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Genetics of somatotype and physical fitness in children and adolescents

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Abstract

Objectives: To analyze the influence of genetic and environmental factors on the variation in somatotype, physical fitness, and their mutual associations.

Methods: Twins from 214 pairs (87 monozygotic) of the Autonomous Region of Madeira, Portugal, from 3 to 18 years of age (51% girls) were assessed in anthropometry and physical fitness tests. We estimated endomorphy, mesomorphy, and ectomorphy based on anthropometric measures and physical fitness using the Eurofit test battery. Two age categories were analyzed: children (3-11 years) and adolescents (12-18 years). Genetic and environmental variations were estimated using quantitative genetic twin modeling.

Results: No genetic sex differences were found, thus boys and girls were pooled in all genetic analyses. Heritability estimates were high for somatotype (a^2 = 0.80-0.93), physical fitness traits (a^2 = 0.67-0.83), and largely similar in children and adolescents. Positive correlations were found for ectomorphy with motor ability and cardiorespiratory endurance as well as for endomorphy and mesomorphy with muscular strength (r = 0.25-0.37). In contrast, negative associations were found for ectomorphy with muscular strength, as well as for endomorphy and mesomorphy with motor ability and cardiorespiratory endurance (−0.46 to −0.26). Twin modeling indicated that these associations were explained mostly by genetic factors in common to the two associated traits (84% or more).

Conclusions: Associations between somatotype and physical fitness tests are mainly explained by common genetic background in children and adolescents. Therefore, interventions in youth should consider that a child's performance in physical fitness tests partly reflects their inherited physique.

Somatotype offers a method to rate and classify the overall body form based on three components: endomorphy (relative fatness), mesomorphy (relative musculoskeletal development), and ectomorphy (relative linearity; Carter & Heath, 1990). Even as imaging techniques directly measuring body tissues have become available (Hu, 2008), they are expensive, not feasible in all situations, and do not appraise the body shape. Thus, somatotype can offer an inexpensive method to also provide indirect information about body composition, which is demonstrated by associations of somatotype with cardiovascular diseases (Katzmarzyk, Malina, Song, & Bouchard, 1998; Williams, Jones, Bell, Davies, & Bourne, 1997) and osteoporosis (Saitoglu, Ardicoglu, Ozgocmen, Kamanli, & Kaya, 2007). The analysis and interpretation of the importance of somatotype have been especially useful in sport sciences to study elite athletes in various sports such as gymnastics (Sterkowicz-Przybycień et al., 2019), martial arts (Chaabène, Hachana, Franchini, Mkaouer, & Chamari, 2012), and ball games (Buśko, Lewandowska, Lipińska, Michalski, & Pastuszak, 2013; Buśko, Pastuszak, Lipińska, Lipińska, & Gryko, 2017). The associations between somatotype and physical fitness in general populations have also attracted scientific interest but are rare as compared to the large body of literature on athletes. A study of physically active males found that mesomorphy was associated with higher and ectomorphy with lower muscular strength (Ryan-Stewart, Faulkner, & Jobson, 2018). Ectomorphy and mesomorphy have also been associated with better gains during aerobic fitness training in children (Marta et al., 2013) and adults (Chaouachi et al., 2005). The association between somatotype and physical fitness in children has important public health implications, since good cardiorespiratory fitness is associated with better metabolic risk factors in childhood (Ruiz, Ortega, Meusel, Harro, & Sjöström, 2006), and this association lasts into adulthood (Mintjens et al., 2018).

Genetic factors are important when explaining individual differences in both physical fitness and physique. Meta-analyses of previous twin studies have shown moderate heritability estimates (ie, the proportion of total variation explained by genetic variation) for aerobic physical fitness (Schutte, Nederend, Hudziak, de Geus, & Bartels, 2016) and muscle strength-related traits (Zempo et al., 2017). For somatotype components, moderate to high heritability estimates have been found in twin studies (Peeters et al., 2003; Peeters et al., 2007; Reis et al., 2007), whereas studies using family and pedigree designs have reported moderate heritabilities and some of them have not been able to distinguish genetic factors from other familial factors (Katzmarzyk et al., 2000; Pereira et al., 2017; Rebato, Jelenkovic, & Salces, 2007; Saranga et al., 2008). Since different models with different assumptions have been used in these studies, it is difficult to compare the heritability estimates derived from them. However, these studies highlight the importance of genetic differences for the variation in both physical fitness and body physique as assessed by somatotype. Heritability components are important since high heritability can indicate inherited liability to develop, for example, a good level of physical fitness through different mechanisms such as better response to physical training stimuli.

