



Review

Stature is the key: A systematic review and meta-analysis on the role of stature and body mass in physical fitness through allometric modeling

Matteo Giuriato^a, Nicola Lovecchio^b, Matteo Vandoni^a, Alessandro Gatti^{a,c,*}, Alan M. Nevill^{d,1}^a Laboratory of Adapted Motor Activity (LAMA), Department of Public Health, Experimental Medicine and Forensic Science, University of Pavia, Italy^b Department of Human and Social Sciences, University of Bergamo, Italy^c National PhD Programme in One Health approaches to infectious diseases and life science research, Department of Public Health, Experimental and Forensic Medicine, University of Pavia, Italy^d Faculty of Education, Health and Wellbeing, University of Wolverhampton, United Kingdom

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ABSTRACT

Objectives: To evaluate how stature and body mass influence youth physical fitness performance across different test modalities using allometric modeling, and to quantify domain-specific allometric exponents for stature and body mass.

Design: Systematic review and meta-analysis.

Methods: A comprehensive literature search was conducted in PubMed and Web of Science (July 2024; CRD420251030848). Sixteen cross-sectional studies involving youth populations (aged 7–19 years) met inclusion criteria. Extracted allometric exponents for stature and body mass were synthesized across four fitness domains: cardiorespiratory fitness, upper-limb strength, lower-limb explosive strength, and speed–agility. Random-effects meta-analyses were performed using Restricted Maximum Likelihood estimation. Heterogeneity was assessed via I^2 and Cochran's Q .

Results: Stature showed a consistently positive association with performance across all domains, with allometric exponents ranging from 0.40 to 1.39 ($p < 0.001$). Body mass demonstrated divergent patterns: negative exponents for cardiorespiratory fitness (boys: -0.24 ; girls: -0.22), explosive strength, and speed–agility; but positive associations for upper limb strength (boys: 0.31; girls: 0.30). All models showed high heterogeneity; moderation and sensitivity analyses confirmed test-type-independent results.

Conclusions: Stature shows a consistent positive association with physical fitness independently of test modalities, whereas body mass exponents are domain-specific, negative in weight-bearing tasks and positive in upper-limb strength. These pooled estimates suggest clear trends in size–performance scaling, though substantial heterogeneity and the absence of independent model validation limit their generalizability. Allometric modeling remains a useful approach to reduce size-related bias when applied alongside sport-specific and developmental considerations.

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Practical implications

Height helps across the childhood: Taller kids tend to perform better in endurance, jumping, sprinting, and strength tests because slim subject of both sexes usually make movement more efficient.

Weight is a double-edged sword: Extra body mass can hurt running, jumping, and agility (probably, because you're moving more weight), but it helps in tasks like grip strength where mass supports force (probably lean body mass).

Fair comparisons matter: Using smarter ways to account for body size avoids unfairly penalizing bigger kids in fitness testing.

Context is everything: A child and adolescent's size can be an advantage or disadvantage depending on the sport or activities, there's no single "ideal" body type.

1. Introduction

Long-term athlete development is a complex process influenced by growth and biological maturation.¹ However, youth development follows an individualized, non-linear, and sex-specific trajectory.

This makes elite performance prediction challenging.^{2,3} This complexity arises partly because human growth itself is non-linear, characterized by asynchronous maturation of different anatomical structures, significantly impacting body composition and motor skills.^{4,5} In this context, anthropometric traits such as greater stature or larger muscle mass are not universally disadvantageous. Indeed, in several sports, such as

* Corresponding author.

E-mail address: alessandro.gatti08@universitadipavia.it (A. Gatti).¹ These authors contributed equally as senior (last) authors.

volleyball, rowing, or basketball, greater stature and segment length are directly advantageous, improving reach, stroke length, or leverage.¹ Similarly, increased muscle mass can mean greater force production, a desirable attribute in strength-oriented disciplines.⁵ The challenge arises when these traits are combined with higher motor potential in youth populations, especially in sports where size per se is not a limiting factor. In such cases, inappropriate ratio scaling can obscure true athletic talent.

Thomis and Towne⁶ demonstrated the significant role of genetics, with stature being highly heritable (~80%), while body mass is more environment-dependent (~40%). Lean mass shows 60–90% heritability, and maturation timing varies, with genetic factors accounting for 50–90% of its variability.⁶ It is widely acknowledged that body size has a significant impact on human performance. For instance, in adolescents, increases in absolute VO_2 peak are closely linked to body mass growth (reported correlations $r \approx 0.70$ – 0.85),⁷ which is influenced by developmental changes in the lungs, heart, and skeletal muscle mass.^{8,9} Although stature correlates moderately to strongly with lean body mass in youth populations (e.g., $r \approx 0.65$ – 0.80 reported in cross-sectional cohorts),^{1,10,11} using stature as a predictor for lean mass can introduce biases in growth-related analyses.¹²

Traditional ratio-based scaling methods further compound these biases, disproportionately disadvantaging heavier athletes.^{13,14} Consequently, more accurate techniques, such as allometric modeling, have been strongly recommended in the literature.

However, they remain inconsistently applied in practice.^{13,15} Allometric modeling offers a more effective solution by accounting for the non-linear relationships between body size and fitness performance tests, reducing heteroscedastic errors, and improving data normalization.⁹

Indeed, allometric modeling provides a dimensionless representation of data, facilitating comparisons across groups with varying sizes, structures, and body shapes.¹⁰ The basic allometric model, $Y = aX^b \cdot \epsilon$, describes a curvilinear relationship between a physiological variable (Y) and an anthropometric measure (X), where the exponent b defines the nature of the relationship: if $b < 1$, Y increases at a slower rate than X; if $b > 1$, Y increases more rapidly.¹⁶ Since body size and shape can influence human motor performance, adjusting physical and motor performance metrics based on body physique components enables more accurate individual and group comparisons.¹⁴ This approach enhances the interpretation of individual differences and improves the scaling of physiological data in pediatric studies.

For example, Nevill et al.¹⁰ demonstrated in Greek schoolchildren (~12 years old) that, in a 20 m endurance shuttle run test, the negative exponent for mass (-0.160) indicated that greater body mass penalizes performance. Conversely, the positive exponent for stature (0.481) suggested that taller individuals perform better. Despite evidence demonstrating the influence of body size on physical fitness through allometric modeling, consensus remains elusive regarding the relative role of stature and body mass across various fitness domains and populations. Although including data from different groups can improve generalizability, it can also increase variability and should be interpreted carefully.

This study aims to fill this gap by synthesizing existing evidence using allometric modeling, while recognizing the heterogeneity that arises from combining studies in different settings. Rather than offering a definitive tool, our findings provide pooled estimates of allometric exponents that can inform the use of scaling methods in youth fitness contexts, especially for practitioners aiming to adjust for body size differences in group assessments.

