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SYSTEMATIC REVIEW

Is Muscular Fitness Associated with Future Health Benefits in Children and Adolescents? A Systematic Review and Meta-Analysis of Longitudinal Studies

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Abstract

Background No previous systematic review has quantitatively examined the association between muscular fitness during childhood and adolescence and health parameters later in life.

Objective The aim was to systematically review and meta-analyze the current evidence for a prospective association between muscular fitness in childhood and adolescence and future health status.

Methods Two authors systematically searched MEDLINE, EMBASE and SPORTDiscus electronic databases and conducted manual searching of reference lists of selected articles. Relevant articles were identified by the following criteria: apparently healthy children and adolescents aged 3–18 years with muscular fitness assessed at baseline (e.g., handgrip, standing long jump, sit-ups, among others), and a follow-up period of ≥ 1 year. The outcome measures were anthropometric and adiposity measurements and cardiometabolic, bone and musculoskeletal health parameters. Two authors independently extracted data.

Results Thirty studies were included in the meta-analysis, yielding a total of 21,686 participants. The meta-analysis found a significant, moderate-large ($p < 0.05$) effect size between muscular fitness at baseline and body mass index ($r = -0.14$; 95% confidence interval (CI) −0.21 to −0.07), skinfold thickness ($r = -0.32$; 95% CI −0.40 to −0.23), homeostasis model assessment estimated insulin resistance ($r = -0.10$; 95% CI −0.16 to −0.05), triglycerides ($r = -0.22$; 95% CI −0.30 to −0.13), cardiovascular disease risk score ($r = -0.29$; 95% CI −0.39 to −0.18), and bone mineral density ($r = 0.166$; 95% CI 0.086 to 0.243) at follow-up.

Conclusion A prospective negative association was observed between muscular fitness in childhood/adolescence and adiposity and cardiometabolic parameters in later life, together with a positive association for bone health. There is inconclusive evidence for low back pain benefits.

Key Points

A high level of physical fitness in childhood and adolescence is associated with lower body mass index, skinfold thickness, homeostasis model assessment estimated insulin resistance, triglycerides, cardiovascular disease risk score and higher bone mineral density values later in life.

There is no convincing evidence linking a high level of muscular fitness with low back pain later in life.

The effect sizes reported using endurance (push-ups, sit-ups, bent arm hang, etc.) or strength tests (handgrip, standing long jump, vertical jump, etc.) were similar.

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1 Introduction

Physical fitness in childhood and adolescence is considered an important health indicator [1]. The fitness components that have been shown to directly relate to improvements in health include cardiorespiratory fitness (CRF), muscular fitness, local muscular endurance, and body composition [2, 3]. Specifically, muscular fitness is an important marker of health throughout life [1], and a valuable indicator for monitoring child [4] and adolescent health [5]. The World Health Organization and the United States Department of Health and Human Services support the promotion of muscle-strengthening activities in addition to aerobic activity as part of their physical activity guidelines for children and adolescents [6, 7]. In spite of this, however, recent evidence indicates that the muscular fitness levels of school-age youth are decreasing [8, 9], and it has been proposed that monitoring temporal trends in muscular fitness could support the development of health-promotion strategies.

Low muscular fitness is recognized as a strong marker of poor metabolic profile during childhood and adolescence and is associated with several non-communicable diseases [1], and also with mortality in adulthood [10]. Indeed, several cross-sectional studies support a strong inverse relationship between low muscular fitness and cardiovascular disease (CVD) risk factors and metabolic syndrome in young people [5, 11]. Observational studies have shown that youth with low levels of muscular fitness are at increased risk of maintaining a low muscular fitness level into adulthood [12]. Despite these recent findings, the importance of muscle fitness and its association with future health is less clear. A previous systematic review by Ruiz et al. [3] found that muscular fitness is strongly associated with overall adiposity, but also found inconclusive evidence for cardiometabolic outcomes. In a similar vein, another systematic review reported a strong association between muscular fitness, total and central adiposity, cardiometabolic outcomes and bone health among youth [13]; however, this study included cross-sectional and longitudinal data.

Although there have been reviews of the benefits of health-related fitness in youth [3, 13], to our knowledge, no previous systematic review has quantitatively examined (meta-analyzed) the association between muscular fitness during childhood and adolescence and health parameters later in life. Therefore, our aim was to systematically review and meta-analyze the current evidence for a prospective association between muscular fitness in childhood and adolescence and future health status.

2 Methods

A systematic review and meta-analysis was conducted following the guidelines of the Cochrane Collaboration [14]. Findings were reported in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) [15]. The review was registered in PROSPERO (registration number: CRD42018111352).

2.1 Search Strategy

Two authors (AG-H and RR-C) systematically searched MEDLINE, EMBASE, and SPORTDiscus electronic databases from inception until 1 October 2018 (Electronic Supplementary Material (ESM) Appendix S1). The following terms were used: ‘muscles’ OR ‘muscle strength’ OR ‘muscular fitness’ OR ‘muscular’ OR ‘strength’ AND ‘longitudinal’ OR ‘prospective’. Searching was restricted to published articles in the English language.

2.2 Selection Criteria

The a priori inclusion criteria for this meta-analysis were as follows: (1) exposure: muscular fitness measured using a muscular fitness test (e.g., handgrip, standing long jump, sit-ups, etc.) and assessed at baseline; (2) participants: generally healthy population and at baseline were aged 3 up to 18 years (mean age); and (3) study design: prospective cohort studies with a follow-up period of ≥ 1 year. The outcomes measures included were classified into the following four categories: (1) anthropometric and adiposity parameters; (2) cardiometabolic parameters; (3) bone health parameters; and (4) musculoskeletal parameters. By protocol, we did not restrict inclusion to a specific primary or secondary outcome. Two authors (AG-H and RR-C) independently assessed the electronic search results. When an article title seemed relevant, the abstract was reviewed for eligibility. When more information was required, the full text of the article was retrieved and appraised. Any differences in the assessments between the two authors were discussed and, if necessary, a third author was involved in decision making (MI). Reasons for exclusion of identified articles were recorded in all cases.