Considering the importance of genetic factors underlying both physical fitness and somatotype components and the body of literature showing association between them, it is interesting that there are no previous studies analyzing how much somatotype components share a common genetic background with physical fitness traits. Thus, we analyzed this question in a cohort of twin children, which allows decomposing the variation of somatotype components and physical fitness traits as well as their mutual correlations into genetic and environmental factors.

1 | DATA AND METHODS

We used data derived from the Madeira Twin Family Study (Maia, Santos, de Freitas, & Thomis, 2013). The executive boards of all public and private schools (n = 236) were contacted in the Autonomous Region of Madeira, Portugal, and asked if they had twin students. Based on the contact information provided by the schools, invitation letters to participate in the study were sent to 434 twin families. From these families, 216 families having twin children from age 3 to 18 years (51% girls) participated in a physical examination in the capital city of Funchal, including a blood sample, detailed anthropometrical measures, and physical fitness assessment. Zygosity was determined by at least 16 genetic markers (single nucleotide polymorphisms or microsatellites): 87 were monozygotic (MZ), 73 same-sex dizygotic (SSDZ), and 56 opposite-sex dizygotic (OSDZ) pairs. The participants and/or their parents or legal guardians provided written informed consent. The Scientific Board of the University of Madeira approved the study protocol.

Anthropometric assessments were done in a swimsuit without shoes and with jewelry removed, based on a standardized protocol (Claessens, Eynde, Renson, & Gerven, 1990). A team of six experienced researchers from the Laboratory of Growth and Development of the University of Madeira took all measurements and scored motor performances. All one-sided measurements were taken on the left side of the body. Height was measured using a Harpenden wall-mounted stadiometer to the last completed unit (1 mm) (Holtain, UK). Body mass was measured on a balance-beam scale accurate to 0.1 kg (Seca Optima 760, Germany). Skeletal breaths (biepicondylar humerus and biepicondylar femur) were assessed with a small spreading caliper with an accuracy of 1 mm (Siber-Hegner, GPM, Switzerland). Girth measurements (flexed arm and calf) were taken with a flexible steel tape accurate to 1 mm (Holtain, UK). Skinfold thickness (subscapular, triceps, suprailiac, and calf) were measured using a skinfold caliper and recorded to the nearest 0.2 mm (Siber-Hegner, GPM, Switzerland). We conducted a pilot study with 25 twin pairs from 6 to 16 years of age, who were measured and who completed the test batteries twice within an 8-day period. Test-retest reliability with ANOVA-based intraclass correlations ranged from 0.91 (subscapular skinfold) to 1.00 (body weight). Technical errors of measurement (TEM) were 0.38 kg for body weight and 0.80 cm for height. TEM for diameters and circumferences ranged from 0.10 (humerus diameter) to 0.41 cm (upper arm circumference flexed), while for skinfolds ranged from 0.88 (calf skinfold) to 2.16 mm (subscapular skinfold). Test-retest reliability for the nine motor tests, based on intraclass correlation coefficients, ranged from 0.83 (plate taping) to 1.00 (handgrip).

These anthropometric measures were used to calculate the three somatotype components—endomorphy, mesomorphy, and ectomorphy—using the Heath and Carter method (Heath & Carter, 1967). We found that the distribution of endomorphy was right-skewed (skewness parameter 0.88) and thus normalized the distribution by using the natural logarithmic transformation decreasing the skewness (skewness parameter 0.10 after the transformation). The distributions of mesomorphy and ectomorphy were roughly normally distributed (skewness parameters 0.38 and 0.08, respectively). We conducted all analyses separately in children less than 12 years of age, who are mainly prepubertal, and in adolescents 12 years of age or older (ie, mainly during or after puberty). The effect of age was adjusted for separately in these two age groups for boys and girls by calculating regression residuals and thus taking into account both age and sex effects.