2. Materials and methods

2.1. Study design

This protocol for the systematic review and meta-analysis was registered in the International Prospective Register of Systematic Reviews (PROSPERO) under the registration number CRD420251030848. The process adhered to the guidelines outlined in the Cochrane

Collaboration Handbook¹⁷ and other key methodological references appropriate for conducting systematic reviews and meta-analyses.^{18,19} The reporting of findings followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines.²⁰ The detailed checklist is provided in Table S1.

2.2. Study eligibility

2.2.1. Inclusion criteria

The primary outcome measure was the estimated static allometric exponent for body mass and stature to scale the outcome of the fitness test. To be selected for quantitative synthesis, studies had to meet all the following criteria: (1) fitness test data were collected from children and adolescents; (2) the research had a cross-sectional design; (3) the allometric exponent was originally derived from the examined sample; (4) either the allometric coefficient (e.g., b), standard deviation (SD), and standard error (SE), or Pearson's correlation coefficient (r) for the allometric model was reported; and (5) details relevant to the identified moderator variables were outlined. The target population included children and adolescents. Only studies that reported empirically derived allometric exponents for both stature and body mass within the same sample were included. Studies that reported ratio-scaled indices, or that provided an exponent for only one dimension (e.g., stature alone or body mass alone) were excluded.

2.2.2. Exclusion criteria

Studies were excluded if: (1) The primary analysis focused solely on ontogenetic allometry in the context of individual development, without an allometric application to specific groups such as children and adolescents; (2) the static exponents were derived from a longitudinal or mixed-longitudinal study; (3) a power function scaling was not performed; (4) power law-based exponents were adopted a priori rather than being derived empirically; (5) the sample and results were identical to a previous publication (duplication); and (6) the full-text manuscript was written in a language other than English.

2.3. Literature search and study selection

The literature search was conducted in PubMed and Web of Science in July 2024. The search targeted studies involving children and adolescents (approximately 7–19 years) and focused on the relationship between body size (i.e., stature and body mass) and physical fitness outcomes using allometric modeling techniques. Keywords included terms related to pediatric populations (e.g., “children,” “adolescents,” “youth”), fitness performance (e.g., “cardiorespiratory fitness,” “ VO_2max ,” “shuttle run test”), anthropometric traits (e.g., “stature,” “body mass,” “BMI”), and scaling methodologies (e.g., “allometry,” “allometric modeling,” “biological scaling”). The complete search string for PubMed is provided in the Supplementary materials (Table S2). Only articles published in English and involving human participants were considered. After removing duplicates, two independent reviewers (AG and MG) screened all titles and abstracts for relevance, followed by full-text assessment of eligible articles. Any discrepancies in study selection were resolved through discussion with a third and fourth reviewer (NL, AMN). Inter-rater reliability during screening was assessed using Cohen's Kappa, obtaining 0.904 and 0.760 for title/abstract and full-text screening, respectively, indicating substantial to almost perfect agreement. All the study selection process was conducted using the Rayyan software.²¹ The review process adhered to PRISMA guidelines, with a detailed overview presented in Fig. 1. Descriptive statistics for studies included in the meta-analysis are shown in Table 1.

2.4. Data extraction and study outcomes

A standardized data extraction protocol, data extraction form (through Excel) and accompanying codebook were developed

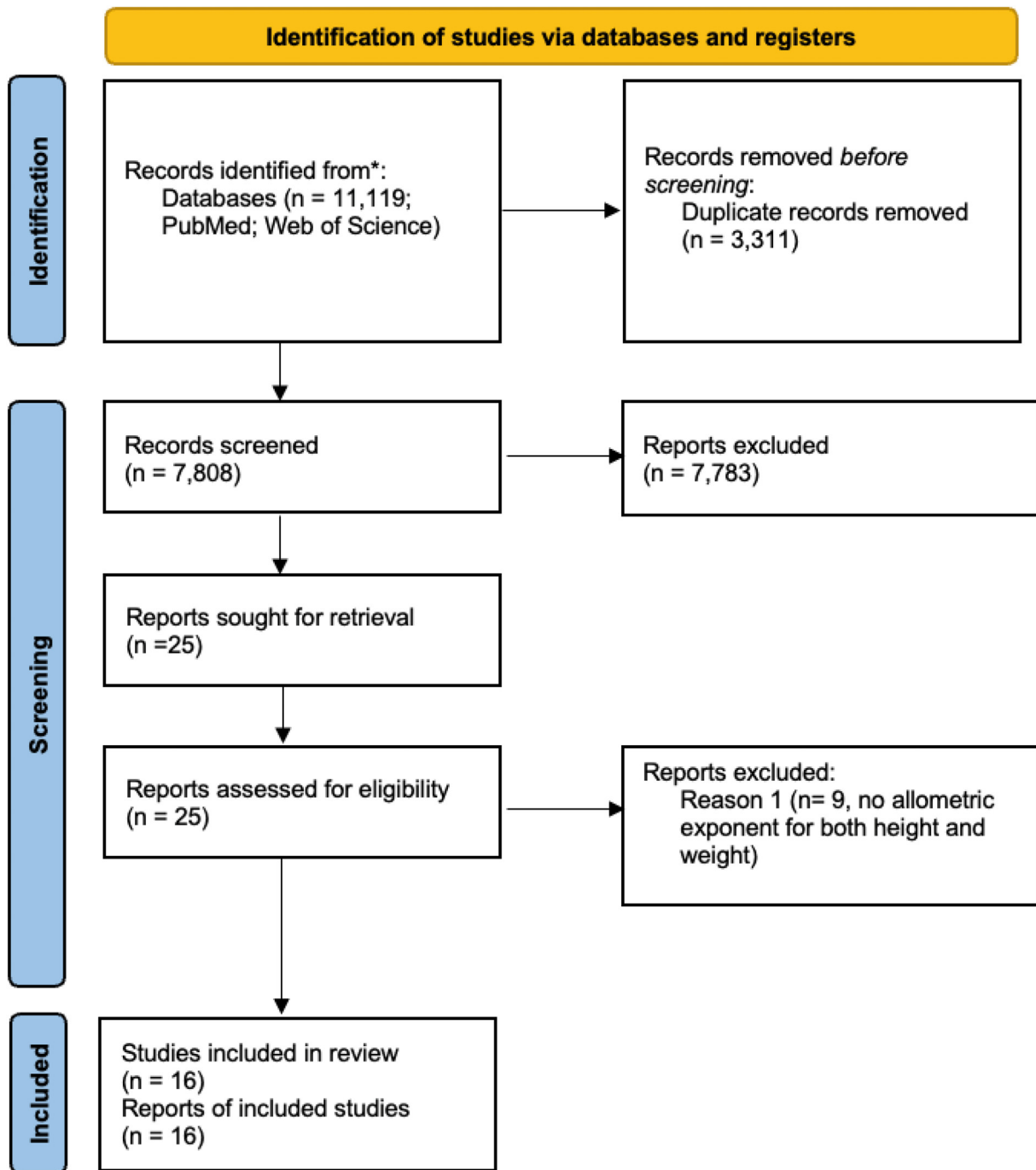


Fig. 1. Flow diagram of the systematic review process. All the studies sought for full text access were eligible and assessed for eligibility.

specifically for this review on allometric scaling and physical fitness. Two independent reviewers (AG and MG) extracted data from the eligible studies, with arbitration provided by a third reviewer (NL) in the case of discrepancies. The primary outcomes of interest were the estimated allometric exponents for body stature and body mass across a variety of physical fitness tests (e.g., cardiorespiratory fitness, muscle strength, explosive power, and speed–agility). Extracted data included extrinsic variables (study author, year of publication), substantive variables (participant age, sex, sample size, anthropometric measures, and type of physical test), and methodological variables (study design, derivation method of allometric exponent, and reported statistics such as standard deviation or confidence interval). Secondary outcomes included subgroup analyses by sex and test type, as well as the examination of heterogeneity and consistency across study results.