2.3 Data Collection Process and Data Items

Two authors (AG-H and RR-C) independently extracted data including the following information: the first author’s name, year of publication, enrollment year, duration of follow-up, study location, sample size, age at baseline examination, results, adjusted variables, method of muscular fitness assessment, and outcome of interest and number of cases. The outcome measures were as follows: body mass index (BMI), waist circumference (WC), body fat, waist–height ratio, waist-to-hip ratio, skinfold thickness, total cholesterol, high-density lipoprotein cholesterol (HDL-C), triglycerides, fasting glucose, fasting insulin, homeostatic model assessment-insulin resistance (HOMA-IR) index, HOMA-beta cell function (HOMA-β), blood pressure, metabolic syndrome, bone mineral density (BMD), bone mineral content (BMC), tension neck, knee injury and low back pain (LBP) (Table 1). When there was insufficient information, the respective corresponding author was contacted [16–19].

2.4 Risk of Bias in Individual Studies

An assessment of risk of bias in selected studies was made using an adjusted format of the Newcastle–Ottawa quality assessment scale [20] by two authors (AG-H and RR-C) independently. This scale contains eight items categorized into three domains (selection, comparability, and exposure). A star system is used to enable semi-quantitative assessment of study quality, such that the highest quality studies are awarded a maximum of one star per item with the exception of the comparability domain, which allows allocating two stars. Thus, the scores ranged from zero to nine stars.

2.5 Summary Measures

Meta-analyses were conducted if at least three studies provided effect sizes for the same health parameter [21]. Two types of effect size estimates were reported: the main meta-analysis was based on correlation coefficients (*r*) as a well-known effect size estimate, and the secondary analysis reported pooled odds ratio (OR). Several of the studies used multivariate linear regression, and so we converted the unstandardized regression coefficients (β) to *r* with a series of transformations [22, 23]. Detailed description of the basic input data is available in ESM Appendix S2. Correlation coefficients and ORs were entered along with the corresponding standard errors or sample size, and the software was set to produce pooled *r* or with 95% confidence interval (CI) using random effects models. The likelihood approach with random effects was used to better account for the inaccuracy in the estimate of between-study variance [24]. The pooled effect size for *r* was classified as small (≤ 0.1), moderate (0.1–0.29) or large (≥ 0.30) [25]. All analyses were carried out using the Comprehensive Meta-Analysis program (version 2; Biostat, Englewood, NJ, USA).

2.6 Synthesis of Results

The percentage of total variation across the studies due to heterogeneity (Cochran's *Q*-statistic) [26] was used to calculate the I^2 statistics, considering I^2 values of $< 25\%$, 25–75%, and $> 75\%$ as small, moderate, and high heterogeneity, respectively [26, 27]. Sensitivity analyses were conducted to assess the robustness of the summary estimates in order to determine whether a particular study accounted for the heterogeneity. Thus, each study was deleted from the model once in order to analyze the influence of each study on the overall results.

2.7 Risk of Bias Across Studies

Small-study effects bias was assessed using the extended Egger's test [28].

2.8 Additional Analysis

We examined potential sources of heterogeneity including sex, muscular fitness constructs (endurance or strength), and time for assessment at follow-up (childhood/adolescence or adulthood) by stratifying meta-analyses by each of these factors. A *p* value of < 0.05 was considered a threshold for statistical significance.

3 Results

3.1 Study Selection

The electronic search strategy retrieved 4112 articles. After removal of duplicate references, and screening of titles and abstracts, we excluded 3884 articles. Of the remaining 228 articles, and after full-text screening and checking the reference lists of included studies and previous reviews for additional relevant articles, a total of 59 studies were read in full. The reasons for exclusion based on full text were (1) inappropriate outcome measurement (18 articles); (2) inappropriate study population (10 articles); and (3) inappropriate study design (1 article) (ESM Appendix S3). Finally, 30 studies met all the inclusion criteria and were included in the systematic review, and of these, 26 studies were included in the meta-analysis (Fig. 1).

3.2 Study Characteristics

Table 1 summarizes the characteristics of the 30 included studies in the systematic review [17–19, 29–54]. The 30 studies included 21,686 participants, with sample sizes ranging from 36 [31] to 6297 [43]. Participants included only boys [33], only girls [31, 51] or both [17–19, 28, 32, 34–54] sexes. Most studies involved adolescents at baseline (≥ 13 years [17–19, 29–34, 38, 39, 42, 45, 46, 48–50, 53, 54]). In four studies [40, 41, 44, 52], the mean age of the included participants at baseline was 12 years or younger;