Physical fitness was assessed with the Eurofit test battery including nine motor tests: flamingo balance, plate tapping, sit and reach, standing long jump, handgrip, sit ups, bent arm hang, shuttle run, and run/walk 12 minutes, as detailed elsewhere (Eurofit, 1992). We conducted an exploratory factor analysis for the age-standardized fitness test values using maximum likelihood estimation by the SPSS Statistics, version 25, software. The analysis showed a two-factor solution explaining 30 and 13% of the total variation in the data (Table S1). When the Varimax rotation was used, all test results loaded on the first factor (the negative loadings are because in these tests higher values indicate lower physical fitness). We thus interpreted this factor to indicate motor ability and cardiorespiratory endurance. The handgrip test loaded strongly on the second factor, and thus we interpreted this factor to indicate muscular strength. We used these two factors in the further analyses of the associations between the somatotype components and physical fitness. In all descriptive analyses, we adjusted for the effect of sampling twin pairs rather than independent individuals on confidence intervals by using the cluster option of Stata software, version 15.1, which takes into account the effect of intrapair correlations on standard errors (Williams, 2000).

The data were analyzed using genetic twin modeling based on the different genetic relatedness of MZ and DZ twins (Posthuma et al., 2003). While MZ twins have virtually the same gene sequence, DZ twins share, on average, 50% of the genetic variance, such as ordinary siblings. Based on this principle, the trait variation can be decomposed into three components. Additive genetic variation (A) includes the effects of all loci affecting the trait and has correlation 1 within MZ and 0.5 within DZ pairs. Shared environmental variation (C) includes the effects of all environmental factors making co-twins similar and has correlation 1 within both MZ and DZ twins. Unique environmental variation (E) includes the effects of all environmental factors making the co-twins dissimilar and has 0 correlation within both MZ and DZ twins.

Further, all measurement error is modeled as part of unique environmental variation. After the univariate models, we conducted Cholesky decomposition to analyze the correlations between the somatotype components and physical fitness factors. This method decomposes the co-variation between the traits into co-variation due to genetic and environmental factors and allows for calculating genetic and environmental correlations between the traits. The genetic twin models were fitted using the OpenMx package, version 2.13.2, of R statistical software (Neale et al., 2016).

We started the analyses by testing the assumptions of genetic twin modeling and finding the best fitting model used in further analyses (Table S2). The DZ correlations were generally slightly more than half of MZ correlations indicating that shared environmental factors may have an effect on the traits (Table S3). Thus, we used the additive genetic/shared environment/unique environment (ACE) model as the starting point of the analyses. The genetic twin modeling makes the fundamental assumption that both MZ and DZ twins have the same amount of genetic and environmental variation, indicating that they represent the same basic population, that is, have similar means and variances by zygosity (Posthuma et al., 2003). We tested this assumption by comparing the model fit statistics of the ACE models to the saturated models, which do not make any assumptions. We found that the *P*-values for all study variables (somatotype components and physical fitness factors) were good (0.08-0.96), indicating that these assumptions were not violated. When we studied individual measures (anthropometric or physical fitness tests), we found some lower *P*-values, but the number of tests was also high (48 tests together), increasing the probability of false positive results (Bonferroni corrected *P*-value .0001 if using the .05 level of statistical significance). We did not find any evidence on the sex-specific genetic effects or different variances in boys and girls. Thus, we pooled boys and girls in the genetic analyses. Further, shared environmental effects were not statistically significant. The final additive genetic/unique environment (AE) model without sex-specific genetic effects and the same variance components for boys and girls showed a good fit for all study variables when compared to the saturated models (*P*-values .10-.98). For the individual measures of anthropometric and physical fitness traits, we found some lower *P*-values, but this was expected given the large number of tests. The lowest *P*-values ($P < .0001$) were found for humerus diameter and bent arm hang in children younger than 12 years due to some outliers. Even so, because these traits were not analyzed separately, we did not remove those measures.

2 | RESULTS

Table 1 presents the descriptive statistics for anthropometric characteristics and physical fitness tests. Clear sex differences in these measures were already found in the children under 12 years of age, and they become larger in the adolescents. Boys had wider humerus and femur diameters whereas girls had thicker triceps, subscapular, suprailiac, and calf skinfolds. No sex differences were found in calf and upper arm circumferences or in body mass. For height, no sex difference was found in children, while adolescent boys were taller than adolescent girls. Boys were more mesomorphic and girls more endomorphic in both age groups. Regarding ectomorphy, no difference was found in children, but in adolescence, girls were slightly more ectomorphic.