2.5. Methodological quality

To assess the methodological quality of the included cross-sectional study, we employed the Critical Appraisal Skills Programme (CASP) checklist for descriptive/cross-sectional studies. This tool provides a structured framework for evaluating key aspects of study design, execution, and reporting, ensuring a rigorous and transparent assessment of the study's validity and reliability. The CASP checklist consists of ten key questions addressing the following domains: (1) clarity of the research question, (2) appropriateness of the study design, (3) recruitment strategy, (4) accuracy of measurements, (5) data collection methods, (6) sample size adequacy, (7) presentation and interpretation of results, (8) rigor of data analysis, (9) clarity of findings, and (10) applicability of results to the target population. Each item was evaluated using a

Table 1
Descriptive characteristics of the studies included in the systematic review.

Study	Participants characteristics				
	Sex	Sample size	Age (years)	Body mass (kg)	Stature (cm)
Giuriato et al. ¹¹	Boys	282	11–13	46.5 ± 10.3	155.6 ± 10.1
	Girls	247	11–13	45.5 ± 9.5	154.5 ± 8.9
Nevill et al. ⁴⁴	Boys	158	9–17	47.0 ± 12.7	153.3 ± 14.8
	Girls	148	9–17	44.3 ± 10.9	147.7 ± 10.7
Batista et al. ⁴⁵	Boys	49	12 ± 1	46.0 ± 11.2	150.9 ± 7.1
	Girls	/	/	/	/
Nevill et al. ¹⁰	Boys	384	12 ± 1	49.1 ± 11.5	153.0 ± 8.0
	Girls	324		49.4 ± 11	154.0 ± 7.0
Silva et al. ⁴⁶	Boys	2175	9–15	44.1 ± 12.3	148.0 ± 13.1
	Girls	2385	9–15	43.0 ± 10.7	146.2 ± 10.1
Dos Santos et al. ⁴⁷	Boys	1872	10–15	Not reported	Not reported
	Girls	2354	10–15	Not reported	Not reported
Valdivia et al. ⁴⁸	Boys	1669	11–17	54.2 ± 12.3	157.1 ± 11.2
	Girls	1955	11–17	50.3 ± 9.4	151.5 ± 6.4
Giuriato et al. ⁴⁹	Boys	3972	8–11	80.4 ± 16.3	136.8 ± 7.4
	Girls	3815	8–11	34.0 ± 7.5	137.1 ± 6.7
Giuriato et al. ⁴³	Boys	401	14–19	Not reported	Not reported
	Girls	331	14–19	Not reported	Not reported
Lovecchio et al. ⁵⁰	Boys	3058	11–14	56.8 ± 13.0	162.1 ± 10.8
	Girls	4044	11–14	52.0 ± 11.6	159.3 ± 8.23
De Marco et al. ⁵¹	Boys	744	15–17	63.2 (56.6–72.7)	175.0 (169.0–182.0)
	Girls	744	15–17	54.6 (48.3–63.8)	163.0 (157.0–170.0)
Sandercock et al. ⁵²	Boys	471	10–11	37.1 ± 8.1	143.6 ± 7.7
	Girls	445	10–11	37.8 ± 7.5	143.8 ± 7.5
Nevill et al. ⁵³	Boys	17,677	14–16	54.9 ± 9.5	164.8 ± 7.2
	Girls	20,421	14–16	53.2 ± 8.5	156.4 ± 5.7
Ndabi et al. ³⁷	Boys	1028	11–14	46.0 ± 11.8	164.8 ± 7.2
	Girls	962	11–14	46.8 ± 11.3	152.5 ± 9.3
Nevill et al. ⁵⁴	Boys	5147	7–17	46.3 ± 16.4	151.2 ± 16.9
	Girls	5871	7–17	45.4 ± 14.1	149.5 ± 13.7
Nevill et al. ⁵⁵	Boys	396	8–15	43.6 ± 13.8	150.4 ± 14.1
	Girls	201	8–15	45.3 ± 14.4	149.9 ± 10.7

Note: kg: kilograms; cm: centimeters; age was presented as age range (minimum–maximum age) or as mean age ± standard deviation; body mass and stature are presented as mean ± standard deviation or as mean (95 % confidence intervals).

standardized response format: “Yes,” “No,” or “Can’t tell.” The final appraisal considered the overall strengths and limitations of the study, with particular attention to potential sources of bias and methodological robustness. Question 11, which pertains to the broader value of the research, was not included in our assessment as it falls outside the scope of our methodological evaluation. The results of the methodological quality evaluation are shown in Fig. S1.

2.6. Statistical analysis

A random-effects meta-analysis using a two- or three-level model, depending on whether multiple effect sizes were reported within the same study, was then conducted, using the inverse variance method to weight each study’s contribution. The Restricted Maximum Likelihood (REML) method was employed to estimate between-study variance (τ^2). Forest plots were generated to visually represent each study’s exponent estimate and corresponding 95 % confidence interval (CI) (also presented from Tables S3 to S6). Heterogeneity among the included studies was assessed using Cochran’s Q test and the I^2 statistic, with I^2 values categorized as follows: might not be important (0–40 %), moderate (30–60 %), substantial (50–90 %), and considerable (75–100 %) heterogeneity. p-Values are reported as absolute values and interpreted on a scale of compatibility with the test hypothesis, while also considering the point estimate, 95 % confidence intervals, and heterogeneity. To explore potential sources of variability, moderation analyses were performed, testing whether the test used systematically influenced scaling exponents. To better understand the source of heterogeneity, supplementary analyses were conducted. Leave-one-out sensitivity analyses were performed to evaluate the influence of individual studies on the overall estimates. Funnel plots and Egger’s regression

tests were used to visually and statistically assess potential publication bias. Influence diagnostics, including Cook’s distance, standardized residuals, leverage (hat values), and DFFITS, were computed to detect overly influential or outlying studies. All analyses were conducted using R software, version 4.4 (R Foundation for Statistical Computing) and the “metafor” package was used to perform the meta-analysis. Forest plots were generated to visualize the pooled exponent and their corresponding weights across studies.

