in line with previous studies with Portuguese children.[6,22] Second, no information was gathered concerning brain myelination factors, cognitive functioning, or fundamental motor skills, all of which may relate to GMC performance in many ways. Yet, these are challenging to obtain within a field study covering four islands and with limited resources. Third, we did not consider school-level variables that may also impact children GMC, although, the variance explained by these covariates has been shown to be relatively low.[44] Fourth, GMC was assessed with the KTK battery, which has a limited number of tasks and coordination domains, yet it has been consistently used showing wide applicability.[2,45]

In conclusion, the current study showed that children with a linear body size/shape, that is, with an ectomorphic dominance, tend to perform better in their GMC. Girls tend to outperform boys across time. Further, physically fitter children in terms of muscular strength (static and dynamic), agility, and speed tend to be more coordinated. TPA was not associated with children GMC, although other studies have demonstrated this relationship and thus future research may seek to further investigate the type of PA that best relates to GMC development, rather than simply focus on TPA or PA intensity.

5 | NEW FINDINGS/BRIEF PERSPECTIVES

Using the innovative approach of allometric modeling to better understand variation as well as changes in children's GMC has enabled us to extend previous literature by illustrating that it is the Reciprocal Ponderal Index rather than BMI that is the body shape characteristic associated with children's superior GMC development. We also showed that when investigating GMC development and simultaneously considering changes in body size and shape, as well as in physical fitness components, girls tend to outperform boys. Additionally, we were also able to show that there is a hierarchy of fitness components that best associates with GMC changes—static strength, speed, agility, aerobic capacity, and flexibility. The findings of this study suggest that to increase children's GMC levels, physical education and intervention programs should focus on increasing children's physical fitness (namely muscular strength, running speed, agility, and aerobic capacity) as well as education regarding healthy eating (to reduce unnecessary body fat), which in all likelihood will lead to a more ectomorphic body shape. Paying attention to these modifiable fitness components may translate into increases in children's health status, as well as reduce the frequency of children with low motor coordination.

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CONFLICT OF INTEREST

Marcos André M. dos Santos, Alan M. Nevill, Rojapon Buranarugsa, Sara Pereira, Thayse Natacha Q. Ferreira Gomes, Lisa M. Barnett, and José António R. Maia declare that they have no conflict of interest.

INFORMED CONSENT

Informed consent was obtained from all individual participants included in the study.

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