We then conducted genetic twin modeling for the somatotype components (endomorphy, mesomorphy and ectomorphy) and the two factors of physical fitness (motor ability and cardiorespiratory endurance and muscular strength) calculated based on the measures described above (Table 2). Genetic factors explained the major part of the variation in somatotype components in children and adolescents, and the heritability estimates varied between 0.80 and 0.93. In the physical fitness factors, genetic factors were also important and the heritability estimates varied between 0.67 and 0.83. The heritability estimates were moderate to high for individual measures varying between 0.55 and 0.91 for anthropometric traits and between 0.39 and 0.89 for physical fitness tests (Table S4). No clear differences in the heritability estimates were found between children and adolescents.

Finally, we analyzed the correlations between somatotype components and physical fitness factors (Table 3). Both endomorphy and mesomorphy were associated with lower and ectomorphy with higher motor ability and cardiorespiratory endurance. For muscular strength, the associations were opposite and when endomorphy and mesomorphy were associated with higher, ectomorphy was associated with lower muscular strength. These associations were mainly due to the common genetic background, and genetic factors explained 85% or more of the associations. Genetic correlations were also higher than the trait correlations. Unique environmental correlations were generally lower and many of them were not statistically significant. One of the unique environmental correlations was opposite in sign to the trait correlation leading to the negative proportion of explained variation, but it was close to zero and not statistically significant. When similar analyses were done between somatotype and individual physical fitness tests,

TABLE 1 Descriptive statistics of anthropometric measures, somatotype components, and physical fitness measures by age and sex

	Younger than 12 years					12 years of age or older				
	Boys (n = 139)		Girls (n = 151)		*P* value of sex difference[a]	Boys (n = 71)		Girls (n = 71)		*P*-value of sex difference[a]
Variables	mean	SD	mean	SD		mean	SD	mean	SD	
Anthropometric measures										
Body weight (kg)	29.6	8.82	30.1	10.40	0.904	53.0	13.99	53.3	10.16	0.428
Height (cm)	129.4	12.31	129.2	12.57	0.316	160.2	11.93	157.1	7.21	0.003
Humerus diameter (cm)	5.3	0.59	5.0	0.51	0.001	6.5	0.51	5.8	0.32	< 0.001
Femur diameter (cm)	7.8	0.76	7.4	0.73	0.001	9.1	0.81	8.3	0.59	<0.001
Calf circumference (cm)	26.5	3.56	26.5	3.59	0.813	32.7	3.91	33.5	4.36	0.600
Upper arm circumference (cm)	20.4	3.23	20.1	3.39	0.274	25.7	3.86	25.3	3.08	0.155
Triceps skinfold (mm)	10.2	4.53	11.7	4.98	0.027	10.4	4.97	15.5	5.19	<0.001
Subscapular skinfold (mm)	7.8	5.10	10.1	6.10	0.003	10.2	6.18	15.1	7.52	0.001
Suprailiac skinfold (mm)	9.1	7.19	11.2	7.69	0.033	13.0	8.78	18.1	9.50	0.004
Calf skinfold (mm)	9.9	4.27	11.8	5.54	0.004	10.3	6.49	16.9	7.08	<0.001
Somatotype components										
Endomorphy	3.43	1.72	4.14	1.76	0.003	3.48	1.78	5.04	1.77	<0.001
Mesomorphy	4.57	1.08	3.98	0.89	<0.001	4.25	1.27	3.51	1.44	0.008
Ectomorphy	2.46	1.31	2.32	1.18	0.345	3.07	1.55	2.33	1.47	0.034
Physical fitness										
Flamingo balance (N of attempts)	24.8	6.65	25.2	6.29	0.506	15.5	7.73	15.5	7.24	0.853
Plate tapping (seconds)	20.0	5.44	19.9	4.67	0.876	13.0	2.26	13.1	2.46	0.298
Sit and reach (cm)	16.3	5.65	19.0	5.86	<0.001	14.8	7.26	20.2	8.32	0.003
Standing long jump (cm)	109.8	26.95	103.1	21.47	0.001	156.3	29.22	131.8	26.35	<0.001
Handgrip (kg)	12.9	5.04	11.5	4.86	<0.001	30.2	9.83	26.0	5.25	<0.001
Sit ups (N in 30 seconds)	13.4	6.81	11.5	5.81	0.005	21.4	5.41	17.5	5.01	<0.001
Bent arm hang (seconds)	4.8	5.85	3.0	3.24	0.008	17.4	15.10	4.7	4.81	<0.001
Shuttle run (seconds)	25.4	3.49	26.0	2.69	0.071	20.8	1.81	23.0	2.28	<0.001
Run/walk 12 minute (m)	1610	360	1440	341	<0.001	1922	643	1647	372	<0.001

[a] Adjusted for age.

the important influence of common genetic variation was also found (Table S4). However, because of less statistical power, the 95% confidence intervals were wide.