3. Results

The systematic search and study selection process is illustrated in the PRISMA flow diagram (Fig. 1). After removing 3311 duplicate records, 7808 records identified through databases (PubMed and Web of Science) were screened by title and abstract. A total of 7783 records were excluded during this stage due to various reasons, including the absence of allometric analysis, trial design issues, randomization or use of animal models. Following this, 25 full-text articles were assessed for eligibility. At this stage, 9 reports were excluded because they did not report allometric exponents for both stature and body mass. Ultimately, 16 studies met the inclusion criteria and were included in the systematic review. All 16 were also included in the synthesis.

The body mass and stature exponents for cardiorespiratory fitness tests (CRF) in girls and boys are shown in Fig. 2. For both boys and girls, the pooled body mass exponents were negative (girls estimated exponent (EE) = -0.22 , 95 % CI = -0.30 , -0.15 , $p < 0.001$; boys EE = -0.24 , 95 % CI = -0.32 , -0.16 , $p < 0.001$), suggesting an inverse relationship with CRF. Conversely, the pooled stature exponents for both boys and girls were positive (girls EE = 0.70 , 95 % CI = 0.47 , 0.94 , $p < 0.001$; boys EE = 0.87 , 95 % CI = 0.64 , 1.09 , $p < 0.001$). However, we found high heterogeneity across the studies’ results ($I^2 > 75$ %). Leave-one-out sensitivity analyses (Figs. S2–S5) indicated that no single study had a disproportionate impact on the pooled estimates for either boys or girls. Funnel plots (Figs. S18–S21) revealed minor asymmetry, with Egger’s test suggesting potential small-study effects in some models ($p < 0.05$ for select comparisons). Influence diagnostics (Figs. S34–S37) identified one to two studies with elevated Cook’s distance or standardized residuals, but their exclusion did not meaningfully affect the pooled exponents or heterogeneity estimates. Moderation analyses indicated that test type did not significantly moderate either body mass or stature exponents in boys or girls ($p > 0.14$). While the Leger test showed a marginally stronger positive association between body mass and CRF in girls ($\beta = 0.24$, $p = 0.024$), this effect was not consistent across models.

The body mass and stature exponents for upper limb MS in girls and boys are shown in Fig. 3. For both boys and girls, the pooled body mass exponents were positive (girls EE = 0.30 , 95 % CI = 0.25 , 0.35 , $p < 0.001$; boys EE = 0.31 , 95 % CI = 0.26 , 0.30 , $p < 0.001$), suggesting a direct relationship with upper limb MS. Additionally, the pooled stature exponents for both boys and girls were positive (girls EE = 1.26 , 95 % CI = 0.93 , 1.59 , $p < 0.001$; boys EE = 1.39 , 95 % CI = 1.21 , 1.56 , $p < 0.001$). However, we found high heterogeneity across the studies’ results ($I^2 > 75$ %). Leave-one-out analyses (Figs. S6–S9) confirmed the pooled estimates, with no single study disproportionately influencing the overall exponent. Funnel plots (Figs. S22–S25) showed mild asymmetry, specifically among boys, though Egger’s tests did not indicate strong evidence of publication bias. Influence diagnostics (Figs. S38–S41) identified a few moderately influential studies, but their impact on model estimates and heterogeneity was minimal. The moderation analysis was not performed since all the exponents were assessed on the same test (handgrip test).

The body mass and stature exponents for explosive strength in girls and boys are shown in Fig. 4. For both boys and girls, the pooled body mass exponents were negative (girls EE = -0.30 , 95 % CI = -0.36 , -0.25 , $p < 0.001$; boys EE = -0.31 , 95 % CI = -0.37 , -0.25 , $p < 0.001$), suggesting an indirect relationship with explosive strength. Additionally, the pooled stature exponents for both boys and girls were positive (girls EE = 1.16 , 95 % CI = 1.04 , 1.27 , $p < 0.001$; boys EE =

