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REVIEW ARTICLE

# The Health Benefits of Muscular Fitness for Children and Adolescents: A Systematic Review and Meta-Analysis

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**Abstract**

*Background* Physical fitness during childhood and adolescence has been identified as an important determinant of current and future health status. While research has traditionally focused on the association between cardio-respiratory fitness and health outcomes, the association between muscular fitness (MF) and health status has recently received increased attention.

*Objective* The aim of this systematic review and meta-analysis was to evaluate the potential physiological and psychological benefits associated with MF among children and adolescents.

*Methods* A systematic search of six electronic databases (PubMed, SPORTDiscus, Scopus, EMBASE, PsycINFO and OVID MEDLINE) was performed on the 20th May, 2013. Cross-sectional, longitudinal and experimental studies that quantitatively examined the association between MF and potential health benefits among children and adolescents were included. The search yielded 110 eligible studies, encompassing six health outcomes (i.e., adiposity, bone health, cardiovascular disease [CVD] and metabolic risk factors, musculoskeletal pain, psychological health and cognitive ability). The percentage of studies reporting statistically significant associations between MF and the outcome of interest was used to determine the strength of the evidence for an association and additional coding was conducted to account for risk of bias. Meta-analyses were also performed to determine the pooled effect size if there were at least three studies providing standardised coefficients.

*Results* Strong evidence was found for an inverse association between MF and total and central adiposity, and CVD and metabolic risk factors. The pooled effect size for the relationship between MF and adiposity was $r = -0.25$ (95 % CI $-0.41$ to $-0.08$). Strong evidence was also found for a positive association between MF and bone health and self-esteem. The pooled effect size for the relationship between MF and perceived sports competence was $r = 0.39$ (95 % CI 0.34–0.45). The evidence for an association between MF and musculoskeletal pain and cognitive ability was inconsistent/uncertain. Where evidence of an association was found, the associations were generally low to moderate.

*Conclusion* The findings of this review highlight the importance of developing MF in youth for a number of health-related benefits.

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## 1 Background

Physical fitness can be defined as the capacity to perform physical activity and is primarily determined by genetics and training [1, 2]. For most individuals, changes in the frequency, intensity, duration or type of physical activity will produce changes in physical fitness, although the amount of adaptation can vary considerably [3]. The fitness components that have been shown to directly relate to improvements in health are cardio-respiratory fitness (CRF) (also known as cardiovascular fitness, cardio-respiratory endurance and maximal aerobic power), flexibility, muscular strength, local muscular endurance and body composition [4–7]. More recently, the term 'muscular fitness' (MF) has been used to represent muscular strength, local muscular endurance and muscular power. Generally defined, muscular strength is the ability to generate force with a muscle or group of muscles; local muscular endurance is the ability to perform repeated contractions with a muscle or group of muscles under sub-maximal load; and muscular power refers to the rate at which muscles perform work [4, 7, 8].

Typically, children exhibit a gradual linear increase in muscular strength and muscular power from 3 years of age until puberty for boys, and until about 15 years for girls [9, 10]. These changes are closely associated with changes in body size and fundamental movement skill aptitude. After this time, boys show a dramatic acceleration of muscular strength until the age of 17 and beyond, and girls show a pronounced plateauing and regression in late adolescence and beyond [7]. Similarly, during childhood both boys and girls make gradual improvements in local muscular endurance, exhibiting similar relative endurance levels (adjusted for body mass) [7]. Importantly, the literature clearly states that performance of any movement task requires varying degrees of MF, given that all movements of the body engage the muscular system to move the skeleton [7]. Consequently, a stronger, more enduring and more powerful musculoskeletal system will enable children and adolescents to perform bodily movements more efficiently and effectively, and may decrease their susceptibility to sports-related injuries [11].

Recent global physical activity guidelines for youth emphasise participation in high-intensity physical activity and include a recommendation to perform 'muscle and bone strengthening' physical activities on at least 3 days per week [12]. Furthermore, supervised and appropriate resistance training activities have been recommended for children and adolescents in a recent international position statement [13]. Despite these guidelines and strong evidence for maintaining high levels of physical fitness, a decline in fitness levels in children and youth has been reported worldwide [14–22]. While much of the focus has been centred on the decline in CRF, a decline in levels of MF has also been observed in young people [20, 23–25]. However, it must be noted that there is no reliable standard assessment battery for the assessment of MF in children and adolescents, making comparisons over time, and between nations and groups, challenging [26, 27].

Traditionally, research investigating the link between physical fitness and health outcomes has focused on CRF, clearly demonstrating that it is strongly associated with health [2, 27]. However, several studies among adults examining the benefits of MF have also shown strong links to health [28–30]. These studies have not only demonstrated that MF is directly linked to all-cause mortality, but also that a threshold effect exists whereby no additional reduction in mortality risk is gained by increasing MF beyond a certain level [28–30]. The impetus for promoting adequate levels of MF in children and adolescents is based on the growing body of evidence associating MF with an array of health benefits. The emerging body of evidence has demonstrated that MF is favourably associated with adiposity [31], insulin sensitivity [32], bone health [33], psychological health and academic performance [34, 35]. Importantly, current literature suggests that many of these benefits are independent of CRF, providing a strong rationale for integrating different types of training into youth fitness programmes [36]. Recent studies also support the benefits of MF for improving sports performance and for injury prevention in young people [37]. Additionally, levels of MF in childhood have been shown to track into adulthood [2, 38] and are linked to future cardiovascular disease (CVD) risk [30, 39].