3 | DISCUSSION

In this study of Portuguese children and adolescents, we found that genetic factors explained a substantial proportion of individual differences in both somatotype and physical fitness traits: the genetic differences explained 80-93% of the variation in somatotype and 67-83% of the variation in physical fitness traits. The heritability estimates did not show any systematic differences between the children under 12 and the adolescents aged 12 years or more. There are a number of previous studies on the heritability estimates of physical fitness and a few studies on the heritability of somatotype components. A Portuguese family study reported a resemblance in somatotype components within siblings, indicating the effect of familial factors but did not report heritability estimates (Pereira et al., 2017). A Canadian family study reported heritability estimates varying between 0.56 and 0.64 (Katzmarzyk et al., 2000) whereas a family study from rural Mozambique reported lower heritability estimates varying between 0.30 and 0.40 (Saranga et al., 2008); these estimates are thus substantially lower than the estimates in our study. Family studies, however, typically produce lower heritability estimates than twin

TABLE 2 Additive genetic and unique environmental variance components with 95% confidence intervals of somatotype and physical fitness traits by age

	Younger than 12 years						12 years of age or older					
	Additive genetic factors			Unique environmental factors			Additive genetic factors			Unique environmental factors		
		95% confidence intervals			95% confidence intervals			95% confidence intervals			95% confidence intervals	
Traits	a^2	LL	UL	e^2	LL	UL	a^2	LL	UL	e^2	LL	UL
Somatotype												
Endomorphy	0.89	0.82	0.92	0.11	0.08	0.18	0.86	0.75	0.92	0.14	0.08	0.25
Mesomorphy	0.84	0.76	0.90	0.16	0.10	0.24	0.80	0.67	0.88	0.20	0.12	0.33
Ectomorphy	0.89	0.83	0.93	0.11	0.07	0.17	0.93	0.88	0.96	0.07	0.04	0.12
Physical fitness												
Motor ability and cardiorespiratory endurance	0.76	0.64	0.84	0.24	0.16	0.36	0.83	0.71	0.90	0.17	0.10	0.29
Muscular strength	0.67	0.54	0.77	0.33	0.23	0.46	0.73	0.57	0.83	0.27	0.17	0.43

Abbreviations: a^2, additive genetic factors; e^2, unique environmental factors; LL, lower limit; UL, upper limit.

studies, well shown for BMI (Elks et al., 2012), which may be because in family studies participants are typically measured at different ages when putative different genetic components may affect body composition as well as body shape. Interestingly, a small twin study (14 pairs) of females reported very similar heritability estimates (0.88-0.97) as in our study (Reis et al., 2007); however, this study lacks basic information on the cohort such as which geographic area the data were collected from. Two Belgian twin studies reported generally lower heritability estimates, varying between 0.21 and 0.86, than our study (Peeters et al., 2003, 2007); however, both studies estimated a shared environmental component, which we did not find in our study, which reduces heritability estimates. Previous results of the heritability of cardiorespiratory fitness (Miyamoto-Mikami et al., 2018) and muscle strength (Zempo et al., 2017) have been described in recent systematic reviews. Based on altogether 39 studies, these heritability estimates have been in general moderate varying between 0.49 and 0.68. They are thus somewhat lower than the heritability estimates for physical fitness in our study. However, there is considerable variation in how physical fitness has been measured in different studies. Thus, it is too early to argue whether there are systematic differences between countries, cultures, socioeconomic status, or other macro-level factors that could modify the heritability estimates of somatotype components or physical fitness traits. Taken together, these results, however, demonstrate the importance of genetic factors behind individual differences in both somatotype components and physical fitness traits.