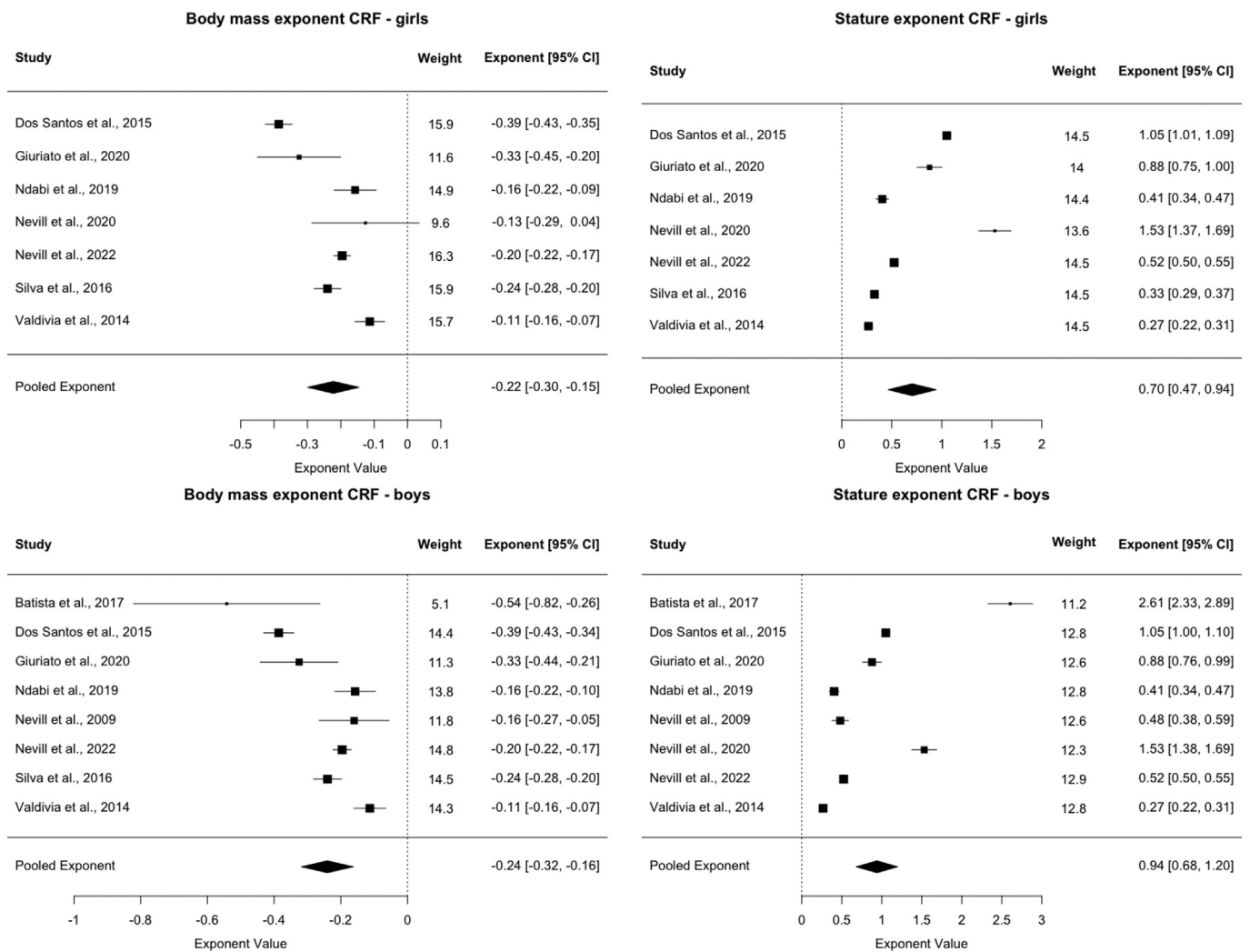


Fig. 2. Forest plot of estimated exponent value for weight and stature in cardiorespiratory fitness tests in both girls and boys. A negative value indicates that the weight or stature is inversely related to the performance, whereas a positive exponent indicates a direct relationship. Abbreviation: CI, confidence interval.

1.13, 95 % CI = 1.01, 1.24, $p < 0.001$). However, we found high heterogeneity across the studies' results ($I^2 > 75\%$). Leave-one-out analyses (Figs. S10–S13) demonstrated that no single study excessively influenced the pooled estimates. Funnel plots (Figs. S26–S29) showed reasonably symmetrical distributions, with minor asymmetry observed in some panels. Influence diagnostics (Figs. S42–S45) identified one or two studies with elevated Cook's distance or leverage, though overall model performance was consistent across all comparisons. Moderation analyses for explosive strength revealed that test type significantly moderated the body mass exponent in both boys ($QM = 18.07$, $p = 0.0012$) and girls ($QM = 12.95$, $p = 0.012$). Specifically, higher exponents were observed in the Five Jump and Standing Long Jump tests (e.g., boys: $\beta = 0.31$ and 0.19 , respectively), indicating that body mass had a higher positive influence on performance in these tests. In contrast, no significant moderation was found for the stature exponent (boys: $p = 0.325$; girls: $p = 0.306$), suggesting that height's contribution to explosive strength remained stable across test types. However, these findings should be interpreted with caution, as the distribution of test types across studies was unbalanced, with some tests (Standing Broad Jump) heavily overrepresented and others (Five Jump, Squat Jump, Countermovement Jump, and Vertical Jump) included in only one study.

The body mass and stature exponents for speed–agility in girls and boys are shown in Fig. 4. For both boys and girls, the pooled body mass exponents were negative (girls $EE = -0.15$, 95 % CI = -0.25 , -0.05 , $p = 0.002$; boys $EE = -0.15$, 95 % CI = -0.25 , -0.06 , $p =$

0.002), suggesting an indirect relationship with explosive strength. Additionally, the pooled stature exponents for both boys and girls were positive (girls $EE = 0.40$, 95 % CI = 0.32 , 0.47 , $p < 0.001$; boys $EE = 0.40$, 95 % CI = 0.32 , 0.47 , $p < 0.001$). However, we found high heterogeneity across the studies' results ($I^2 > 75\%$). Leave-one-out analyses (Figs. S14–S17) indicated that no single study had an undue influence on the pooled estimates. Funnel plots (Figs. S30–S33) displayed general symmetry, though Egger's test suggested potential publication bias in the body mass analysis for boys ($p = 0.018$). Influence diagnostics (Figs. S46–S49) did not identify any critical outliers; most studies exhibited moderate leverage and Cook's distance, indicating no disproportionate impact on the overall model. Moderation analyses revealed that test type did not significantly affect the body mass exponent in either boys or girls ($p > 0.97$). In contrast, test type significantly moderated the stature exponent ($p < 0.001$), with higher values observed in linear sprint tests (30 m and 40 m), suggesting that stature contributes more to performance in these assessments (Fig. 5).

4. Discussion

The results of our review synthesize existing evidence on how body mass and stature are associated with physical fitness performance in children and adolescents through allometric modeling. The estimated exponents for body mass and stature differed across physical fitness dimensions, suggesting that the strength and, in some cases, direction of