While there have been reviews of the benefits of health-related fitness in youth and the importance of MF for CVD risk reduction [2, 31], it appears that no previous systematic review has examined the association between MF in youth and the range of physiological and psychological benefits. Therefore, the purpose of this review is to systematically examine the association between MF in children and adolescents and the potential health benefits in each of these domains.

## 2 Methods

### 2.1 Identification of Studies

A systematic search of six electronic databases (PubMed, SPORTDiscus, Scopus, EMBASE, PsycINFO and OVID MEDLINE) was performed on 20th May, 2013 following consultation with an academic librarian. The following search strings were used: Musc* AND (strength OR endurance OR power) OR ('resistance training' OR 'weight training') AND (adolescen* OR teen* OR child* OR student* OR youth* OR school* OR young*) AND (health OR risk OR consequence* OR benefit* OR psych* OR behavio* OR effect*). No limits on date of publication were imposed; however, only articles published in refereed journals and in English language were considered for review. Conference proceedings, abstracts and theses were not included. Relevant articles were identified through two stages of screening performed independently and compared by two researchers. In the first stage, titles and abstracts of the search results were checked for relevance. In the second stage, full texts were located and assessed for eligibility. The reference lists of all included articles and previous reviews on the topic were also checked to identify any articles that were not located through the database search.

### 2.2 Criteria for Inclusion/Exclusion

Two authors independently assessed the eligibility of studies based on the following criteria. (i) Study participants were school-aged youth (i.e., 4–19 years) in the general population. Studies with targeted groups from special populations were excluded (e.g., athletes, clinically obese, subjects with mental illness etc.). Although studies have found that resistance training may be protective against sports-related injuries [11], the benefits of MF for young athletes was beyond the scope of this review. (ii) Study provided a quantitative assessment of MF (e.g., strength, power or local muscular endurance). (iii) Study provided a quantitative assessment of at least one potential benefit (e.g., insulin resistance, adiposity, self-esteem, etc.). (iv) Study provided a quantitative analysis of the association between MF and the potential benefit(s). (v) Study published in English in a peer-reviewed journal. Following independent assessment of eligibility, the two lists of included articles were compared. Any discrepancies were discussed and agreed upon prior to inclusion or exclusion. Consensus was reached on all articles included in the review.

### 2.3 Criteria for Risk of Bias Assessment

Two authors independently assessed the risk of bias of included studies, which occurred at the study level. The criteria for assessing risk of bias were based on the Consolidated Standards of Reporting Trials (CONSORT) statement [40] and the Studies in Epidemiology (STROBE) statement [41]. A risk of bias score was allocated to each study by assigning a value of 0 (criteria not met) or 1 (criteria met) based on the following: (i) study sites or participants were randomly selected and the randomisation procedure was adequately described; (ii) adequate description of the study sample (i.e., number of participants, mean age and sex); (iii) adequate assessment/reporting of MF (i.e., validity/reliability of fitness test reported and/or detailed description of testing protocols); (iv) adequate assessment of the potential benefit (i.e., validity/reliability of outcome measure reported and/or measurement procedure adequately described); and (v) adjustment for confounders (i.e., age and sex) in the statistical analyses where necessary. The scores for each criterion were summed to provide a total score out of 5. Studies that scored 0–2 were considered to have a 'high risk' of bias, those that scored 3 were considered to have a 'moderate risk' of bias, and those scoring 4–5 were considered to have a 'low risk' of bias. Inter-rater agreement for the risk of bias assessment was determined by the percentage agreement between raters. Furthermore, *Kappa* analysis was conducted using SPSS software, version 21.0 (SPSS Inc, Chicago, IL, USA).

### 2.4 Categorisation of Variables and Level of Evidence

Data were extracted into an Excel spreadsheet using a template designed specifically for the review. A separate author checked all of the extracted data for accuracy. If any additional data (e.g., coefficients for the associations) were required, the corresponding author of the included study was contacted by email. The outcome variable(s) of each study were grouped into two broad categories: 'physiological' (e.g., adiposity) and 'psychological and cognitive' (e.g., self-esteem). Results were coded using the method first employed by Sallis et al. [42], and more recently used by Lubans et al. [43]. If 0–33 % of studies reported a significant association, the result was classified as no association (0). If 34–59 % of studies reported a significant association or if fewer than four studies reported on the outcome, the result was classified as being inconsistent/uncertain (?). If ≥60 % of studies found a significant association, the result was classified as positive (+) or negative (−), depending on the direction of the association. Additional coding was performed to account for risk of bias using the method proposed by Lubans et al. [43]. If ≥60 % of studies with low risk of bias found a significant association then the result was classified as strong positive (++) or strong negative (− −), depending on the direction of the association. If studies employed multiple analyses, only findings from the highest level of analysis (i.e., multivariate) were considered.