Table 1 Summary of included studies

Study	Sample; age (SD) at baseline; sex (M/F); location	Follow-up duration (years)	Adjustment for confounders	Muscular strength measure(s)	Outcomes of interest	Findings
Agostinis-Sobrinho et al. [29]	$n = 734$; 14.3 (1.7) years; (385/349); Portugal	2	Height and pubertal stage at follow-up, baseline values of the dependent variables, WC and CRF	Handgrip, SLJ, MFS	Systolic BP, diastolic BP	Muscular strength at baseline was inversely associated with systolic BP and rate product pressure at follow-up
Aires et al. [16]	$n = 345$; 13.9 (1.4) years; (147/198); Portugal	2	Time, all fitness variables	Curl-ups, push-ups	BMI	The results showed an important relationship between lower abdominal strength levels and the risk of being overweight/obese
Barnekow-Bergkvist et al. [30]	$n = 278$; 16.1(0.3) years; (157/121); Sweden	18	NR	Two-hand lift, bench press	BMI; waist–hip ratio, total cholesterol, systolic BP	Higher performance in the bench press was associated with greater odds of high BMI for males. Higher performance in the two-hand lift was associated with increased odds of high BMI for females but not males at age 34 years
Barnekow-Bergkvist et al. [31]	$n = 36$; 16.0 (0.3) years; 15–17 years; (36 girls); Sweden	20	Weight, height, and age	Hanging leg lift, handgrip, two-hand lift	Multiple-site BMD	Muscular strength during adolescence independently predicted BMD of the whole body, arms, legs and trochanter in adulthood
Castro-Piñero et al. [54]	$n = 511$; 6–18 years; (270/241); Spain	2	Age, cardiovascular risk factors, and CVD risk score were adjusted for levels at baseline, and CRF	Handgrip, SLJ	Systolic BP, CVD risk factors and combined CVD risk score	Muscle fitness was associated with present and future cardiovascular health in youth, and was independent of CRF
Cheng et al. [32]	$n = 179$; 12–13 years; (92/87); China	3	Age, weight, height, bone width, genitalia/breast, pubic hair, size of testis/menarche, level of sports, 3-min step test, mean score in flextest, 1-min sit-up, handgrip, VJ, calcium intake	Handgrip, knee flexion torque, 1-minute sit-ups, VJ	Distal radius BMC, spine BMD	Peak flexion torque at baseline was a significant predictor of BMD for girls only later in life

Table 1 (continued)

Study	Sample; age (SD) at baseline; sex (M/F); location	Follow-up duration (years)	Adjustment for confounders	Muscular strength measure(s)	Outcomes of interest	Findings
Delvaux et al. [33]	n = 126; 13 years; (126 boys); Belgium	27	Anthropometry, motor fitness, and PA	Hanging leg lifts, sit-ups, BAH, VJ, pull-ups, handgrip	Multiple site BMC, BMD	Static arm strength and trunk muscle strength demonstrated a significant correlation with adult total and lumbar BMC, respectively
Feldman et al. [34]	n = 502; 13.8 (0.1) years; (264/238); Canada	1	Age, sex, height, PA, mental health index, smoking, and flexibility	Sit-ups	LBP	Logistic regression analysis determined that abdominal strength was not associated with LBP at 1 year
Foley et al. [35]	n = 1434; 11.1 (2.5) years; (691/743); Australia	20	Adjusted for childhood BMI (*Z*-score) and adult PWC170	Leg strength, SLJ	Bone mass	In females, there were modest but significant beneficial relationships between the childhood SLJ and adult bone mass
Fraser et al. [37]	n = 737; 11.9 (2.5) years; (361/376); Australia	20	Age, sex, and length to follow-up, CRF and WC	Handgrip, leg strength, shoulder extension and flexion, push-ups, SLJ	Individual CVD risk factors, metabolic syndrome	Childhood muscular strength predicted adult metabolic syndrome outcomes independently of childhood CRF
Fraser et al. [36]	n = 737; 11.9 (2.5) years; (361/376); Australia	20	Age, sex, and length to follow-up, CRF and WC	MFS	Fasting insulin, fasting glucose, HOMA-IR, HOMA-B	Muscular strength (males) was associated with fasting glucose, fasting insulin, HOMA-IR and HOMA-B in adulthood. Adjustment for childhood WC reduced the effect by 0–15% (males)
Freitas et al. [38]	n = 450; 8–16 years; (231/219); Portugal	7	NR	Handgrip, sit-ups, BAH, SLJ	Overweight/obesity (BMI, sum of 5 skinfolds, and WC)	Muscular strength at baseline among the three age groups was predictive of adiposity 7 years later. Sit-ups, handgrip, and SLJ were significant predictors of adiposity among boys and BAH and SLJ were significant predictors among girls

Table 1 (continued)

Study	Sample; age (SD) at baseline; sex (M/F); location	Follow-up duration (years)	Adjustment for confounders	Muscular strength measure(s)	Outcomes of interest	Findings
Grøntved et al. [18]	$n=332$; 15.6 (0.4) years; NR; Denmark	12	Baseline information on TV watching, parental educational level, smoking, family history of CVD, frequency of intake of soft drinks, fruit, and vegetables, CRF and BMI or WC	Relative isometric strength	BMI, WC, individual CVD risk factors and combined CVD risk score	Strength in youth was significantly associated with individual risk factors and the combined CVD risk score in young adulthood (adjusted for age, sex, recruitment period, and CRF). In multivariable-adjusted analyses including CRF, each 1 SD increase of isometric muscle strength in youth was associated with 0.59 lower odds of general overweight or obesity in young adulthood
Grøntved et al. [17]	$n=317$; 15.6 (0.4) years; NR; Denmark	12	Baseline information on television watching, parental educational level, smoking, family history of CVD, frequency of intake of soft drinks, fruit, and vegetables, CRF and BMI or WC	Relative isometric strength	Fasting insulin, fasting glucose, HOMA-IR, HOMA-B	Isometric muscle strength in youth was inversely associated with fasting insulin and markers of insulin resistance and β-cell function in young adulthood
Hasselstrøm et al. [39]	$n=203$; 15–19 years; (88/115); Denmark	8	Age	MFS	WC, %BF, individual CVD risk factors and combined CVD risk score	Strength at baseline was inversely associated with %BF 8 years later in men but not women
Hruby et al. [40]	$n=2793$; grades 1–7; (1456/1337); USA	4	Age, race/ethnicity, family SES, follow-up time, and within-school correlation structure	Sit-ups, pull-ups, BAH	Weight status (BMI)	Following adjustment for multiple confounders, achieving and maintaining 'adequate' fitness over the 4 years was associated with increased odds of being a healthy weight at follow-up
Janz et al. [41]	$n=112$; 10.5 years; (54/58); USA	5	Age, sex, fat-free mass, and Tanner	Handgrip	WC, sum of 6 skinfolds, individual CVD risk factors	Change in handgrip and average handgrip over the 5-year period were significantly associated with WC and sum of skinfold thickness at follow-up, following adjustment for multiple confounders