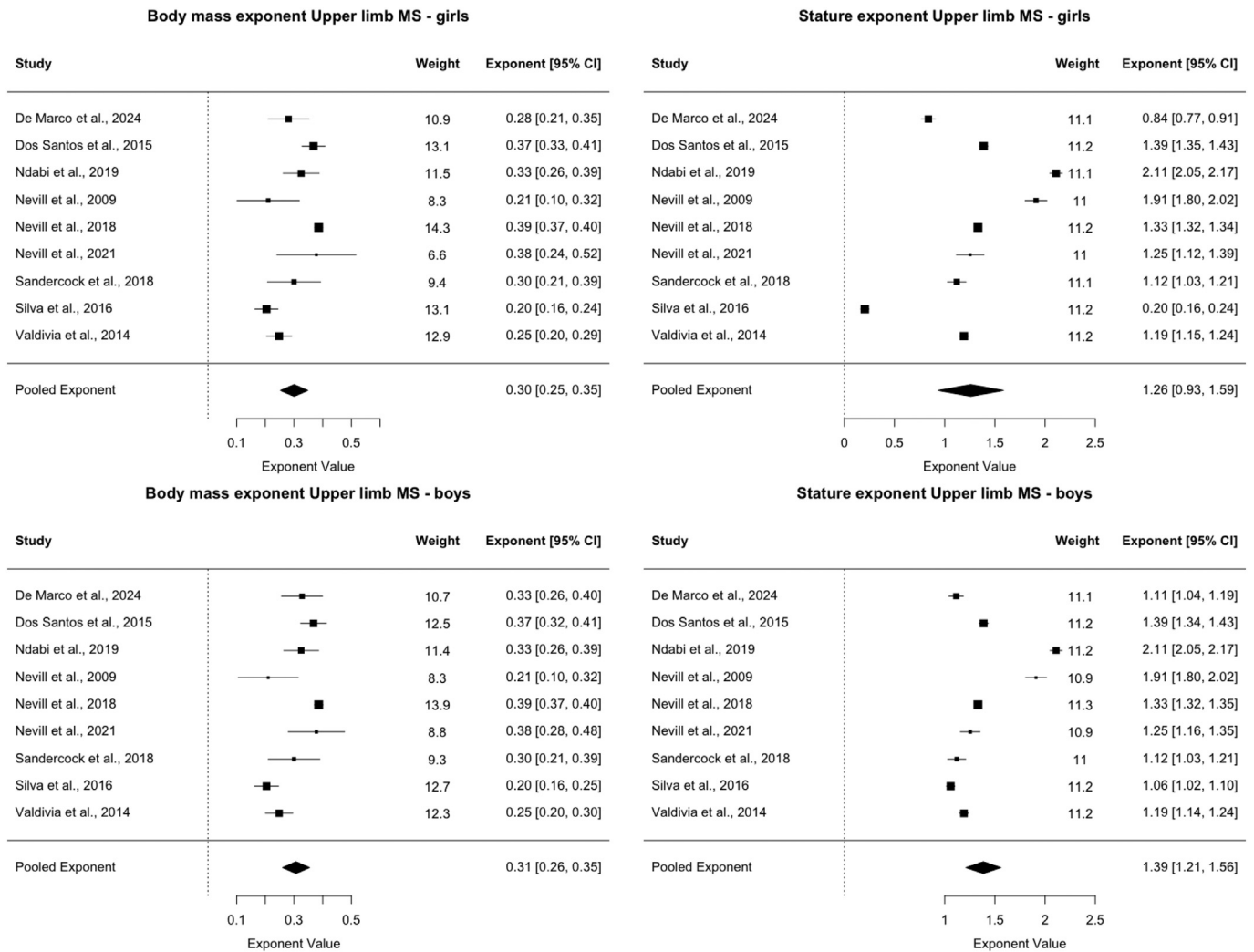


Fig. 3. Forest plot of estimated exponent value for weight and stature in upper limb strength (handgrip test) in both girls and boys. A negative value indicates that the weight or stature is inversely related to the performance, whereas a positive exponent indicates a direct relationship. Abbreviation: CI, confidence interval.

these associations are domain-specific. However, we have found high heterogeneity between studies, and, for this reason, our exponents should be interpreted with caution. The stature exponent was consistently positive across all tests, while the body mass exponent changed direction in the relationship depending on the physical fitness domain considered. While Caspersen et al.²² categorized physical fitness into five fundamental components (cardiorespiratory endurance, muscular strength, speed, flexibility, and body composition), our classification further included biomechanical considerations. Specifically, we distinguished between tests that require active support and displacement of body mass (weight-bearing) versus those involving minimal or none whole-body movement (non-weight-bearing).²³ This distinction is critical for allometric modeling, as body mass represents a mechanical constraint in weight-bearing activities and can lead to systematic biases in analyses. Consistently with this reasoning, our results showed that the body mass exponent was negatively associated with weight-bearing tasks and positively associated with non-weight-bearing tasks such as upper-limb strength (handgrip). For CRF, the negative exponent may reflect the “additional load” that excess body mass places on children and adolescents during endurance performance, which leads to a negative impact on aerobic performance.²⁴ This effect is relevant in tests with repeated accelerations, decelerations, and directional changes, such as the Yo-Yo intermittent recovery or agility-based shuttle runs, where the mechanical burden of non-functional mass is amplified.²⁵ Furthermore, the negative exponents reported may partially reflect the

composition of body mass. While total mass encompasses both functional (lean) tissue and non-functional (fat) tissue, only lean mass positively contributes to force production. If lean mass was considered in the allometric modeling, the exponent may be shifted toward a positive value, as previously suggested in compositional analyses of youth athletes.^{26,27} Unfortunately, none of the included studies reported lean or muscle mass exponents. Consequently, given the relevant role of lean mass in physical fitness, future studies should employ the allometric approach to analyze the impact of lean mass on physical fitness tests.

This interplay between body composition and task-specific demands also has implications for underlying physiological efficiency, as excess fat mass not only hinders mechanical performance but may also disrupt metabolic processes during exercise.^{28,29}

Our results indicate that even in speed–agility tests the weight exponent remained inversely related to performance. Different authors showed a close relationship between body composition and the ability to change direction, finding an inverse correlation ($r = -0.8$) between body fat percentage and performance in COD tests.³⁰ Athletes with a lower body fat percentage tended to complete change-of-direction tasks more quickly. Indeed, the force they need to apply to the ground is influenced by their mass, their velocity as they approach the change, and the sharpness of the directional shift.³¹ Similarly, an athlete with a greater mass will require more energy to increase initial speed and, for the same amount of force applied, will accelerate more slowly than a lighter athlete. In lower limb explosive strength tests, the negative

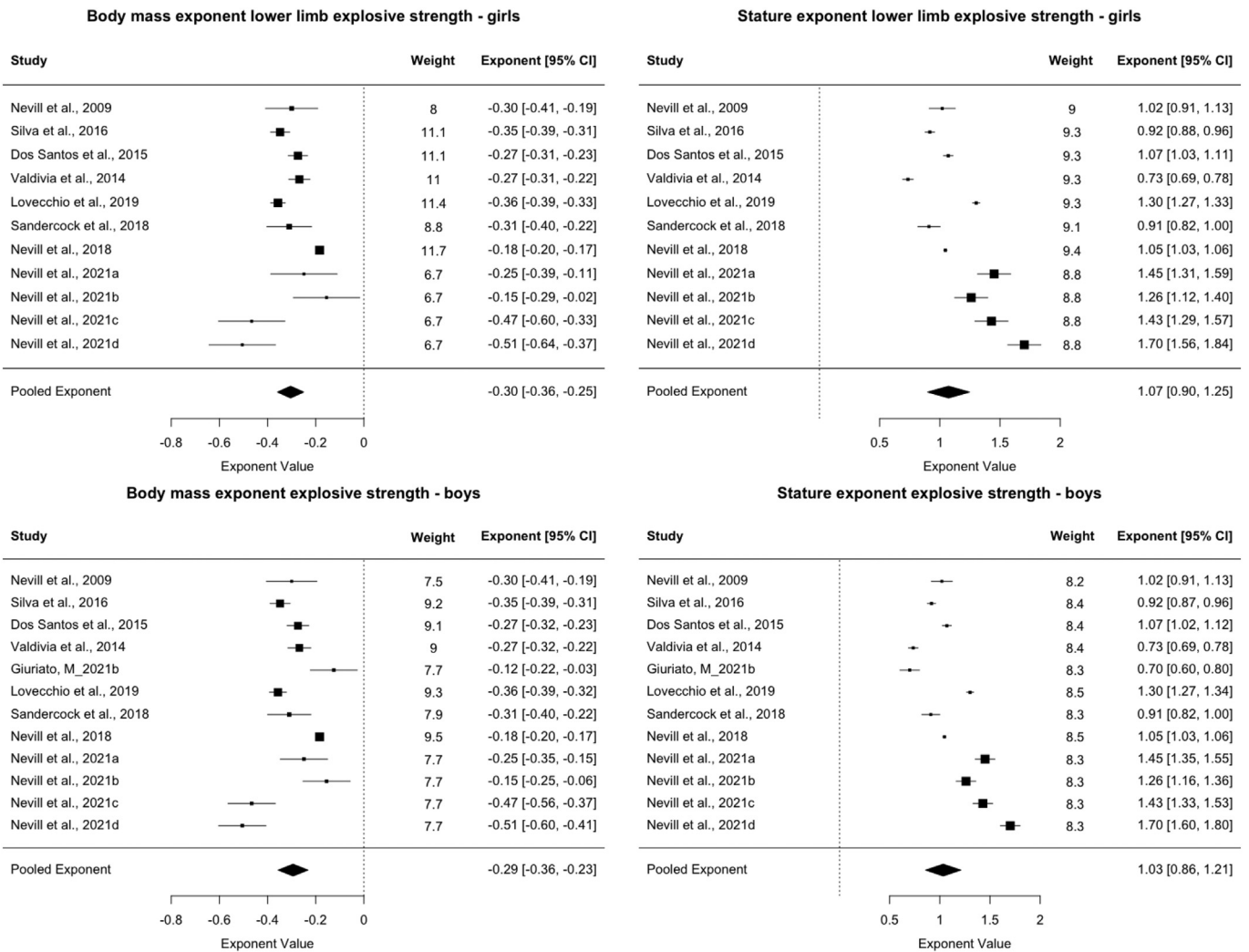


Fig. 4. Forest plot of estimated exponent value for weight and stature in lower limb explosive strength in both girls and boys. A negative value indicates that the weight or stature is inversely related to the performance, whereas a positive exponent indicates a direct relationship. Abbreviation: CI, confidence interval.