When analyzing the individual anthropometric and physical fitness measures, we found largely expected differences between boys and girls. It is well known that females have more fat mass and males fat-free mass, even though the proportions may differ between populations (Wells, 2012). This sexual dimorphism increases during puberty, but is already present in early childhood (Wells, 2007). Accordingly, we found that humerus and femur diameters were broader in boys and all four skinfolds (triceps, subscapular, suprailiac, and calf) were thicker in girls. Correspondingly, boys were more mesomorphic and girls were more endomorphic in childhood and adolescence. These sex differences were already present in children but were larger in adolescents. As reported previously (Malina, Bouchard, & Bar-Or, 2004), the sex difference in fat-free mass was also seen in physical fitness measures; in our study, boys performed better in all tests reflecting muscle strength and cardiorespiratory fitness, whereas girls performed better in the sit and reach test. The differences were already present in prepubertal children, as also reported in a previous study (Marta, Marinho, Barbosa, Izquierdo, & Marques, 2012). Despite the sex differences in means, we did not find any sex differences in the genetics of anthropometric or physical fitness traits. This suggests that the mean differences in boys and girls are because of hormonal and other sex-specific differences affecting the expression of genes, but

TABLE 3 Trait correlations between somatotype and physical fitness and correlations between additive genetic and unique environmental variance components explaining these correlations

		Trait correlations			Additive genetic correlations				Unique environmental correlations			
			95% confidence intervals			95% confidence intervals				95% confidence intervals		
Trait 1	**Trait 2**	**r**	**LL**	**UL**	**r_A**	**LL**	**UL**	**% explained**	**r_E**	**LL**	**UL**	**% explained**
Younger than 12 years of age												
Motor ability and cardiorespiratory endurance	Endomorphy	−0.46	−0.56	−0.35	−0.49	−0.61	−0.36	88	−0.33	−0.54	−0.08	12
Muscular strength		0.30	0.18	0.41	0.33	0.17	0.49	86	0.22	−0.03	0.44	14
Motor ability and cardiorespiratory endurance	Mesomorphy	−0.27	−0.38	−0.14	−0.32	−0.48	−0.16	97	−0.04	−0.30	0.22	3
Muscular strength		0.37	0.25	0.47	0.50	0.33	0.65	103	−0.05	−0.29	0.21	−3
Motor ability and cardiorespiratory endurance	Ectomorphy	0.37	0.26	0.48	0.41	0.26	0.55	91	0.21	−0.05	0.45	9
Muscular strength		−0.37	−0.48	−0.26	−0.40	−0.54	−0.24	84	−0.32	−0.53	−0.07	16
12 years of age or older												
Motor ability and cardiorespiratory endurance	Endomorphy	−0.37	−0.52	−0.19	−0.39	−0.57	−0.17	88	−0.29	−0.57	0.03	12
Muscular strength		0.25	0.06	0.42	0.27	0.02	0.50	86	0.19	−0.15	0.48	14
Motor ability and cardiorespiratory endurance	Mesomorphy	−0.26	−0.42	−0.08	−0.28	−0.49	−0.05	88	−0.17	−0.46	0.15	12
Muscular strength		0.32	0.15	0.48	0.36	0.12	0.58	85	0.20	−0.11	0.48	15
Motor ability and cardiorespiratory endurance	Ectomorphy	0.29	0.11	0.45	0.29	0.08	0.48	89	0.28	−0.04	0.55	11
Muscular strength		−0.36	−0.51	−0.19	−0.37	−0.55	−0.15	84	−0.41	−0.64	−0.12	16

Abbreviations: LL, lower limit; *r*, trait correlation; r_A, additive genetic correlation; r_E, unique environmental correlations; UL, upper limit.

the genetic background of the body form is similar in both sexes.

The associations between somatotype and physical fitness measures were comparable to previous studies. We found that ectomorphy was associated with higher and both mesomorphy and endomorphy with lower motor ability and cardiorespiratory endurance. When studying muscular strength, the results were opposite: both mesomorphy and endomorphy were associated with higher and ectomorphy with lower muscular fitness. Additionally, in previous studies including physically active males (Ryan-Stewart et al., 2018) and members of a special police unit (Araújo, Cancela, Rocha-Rodrigues, & Rodrigues, 2019), similar associations for mesomorphy and ectomorphy were found showing that these associations are roughly similar in different populations.