Table 1 (continued)

Study	Sample; age (SD) at baseline; sex (M/F); location	Follow-up duration (years)	Adjustment for confounders	Muscular strength measure(s)	Outcomes of interest	Findings
Jekal et al. [42]	$n = 1006$; NR; (597/409); Korea	22	NR	MFS	Individual CVD risk factors and metabolic syndrome	Participants with low fitness levels during adolescence were more likely to be overweight (girls) and have abnormal HDL-C in adulthood vs those with high fitness levels
Kim et al. [43]	$n = 6297$; 5–14 years; NR; USA	1	Baseline BMI *Z*-score	Sit-ups, pull-ups, BAH	Weight status (BMI)	Baseline upper-body strength significantly predicted incidence of overweight 1 year later for boys and girls. However, adjustment for baseline BMI *Z*-score eliminated the association
Lopes et al. [44]	$n = 285$; 5.9 (0.3) years; (143/142); Portugal	4	Sex and time	Sit-ups, pull-ups	Sum of 2 skinfolds	For each unit improvement in sit-ups and pull-ups, skinfold thickness was reduced by 0.06 and 0.04 mm, respectively
Mikkelsson et al. [45]	$n = 1121$; 12–17 years; (801/880); Finland	25	Age, BMI, flexibility, PA at baseline and follow-up	Sit-ups	Tension neck, LBP, knee injury	High sit-ups at baseline was associated with reduced risk of tension neck in adulthood for women in the univariate model. There was an increased risk of knee injury in men with high sit-ups at baseline in the multivariate model. No association was found for sit-ups and LBP
Minck et al. [46]	$n = 181$; 13.0 years; (83/98); Holland	15	PA, body weight and height	Arm pull, BAH, VJ, 10 leg lifts	Sum of 4 skinfolds	In adjusted analyses, skinfold thickness was longitudinally associated with VJ and leg lifts
Newcomer and Sinaki [47]	$n = 96$; 10–19 years; (53/43); USA	4	Age and sex	BME	LBP	Subjects with higher back strength had a significantly higher percentage of positive responses to experiencing LBP ever and in the past year, after adjustment for confounders

Table 1 (continued)

Study	Sample; age (SD) at baseline; sex (M/F); location	Follow-up duration (years)	Adjustment for confounders	Muscular strength measure(s)	Outcomes of interest	Findings
Peterson et al. [48]	$n = 368$; 9.18 (0.39) years; (235/239); USA	2	FFMI, CRF, and PA at baseline	Handgrip normalized by body mass	Cardiometabolic risk	Greater normalized handgrip strength at baseline was associated with longitudinal health maintenance in adolescents
Salminen et al. [49]	$n = 62$; 15 years; (29/33); Finland	3	NR	Six-stage sit-ups, isometric abdominal hold, BME	LBP	Diminished abdominal and back muscle endurance at baseline was associated with increased frequency of LBP. Low muscle endurance at baseline did not predict future LBP
Sjölie and Ljunggren [50]	$n = 86$; 14.7 (0.6) years; (50/38); Norway	3	Sex, high time spent on television/computer, PA, and well-being	BME	LBP	Baseline BME significantly predicted LBP at follow-up after adjustment for confounders
Toriola et al. [19]	$n = 283$; NR; (111/172); South Africa	2	Age and race	Sit-ups, SLJ, BAH	BMI, %BF, WHtR	The changes in BMI were inversely associated with BAH in girls. The changes in body fat were negatively associated with SLJ and BAH in both boys and girls. A low significant positive association was found between changes in WHtR and SLJ in both sexes, whilst low inverse associations were found between WHtR and BAH in girls
Wang et al. [51]	$n = 258$; 10–13 years; (258 girls); Finland	2	Lean mass	Upper and lower body maximal strength	Multiple-site BMC	BMC of arm and leg correlated significantly with strength of elbow flexors and knee extensors at baseline, respectively
Welten et al. [53]	$n = 182$; 13 years; (84/98); The Netherlands	15	NR	Arm pull, VJ	Spine BMD	BMD was positively related to static arm strength (arm pull) and with explosive leg strength (standing high jump) in boys and girls, respectively

Table 1 (continued)

Study	Sample; age (SD) at baseline; sex (M/F); location	Follow-up duration (years)	Adjustment for confounders	Muscular strength measure(s)	Outcomes of interest	Findings
Zaqout et al. [52]	$n = 1635$; 8.4 (1.6) years; (822/813); 8 European countries (Belgium, Cyprus, Estonia, Germany, Hungary, Italy, Spain and Sweden)	2	Sex, age, parental education, intervention status (intervention/control region), diet, BMI, and PA	Handgrip, SLJ	WC, individual CVD risk factors and combined CVD risk score	Lower-limb strength was an important longitudinal predictor for metabolic syndrome, WC, lipids and HOMA-IR

%BF percent body fat, *BAH* bent arm hang, *BMC* bone mineral content, *BMD* bone mineral density, *BME* back muscle endurance, *BMI* body mass index, *BP* blood pressure, *CRF* cardio-respiratory fitness, *CVD* cardiovascular disease, *HDL-C* high-density lipoprotein cholesterol, *HOMA-IR* homeostatic model assessment of insulin resistance, *HOMA-B* homeostasis model assessment 2-beta cell function, *LBP* low back pain, *M/F* male/female, *MFS* muscular fitness score, *NR* not reported, *PA* physical activity, *PWC170* physical work capacity at 170 beats/min, *SD* standard deviation, *SLJ* standing long jump, *VJ* vertical jump, *WC* waist circumference, *WHtR* waist-to-height ratio

these were considered children. In the nine remaining studies [16, 35–38, 43, 47, 51, 55], both children and adolescents were included. The length of follow-up ranged from 1 year [34, 43] to 27 years [33] (mean 8.6 years).