exponent could be explained by Buccheit et al.²⁹ who have shown that an increase in fat mass was associated with low results in a vertical jump in adolescents. Additionally, relative strength (force per unit mass) is crucial for the first phase of a jump or sprint.³² Indeed, body mass gain not attended by a corresponding increase in strength reduces acceleration and, therefore, performance.³² During this developmental stage, there is an association between skeletal muscle mass and isometric grip strength ($r = 0.4$), highlighting the useful role of body weight for the evaluation of neuromuscular development.³³ Our meta-analysis suggests that greater body mass does not impair handgrip performance, likely because this test is non-weight-bearing. Consequently, it better isolates upper-limb muscular capacity without the confounding influence of excess mass that penalizes whole-body tasks. However, this advantage must be interpreted within a broader physiological context: muscle strength in youth reflects not only increased mass, but also neuromuscular coordination, maturation status, and fiber-type composition.^{1,5} Given the high heterogeneity across studies, caution is warranted, especially when body composition data are lacking or not adjusted for maturation.

The main results of our meta-analysis show the positive role of stature in all performance. However, we found high heterogeneity in our results for both stature and body mass exponents ($I^2 > 75\%$). The substantial heterogeneity observed likely stems from unaccounted methodological differences across studies. While moderation analyses found no consistent effect of test type on scaling exponents, variability

in protocols, and age of the participants likely contributed to residual noise. Even if not statistically significant, these inconsistencies may obscure underlying biological relationships and should be addressed in future standardization studies. Importantly, allometric exponents quantify the curvilinear scaling relationship between body size and performance and are not fixed biological constants. High heterogeneity in these values therefore reduces their generalizability and limits their usefulness as universal correction factors. Although the pooled stature exponent provides a valuable summary of average scaling behavior, its practical application should be context dependent. Practitioners should use these values as general guides to reduce size-related bias in group comparisons, not as fixed rules for judging individual performance. Where feasible, deriving cohort-specific exponents is preferable, especially in elite or developmentally unique populations, and applying pooled estimates should be limited to early-stage screening or normative profiling in general youth populations. The pooled values from our meta-analysis are most useful in early testing phases or when comparing average performance in general youth groups. Still, the consistent direction of our results suggests they can be a helpful starting point when more specific data are not available. Despite the acknowledged high heterogeneity between studies, the direction of the stature exponent remained consistent. While greater stature can offer mechanical benefits, it may also pose disadvantages in activities requiring fast stopping, effective postural control, or high-frequency coordinated movements. Therefore, although the stature exponent appears

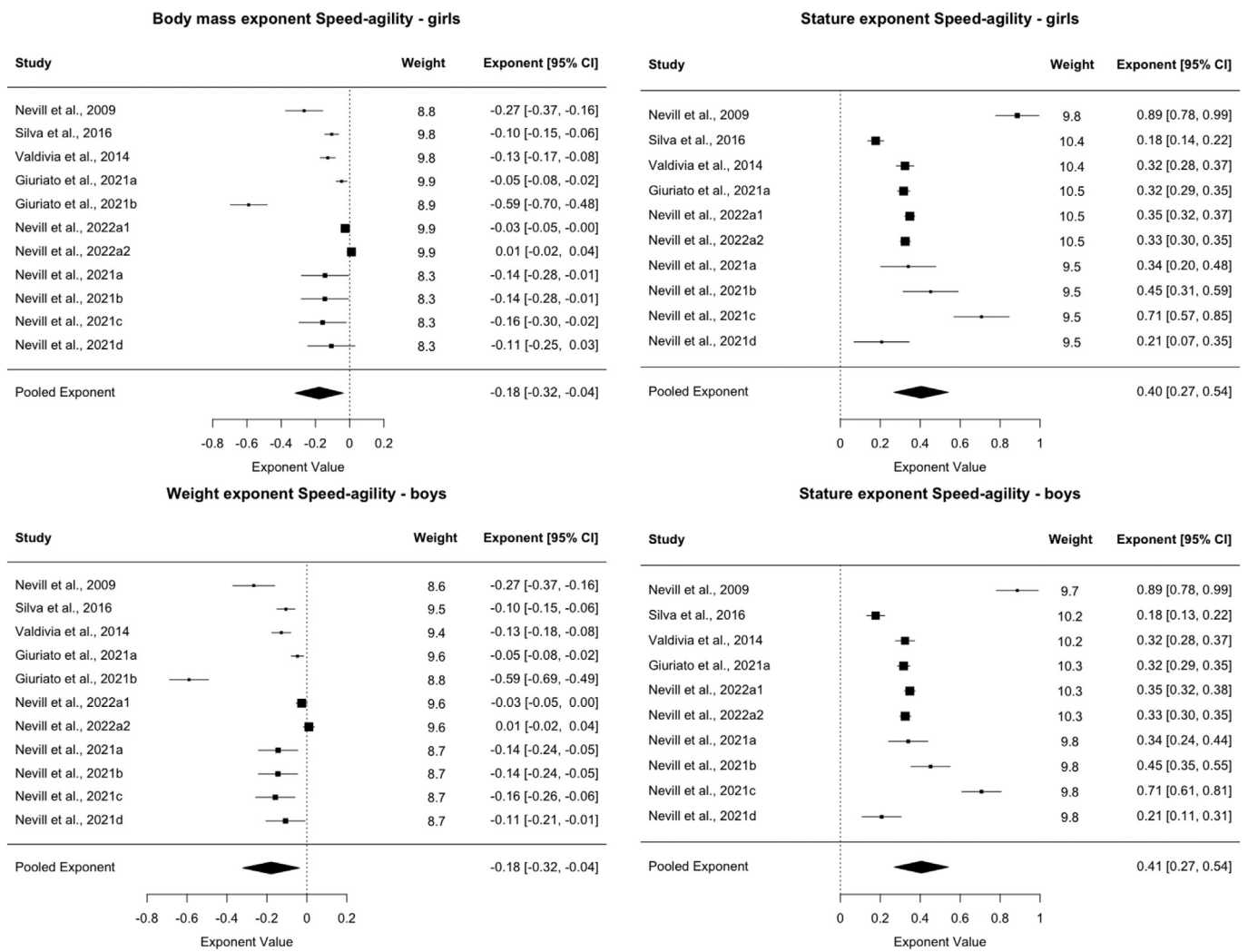


Fig. 5. Forest plot of estimated exponent value for weight and stature in speed-agility performance in both girls and boys. A negative value indicates that the weight or stature is inversely related to the performance, whereas a positive exponent indicates a direct relationship. Abbreviation: CI, confidence interval.