Our most novel results concerned how a common genetic background explains the associations between somatotype and physical fitness measures. We found that around 90% of these associations were explained by genetic factors. Subsequently, the genetic correlations were higher than the trait correlations. When we studied how the somatotype components were associated with individual physical fitness tests, the results were largely similar. The confidence intervals were wide for individual tests, but generally, more than 80% of the associations were explained by genetic factors. These results show that somatotype components and physical fitness traits largely reflect the same genetic background, suggesting that the same set of genes affects these different traits. A plausible explanation for this common genetic background is that the same factors, such as muscle mass, underlie somatotype and physical fitness levels. Confirming this would need, however, detailed measures of body tissues available through, for example, computed tomography. Genome-wide association studies would also reveal genetic polymorphisms explaining variation in somatotype components and ratings as well as physical fitness levels and allow for calculating genetic correlations between them directly. A recent study of 195 180 participants identified 16 genome-wide significant loci associated with handgrip strength (Willems et al., 2017). However, expectedly, the effect sizes of them were modest (0.14-0.42 kg per allele). The genome-wide common variant heritability was estimated at 23.9% with a SE of 2.7%. This indicates that measured genes can account for a substantial fraction of the indirect twin-based estimate. The use of less common and rare variants will probably increase this proportion. Thus, very large studies are needed if a proportion of the common genetic variance identified by a twin design can be allocated to candidate genes.

Our results on the central role of genetic factors behind the variation of somatotype components and physical fitness traits, as well as their mutual associations, have potential policy implications, but they are not straightforward. The high genetic proportion suggests that some children may be more prone to specific tasks required in certain types of sports and may also show more rapid progress in their response to training. This is supported by previous results indicating that ectomorphic and mesomorphic children (Marta et al., 2013) and adults (Chaouachi et al., 2005) tend to display better gains during aerobic fitness training. In light of our results, it is very likely that genetic factors are behind these associations. This can lead children who find physical exercise training most rewarding to both self-select to environments supporting physical exercise, such as sport clubs, and to get support from others, such as physical education teachers. These selection mechanisms are called as active and reactive gene-environment correlations (Jaffee & Price, 2007), and they can notably increase genetic variation during child and adolescence development. Thus, many policy interventions to improve physical exercise can strengthen genetic variation. In some cases, such as when selecting the most talented children to become elite athletes, this is probably a desired strategy. However, in general sport education, it is important to consider that genetically less talented children may need more encouragement from physical education teachers so that they can benefit from the health effects of adequate physical fitness levels.

Our data have some strengths and weaknesses. Our main strength is that we had both somatotype and physical fitness measures available in genetically informative data allowing us to evaluate the common genetic background of these traits. We are not aware that this research question has been analyzed before. Also, in general, genetic studies in Southern European populations are less common compared to Northern European and North American populations of European ancestry. The main weakness of the current study is that the sample size is too small to analyze in detail how the genetic architecture of somatotype components, physical fitness, and their mutual associations change during development. Thus, we needed to divide our data into two broad age categories, but did not find systematic differences between them. It is quite possible that if more data had been available, it might have revealed differences between ages such as has been previously found for height (Jelenkovic et al., 2016) and body mass index (Silventoinen et al., 2016). Such analyses may be enabled by pooling data from different cohorts and studies. The test-retest analysis in a pilot sample showed good reliability of our measures but such as in all empirical research they include also measurement error. In our genetic modeling, the measurement error is modeled as part of unique environmental variation, and thus our estimates of heritability show the lower limit of genetic influence. In bivariate analyses, the trait correlations are likely to be underestimated because of measurement error, but they do not have effect on the results of the proportion of trait variation explained by genetic and unique environmental factors.

In conclusion, we found that somatotype components are moderately associated with performance in tested physical fitness factors. Ectomorphic children and adolescents performed better in tests measuring motor ability and cardiorespiratory endurance components, and their mesomorphic and endomorphic peers in tests measuring muscular strength. These associations reflected the influence of common genetic factors. In schools, clubs, or other institutions, it is important to consider that children's performance in physical fitness tests can partly reflect their inherited anthropometric characteristics. Those children and adolescents whose physique may be less optimal for certain kinds of sports may need adequate encouragement and training from physical education teachers to obtain the benefits from adequate physical fitness levels.

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CONFLICT OF INTEREST

The authors declare no potential conflict of interest.

AUTHOR CONTRIBUTIONS

Karri Silventoinen: Formal analysis; writing-original draft. **José Maia:** Conceptualization; writing-review and editing. **Aline Jelenkovic:** Writing-review and editing. **Sara Pereira:** Writing-review and editing. **Élvio Gouveia:** Resources; writing-review and editing. **António Antunes:** Writing-review and editing. **Martine Thomis:** Conceptualization; resources; writing-review and editing. **Johan Lefevre:** Conceptualization; resources; writing-review and editing. **Jaakko Kaprio:** Writing-review and editing. **Duarte Freitas:** Conceptualization; resources; writing-original draft.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of this article.

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