3.3 Muscular Fitness Measurement

Muscular fitness was measured in a variety of ways (Table 1). Most of the studies assessed muscular endurance using the following tests: sit-ups test [19, 32–34, 38, 40, 43–45, 49], bent arm hang test [19, 38, 40, 43, 46], pull-ups test [33, 40, 43, 44], push-ups test [16, 33, 37], and the back muscle endurance test [47, 49, 50]. Other studies assessed muscular strength using the handgrip strength test [23, 29, 32, 33, 37, 38, 41, 52, 54] and the standing long jump (SLJ) test [19, 29, 37, 38, 52, 54]. Finally, six studies used a muscular fitness score [17, 18, 29, 36, 39, 42] and other tests different from those mentioned.

3.4 Risk of Bias Within Studies

All 30 studies met at least five Newcastle–Ottawa quality assessment scale criteria and were considered to have moderate methodological quality. The average score was 6.3/9.0 (ESM Appendix S4).

3.5 Meta-Analysis

Table 2 shows the synthesis of results and subgroup analysis. Forest plots are shown in ESM Appendix S5. BMI at follow-up was related to muscular fitness at baseline with a moderate effect size ($r = -0.14$; 95% CI -0.21 to -0.07; $p < 0.001$; $I^2 = 27.04$); similar results were obtained when analyzing muscular endurance tests (BMI: $r = -0.14$; 95% CI -0.22 to -0.07, $p < 0.001$; $I^2 = 0\%$). Skinfold thickness was also related to muscular fitness at baseline with a large effect size ($r = -0.32$; 95% CI -0.40 to -0.23; $p < 0.001$; $I^2 = 81.15\%$), and showed similar results in boys and girls. The effect sizes were higher when analyzing muscular endurance tests ($r = -0.34$; 95% CI -0.45 to -0.22; $p < 0.001$; $I^2 = 82.33\%$), strength tests ($r = -0.41$; 95% CI -0.50 to -0.31; $p < 0.001$; $I^2 = 76.14\%$), and analyzing only studies that included the assessment in childhood.

Regarding cardiometabolic parameters, HOMA-IR ($r = -0.10$; 95% CI -0.16 to -0.05; $p < 0.001$; $I^2 = 67.12\%$), triglycerides ($r = -0.22$; 95% CI -0.30 to -0.13; $p < 0.001$; $I^2 = 74.41\%$), and CVD risk score ($r = -0.29$; 95% CI -0.39 to -0.18; $p < 0.001$; $I^2 = 84.56\%$) at follow-up showed a moderate relationship with muscular fitness at baseline.

BMD at follow-up was related to muscular fitness at baseline with a medium effect size ($r = 0.17$; 95% CI 0.09–0.24; $p < 0.001$) and low heterogeneity ($I^2 = 24.92\%$). The effect sizes were slightly higher when we analyzed only girls and