consistent, it likely obscures important, test-specific influences that should be explored in future studies.^{34,35} This suggests that stature may be a basic structural element which influences different phenomena, beyond specific situations. This recurrent positive exponent in stature, with a negative exponent in body mass, could be associated with a tendency to ectomorph body shape.³⁶ Stature and consequent greater length of the limbs often represent a biomechanical advantage in explosive and endurance actions: in speed-agility, for example, an athlete with longer lower limbs can cover the same distance with fewer steps, thus increasing locomotor efficiency.³⁴ Nevill et al.³⁷ explained that anthropometric characteristics such as stature are strongly associated with selection and athletic success, specifically in sports requiring high strength and endurance components. However, Young et al.³⁵ showed that also change of direction performance depends on the ability to control these major levers. Furthermore, while a negative exponent in body mass can be introduced as an “extra weight to transport” in cyclic or antigravity tasks (e.g., jumps, sprints), stature, allometrically corrected, reflects an advantageous morphological proportionality.¹³ However, it is essential to consider a broader biopsychosocial framework when interpreting the impact of anthropometric factors on talent development. Stature, limb length and muscle mass are only some components of an athlete’s profile and must be considered alongside perceptual and motor learning, psychological and social factors.³⁸ Moreover, an athlete’s morphology does not act in isolation but dynamically co-evolves with task demands and environmental conditions, shaping

individualized development paths.^{3,38–40} These dynamic interactions are not captured by statistical scaling alone, making the world of sport during childhood extremely challenging and complex. Therefore, while our meta-analytic findings support the value of allometric modeling to reduce size-related statistical bias, practitioners should integrate scaled metrics with qualitative assessments of motor competence, tactical understanding, and psychological readiness when designing talent identification and long-term athlete development strategies. It is also essential to note that allometric scaling is not a universal corrective for all contexts. While it can substantially reduce statistical confounds related to body size in weight-bearing or developmental comparisons, scaling is inappropriate when the performance trait of interest is inherently absolute.¹⁶ Similarly, in applied talent identification, an over-reliance on scaled values may overlook athletes whose absolute outputs are exceptional and sport-specific. Therefore, allometric models should be applied judiciously, with careful consideration of whether the sport or test emphasizes relative efficiency or absolute output.³² Nevill et al.¹³ noted that over-scaling can remove meaningful variation. Indeed, in certain sports, the effect of absolute body size is a fundamental component of performance and should not be normalized or adjusted out, as doing so may obscure key performance determinants inherent to the discipline. Further, Welsman & Armstrong^{16,41} emphasized the importance of context-specific interpretation, as the relevance of size-scaled indices depends on the primary factors that determine performance in the specific sport or task being evaluated.

While our findings highlight that allometric modeling can mitigate the bias introduced by simple ratio scaling in youth assessments, we do not suggest that anthropometric differences should be disregarded in talent identification.¹³ Specific sports place a premium on certain physical attributes; for example, taller stature can be advantageous in volleyball or rowing, and greater body mass linked to muscle mass may enhance performance in weightlifting.³⁶ Our recommendation is not to eliminate the consideration of body size but to contextualize it within sport-specific demands and to employ allometric approaches where appropriate to distinguish structural advantages from underlying motor competence.^{11,36,42}

Despite the strengths of this systematic review and meta-analysis, some important limitations must be acknowledged. First, considerable heterogeneity ($I^2 > 75\%$) was evident across the included studies, reflecting differences in test protocols, age groups, and analytical methods. Such variability diminishes the precision of pooled estimates and constrains the generalizability of the allometric exponents derived. Second, although including studies with different testing methodologies might help having a complete overview of the topic, on the other hand, this approach likely contributed to increased heterogeneity. Additionally, the meta-analytic synthesis itself does not equate to independent validation; the pooled exponents derived have not been cross validated in separate cohorts or datasets. As discussed above, this level of heterogeneity does not invalidate the directionality or interpretive value of the findings, but it does require caution in applying the results outside of similar contexts. These limitations should be carefully considered when interpreting our results and highlight the necessity for future research employing standardized methodologies, longitudinal designs, and explicit validation of allometric models across varied athletic and developmental populations.

5. Conclusion

Our findings indicate that stature consistently and positively correlates with youth physical fitness across multiple domains, though the strength of this correlation varies depending on the test. In contrast, body mass's influence is task-specific: it is detrimental in weight-bearing activities and advantageous in upper limb strength assessments. However, these results should be evaluated with caution given the substantial heterogeneity ($I^2 > 75\%$) among studies. This heterogeneity might reflect both biological variation and methodological variation, which, while limiting generalizability, does not undermine the consistent direction of the observed associations. While our meta-analysis synthesizes the best available evidence, it does not establish universal scaling parameters. Instead, it highlights the potential of allometric modeling to reduce size-related bias in youth assessments when applied judiciously and in conjunction with sport-specific criteria and broader developmental factors (e.g., psychological). Future research should explore allometric modeling across a wider range of outcomes (e.g., lean mass) and incorporate a comprehensive perspective that includes psychosocial and environmental factors.

6. Perspectives

These findings provided some evidence that stature is consistently associated with youth physical fitness, while body mass effects are task-specific, negative in tests involving mass propulsion or support (e.g., running, jumping) and positive in non-mass-propulsion tasks such as handgrip strength. This interpretation is consistent with earlier recommendations on allometric approaches.^{11–16,42,43} These differences, also in exponent magnitude, might help define an optimal body size profile for different physical tasks, supporting an initial phase of talent identification by trainers and sport scientists. However, the pooled exponents derive from only 20 studies. They are characterized by small effect sizes for stature, mixed findings for body mass, and high heterogeneity, that might reduce the applicability of our results. Future research should

extend allometric modeling to different outcomes and adopt a comprehensive biopsychosocial approach to explain this variability.

CRedit authorship contribution statement

Matteo Giuriato: Data curation, writing – original draft, and project administration.

Nicola Lovecchio: Writing – review & editing and supervision.

Matteo Vandoni: Writing – review & editing and supervision.

Alessandro Gatti: Software, formal analysis, writing – original draft, and project administration.

Alan M. Nevill: Conceptualization, methodology, statistical oversight, and writing – review & editing.

Consent to participate

Not required.

Confirmation of ethical compliance

Not required.

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Declaration of interest statement

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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