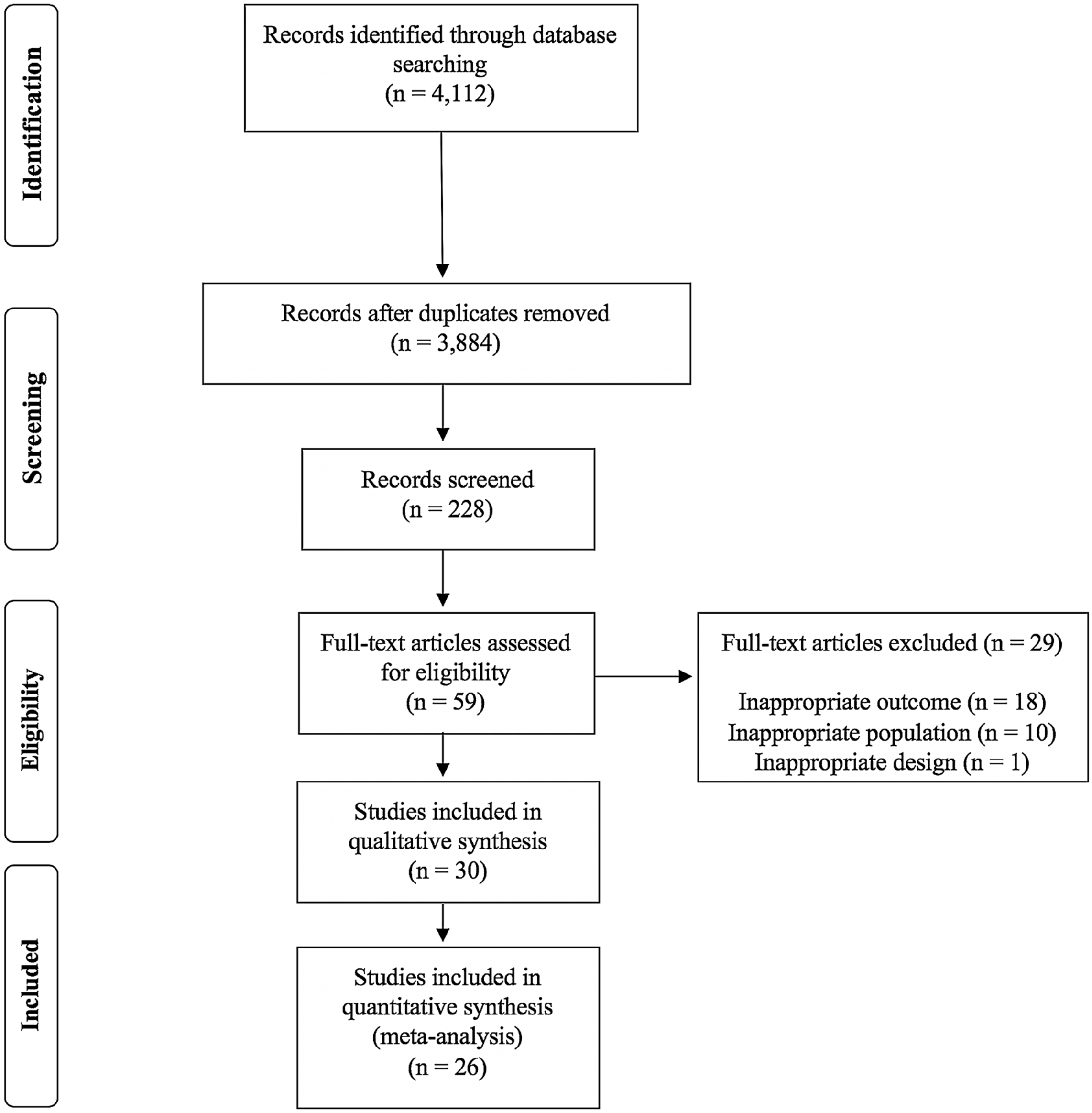

Fig. 1 PRISMA flow diagram

muscular endurance tests (girls: $r = 0.24$; 95% CI 0.09–0.38; $p = 0.002$; $I^2 = 33.06\%$; muscular endurance tests: $r = 0.20$; 95% CI 0.10–0.29; $p < 0.001$; $I^2 = 0\%$). However, analyzing only studies that included the assessment at adulthood, the relationship decreased slightly and the heterogeneity increased ($r = 0.12$; 95% CI 0.05–0.19; $p = 0.001$; $I^2 = 73.63\%$).

Finally, muscular fitness was not significantly related to other musculoskeletal parameters (Table 2).

3.6 Publication Bias and Sensitivity Analysis

Egger's linear regression tests provided evidence that there was no indication of study bias. In the sensitivity analysis, with each study deleted from the model once, the results remained consistent across all deletions.

4 Discussion

We here summarize the evidence for a prospective relationship between muscular fitness and health parameters in youth. The evidence for a prospective association between muscular fitness at baseline and lower BMI, skinfold thickness, HOMA-IR, triglycerides, CVD risk score or higher BMD later in life is consistent, and is supported by the meta-analysis. Accordingly, muscular fitness should be

Table 2 Synthesis of results

	n	*r*/OR[a]	95% CI	*p* value	I^2	Egger test (*p*)
Anthropometric and adiposity parameters						
Body mass index	3	− 0.14	− 0.21 to − 0.07	< 0.001	27.04	0.171
Muscular endurance tests	3	− 0.14	− 0.22 to − 0.07	< 0.001	0	0.693
Waist circumference	6	− 0.10	− 0.24 to 0.04	0.161	95.29	0.891
Upper-body muscular tests	3	− 0.07	− 0.23 to 0.09	0.393	79.14	0.650
Assessment at adulthood	4	− 0.09	− 0.32 to 0.14	0.449	94.90	0.042
Skinfold thickness	5	− 0.32	− 0.40 to − 0.23	< 0.001	81.15	0.103
Muscular endurance tests	3	− 0.34	− 0.45 to − 0.22	< 0.001	82.33	0.173
Strength tests	4	− 0.41	− 0.50 to − 0.31	< 0.001	76.14	0.167
Boys	3	− 0.36	− 0.49 to − 0.21	< 0.001	82.17	0.171
Girls	3	− 0.35	− 0.43 to − 0.26	< 0.001	49.25	0.315
Assessment at childhood	3	− 0.40	− 0.53 to − 0.26	< 0.001	89.99	< 0.001
Overweight/obese	4	*0.94*	0.65 to 1.36	0.754	65.04	0.219
Boys	3	*0.73*	0.43 to 1.23	0.232	57.26	0.907
Girls	3	*1.04*	0.61 to 1.78	0.887	54.49	0.683
Upper-body muscular tests	3	*0.71*	0.44 to 1.14	0.153	54.18	0.152
Assessment at adulthood	3	*0.98*	0.53 to 1.83	0.949	74.09	0.228
Cardiometabolic parameters						
Systolic blood pressure	7	− 0.02	− 0.05 to 0.01	0.323	33.79	0.481
Muscular endurance tests	4	− 0.01	− 0.04 to 0.02	0.531	9.34	0.048
Assessment at adulthood	3	0.02	− 0.09 to 0.14	0.700	74.68	< 0.001
Diastolic blood pressure	5	− 0.05	− 0.14 to 0.04	0.268	85.51	0.416
Assessment at adulthood	3	− 0.06	− 0.25 to 0.14	0.571	91.32	0.057
Abnormal blood pressure	3	*1.22*	0.88 to 1.69	0.228	14.48	0.206
HOMA-IR	4	− 0.10	− 0.16 to − 0.05	< 0.001	67.12	0.267
Fasting glucose	3	0.02	− 0.05 to 0.10	0.521	60.54	0.356
Triglycerides	4	− 0.22	− 0.30 to − 0.13	< 0.001	74.41	0.335
CVD risk score	4	− 0.29	− 0.39 to − 0.18	< 0.001	84.56	0.057
Bone health						
Bone mineral density	4	0.17	0.09 to 0.24	< 0.001	24.92	0.075
Girls	3	0.24	0.09 to 0.38	0.002	33.06	0.555
Muscular endurance tests	3	0.20	0.10 to 0.29	< 0.001	0	0.056
Strength tests	3	0.21	− 0.28 to 0.42	0.084	69.50	0.560
Assessment at adulthood	4	0.12	0.05 to 0.19	0.001	73.63	0.065
Musculoskeletal disorders						
Low back pain	3	*1.30*	0.96 to 1.75	0.094	55.07	0.176

CI confidence interval, *CVD* cardiovascular disease, *HOMA-IR* homeostatic model assessment of insulin resistance, *OR* odds ratio

[a]Non-italicized entries = *r* values; italicized entries = OR values

developed during childhood and adolescence in order to promote healthier adiposity, cardiometabolic and bone health outcomes later in life. The evidence for LBP outcomes is inconclusive. That said, the results of the present meta-analysis should be interpreted with caution because of (1) the variety of tests used to assess muscular fitness (strength, power or endurance); (2) the outcome measures; (3) the follow-up time (from 1 year to 25 years); (4) the age of the participants; and (5) the role of potential confounders.

4.1 Anthropometric and Adiposity Parameters

Our findings provide evidence of an inverse moderate association between muscular fitness and some anthropometric parameters (BMI and skinfold thickness) later in life. In line with the present study, a systematic review published in 2014 suggested an inverse association between muscular fitness and adiposity ($r = -0.25$) [13]; however, this study included cross-sectional results and, therefore, the association is probably bidirectional with increases in fitness or adiposity likely to impact on each other. Another systematic review gave support to the notion that muscular fitness is highly influenced by body weight in children aged 6–17 years [3], especially with regards to weight-bearing tests. However, individual studies included in our meta-analysis have shown that muscular fitness measured both in absolute terms [38] and relative to body weight [19, 39, 41] is inversely associated with adiposity later in life. Also, the effect sizes reported using endurance (push-ups, sit-ups, bent arm hang, etc.) or strength tests (handgrip, SLJ or vertical jump) were similar.

The inverse relationship between muscular fitness at baseline and anthropometric parameters at follow-up may occur through both physiological and psycho-behavioral mechanisms. For example, higher muscular fitness performance favors greater participation in physical activity [56], larger work capacity amongst youth [57], and is hence more enjoyable [58]. Also, because skeletal muscle is a highly energetic tissue that contributes substantially to basal metabolic rate [59], high muscular fitness levels at baseline may reflect larger skeletal muscle mass, higher metabolic efficiency of muscle (i.e., lipid oxidation and glucose transport capacity), or both, resulting in greater overall daily energy expenditure [60].

The pooled effect size of four studies [18, 30, 42, 43] revealed a non-significant relationship between low muscular fitness level at baseline and overweight/obesity at follow-up, also by sex and analyzing only the upper-body muscular tests. However, Hruby et al. [40] showed, in a large sample of 2793 American children, that both achieving and maintaining adequate muscular fitness over a 4-year period resulted in significantly greater odds of a healthy weight at 4-year follow-up. By contrast, Barnekow-Bergkvist et al. [30] reported that higher performance in the bench press and two-hand lift was associated with greater odds of high BMI for both males and females at age 34 (20 years later). Due to the heterogeneity of the results, further investigations are warranted to clarify the relationship between muscular fitness in children and future body weight.

4.2 Cardiometabolic Parameters

A low muscular fitness level is recognized as a marker of poor metabolic profile during childhood and adolescence [5]. In their systematic review, Smith et al. [13] provided strong evidence for the importance of muscular fitness during childhood and adolescence for cardiometabolic risk. Despite individual studies demonstrating that muscular fitness during childhood and adolescence was inversely associated with cardiometabolic risk/metabolic syndrome (several risk factors) [18, 48, 52], lipids [18, 42, 52], blood pressure [18, 29, 37], and fasting glucose and insulin [17, 36] in later life, our pooled analysis revealed only an inverse association between muscular fitness and HOMA-IR, with a small effect size and moderate-high heterogeneity. Because muscle-strengthening activities are strongly related to gains in muscle strength in youth [61, 62], these observations support our analysis and suggest that low muscle fitness is causally related to development of unfavorable levels of insulin resistance. A possible mechanism through which high muscular fitness may influence insulin resistance is by stimulating proteins in the insulin-signaling cascade [63]. Consistent with this, several experimental studies support the biological plausibility of our findings, suggesting that increased muscular fitness via resistance training favors increased insulin sensitivity [64]. For example, Fraser et al. [36] found that muscular endurance and muscular strength (in males) are associated with measures of insulin resistance and beta cell function in adulthood, independent of the CRF phenotype and WC. These authors also suggested that WC attenuates the association between childhood muscular fitness and adult insulin resistance outcomes, which could explain our findings (i.e., we reported an inverse relationship between muscular fitness and some anthropometric parameters, which in turn may be related to lower levels of insulin resistance). Therefore, moderate heterogeneity in our results could be due to covariates included in the analysis.

Although the present meta-analysis did not include pooled data for metabolic syndrome or cardiometabolic risk (due to the limited number of studies), several single-study reports yielded inconclusive results, with a negative [18, 37, 48] or no [39, 42, 48] significant association with muscular fitness. In a recent study of 235 American adolescents, Peterson et al. [48] suggested that greater baseline body-mass–normalized handgrip strength was associated with both cardiometabolic health maintenance (no risk factors identified at either time point) and health improvements (presence of ≥ 1 baseline risk factor and fewer or no risk factors at follow-up) over a 2-year period. By contrast, Jekal et al. [42] studied 1006 Korean adolescents and reported that low muscular fitness during adolescence was not related to metabolic syndrome prevalence 22 years later.

4.3 Bone Health

There is scientific evidence to indicate that childhood may be the opportune time to build bone mass and enhance bone structure through participation in weight-bearing physical activities [65]. The majority of adult bone mass is laid down before 17 years of age [66] and is determined, to a large extent, by genetics [67], and also by a number of modifiable determinants such as physical activity, nutritional factors [68] and muscular fitness [69]. The findings of our meta-analysis support the role of muscular fitness during youth and its association with BMD later in life, with a medium effect size. Notwithstanding that bone mass is, in part, racially determined [70], our meta-analysis included youth from diverse ethnic groups (Asian and Caucasian) and the results showed low heterogeneity. Consistent with this, Foley et al. [35] reported modest but significant beneficial relationships between childhood SLJ and adult quantitative ultrasound index. Moreover, two longitudinal studies included in this systematic review reported an association between upper- and lower-body strength and BMC [33, 51].

Regarding sub-group analysis, the present findings reported a slightly higher effect size for upper-body muscular tests compared with overall pooled results, but there was no significant association between BMD and lower-body muscular tests (Table 2). As suggested by Foley et al. [35], the relationship between childhood and adolescent SLJ and adult bone mass could be attenuated after adjustment for adulthood SLJ measure, suggesting that muscular power is only an important determinant of adult bone mass if sustained into adulthood. Overall, it would seem to be worthwhile to promote exercise combining strength and impact training (e.g., plyometric training) [71] in growing children to favor bone mass response [72].

4.4 Musculoskeletal Disorders

Musculoskeletal disorders such as LBP, neck pain and osteoarthritis are highly prevalent in the adult population [73]. LBP is among the most commonly reported health problems in the United States and up to 80% of individuals are expected to consult their physician about LBP at some point in their lifetime [74]. In addition, back pain impacts over 100 million individuals in the US and costs more than US$200 billion per year due to job absenteeism, medical and legal fees, disability payments, worker's compensation, and long-term disability insurance [75]. When considering muscle strength in youth as a potential risk factor in the longer term, previous systematic reviews suggest that its association with future LBP is relatively unknown [3, 13], despite the fact that strength training seems to be important for secondary and tertiary prevention of LBP [76]. Also, Mikkelsson et al. [45] showed that good flexibility in boys and good endurance strength in girls may contribute to a decreased risk of neck tension, and that high endurance in boys may indicate an increased risk of knee injury. The present meta-analysis reinforces these findings with inconclusive evidence, indicating that low muscular fitness in childhood and adolescence might not be a predictor of LBP later in life, together with a moderate heterogeneity (OR 1.29; 95% CI 0.96–1.75; $p=0.094$; $I^2=55.07\%$). A large study of 5489 young adult men (mean age 18.2 years) from Sweden seems to confirm our findings and does not provide evidence in support of a theoretical model in which low muscle fitness in young adult men is associated with an increased risk of musculoskeletal pain later in life [77]. Another two studies included in this systematic review [47, 49] confirm this non-association. By contrast, the study by Sjölie and Ljunggren [50] indicated that low lumbar extension strength may be a risk factor for LBP later in life.

4.5 Strength and Limitations

To the best of our knowledge, this is the first meta-analysis to provide a quantitative and comprehensive evaluation of the range of future health parameters associated with muscular fitness during childhood and adolescence. Furthermore, our meta-analysis provides an update of the evidence reported within earlier reviews [3, 13].

There are some limitations that warrant discussion. First, the included studies were heterogeneous with respect to methodology, measurement of muscular strength, outcomes, length of follow-up, ethnicity, and potential confounders such as adiposity and CRF, which might explain the inconsistent findings. However, only a few pooled parameters (4/13: WC, skinfold thickness, diastolic blood pressure, and CVD risk score) in our meta-analysis showed high heterogeneity (i.e., $I^2 \geq 75\%$). Second, only two studies adjusted the outcome variable of interest for baseline values, a key issue with great implications for the interpretation of the temporal sequence and thus causality [78]. Third, most of the studies included children and adolescents in their analysis, and therefore sexual maturation could have affected baseline muscular fitness [78]. Fourth, due to sample loss, individuals examined at follow-up could have been unrepresentative of those at baseline, which could have led to overestimated or underestimated associations. Fifth, our pooled analysis included a variety of tests used to assess muscular fitness (i.e., strength, power or endurance) and that may lead to bias; however, the heterogeneity in most of the results was low-moderate. Finally, only three studies [17, 18, 48] used 'relative' muscular fitness (i.e., divided by body mass) to determine their relationship with health outcomes, and therefore the association can change and even reverse in comparison with 'absolute' muscular fitness (many weight-bearing muscular strength tests are correlated with body mass and/or adiposity) [79].

5 Conclusion

The present results show moderate-large relationships between muscular fitness in childhood and adolescence and future levels of BMI, skinfold thickness, HOMA-IR, triglycerides, CVD risk score, and BMD, but evidence for LBP was unconvincing. Therefore, the early identification and treatment of youth with low levels of muscular fitness could improve long-term health outcomes, since the prevention of chronic diseases should start as early in life as possible. Recommendations for future research include the exploration of whether sustained high levels or improving muscular fitness in children and adolescents leads to fewer health problems later in life [19, 29, 39].

Data availability statement The data that support the findings of this review are available on reasonable request from the corresponding author (Antonio García-Hermoso).

Compliance with Ethical Standards

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Conflict of interest Antonio García-Hermoso, Rodrigo Ramírez-Campillo, and Mikel Izquierdo declare that they have no conflicts of interest relevant to the content of this review.

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