### 2.5 Meta-Analyses

Meta-analyses were conducted to determine the pooled effect size between MF and the outcome of interest. Meta-analyses were conducted if at least three studies provided standardised coefficients between MF and potential benefits. Analyses were conducted using comprehensive meta-analysis software, version 2 for Windows (Biostat company, Englewood, NJ, USA) [44] with random effects

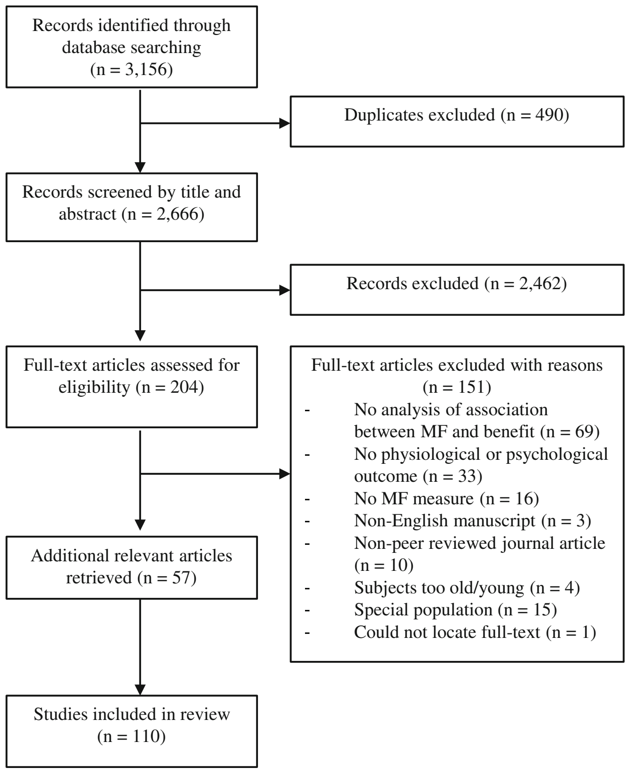


**Fig. 1** Flow of studies through the review process. *MF* muscular fitness

models. Heterogeneity was determined by Cochrane's *Q* statistic and $I^2$ values. For interpretation, $I^2$ values of 25, 50 and 75 were considered to indicate low, moderate and high heterogeneity, respectively [45]. Publication bias was analysed using Rosenthal's *classic fail-safe N* [46] and Duval and Tweedie's *trim and fill* procedure [47]. Correlations between variables were interpreted as follows: 0–0.19 (no correlation), 0.2–0.39 (low correlation), 0.4–0.59 (moderate correlation), 0.6–0.79 (moderately high correlation) and ≥0.8 (high correlation) [48].

## 3 Results

### 3.1 Overview of Studies

The systematic search yielded 2,666 potentially relevant articles following the removal of duplicates (Fig. 1). After full-text screening and checking the reference lists of included studies and previous reviews for additional relevant articles, a total of 110 studies were included. Of the included studies, 86 were cross-sectional, 20 were longitudinal and 4 were experimental. The number of study participants ranged from 20 [49] to 1,142,599 [30]. Further details on study characteristics are presented in Table S1 of the electronic supplementary material (ESM).

### 3.2 Overview of Study Quality

There was 95 % agreement between raters for risk of bias, and consensus was achieved on all included studies following discussion. Inter-rater agreement was found to be high ($\kappa = 0.86$, $p < 0.001$). The results of the risk of bias assessment can be found in Table S2 of the ESM. Overall, one study (1 %) was considered to have a high risk of bias, 34 studies (31 %) were considered to have a moderate risk of bias, and 75 studies (68 %) were considered to have a low risk of bias. 'Random selection of study sites or participants was the most poorly satisfied criterion with 54 studies (49 %) scoring zero. The most consistently satisfied criterion was 'adequate description of the study sample' with only four studies (4 %) scoring zero.

### 3.3 Physiological Benefits

A summary of the associations between MF and each of the potential benefits can be found in Table 1.

#### *3.3.1 Adiposity*

Fifty-one studies reported on the association between MF and measures of adiposity (e.g., body mass index [BMI], sum of skin-folds, waist circumference [WC] etc.). Forty-two studies were cross-sectional, seven were longitudinal, and two were experimental. A number of measures were used, both between and within studies, to measure adiposity. These measures can be broadly classified as measuring either total body fatness (e.g., BMI) or central body fatness (e.g., WC). Of the 50 studies reporting on the association between MF and measures of total body fatness, 45 (90 %) reported significant inverse associations. These associations were generally low to moderate. Nine of these studies however, also reported a significant positive association between one measure of MF and adiposity. Positive associations were only found for tests of MF in which the subject was not required to support their body weight during movement (e.g., handgrip strength). Performance in MF tests in which the subject was required to either lift their body weight (e.g., curl ups, push ups) or propel their body through space (e.g., vertical jump, standing long jump) was consistently found to be inversely associated with adiposity. Of the 37 studies with a low risk of bias, 33 (89 %) found a significant association, providing strong evidence of an inverse association with MF.

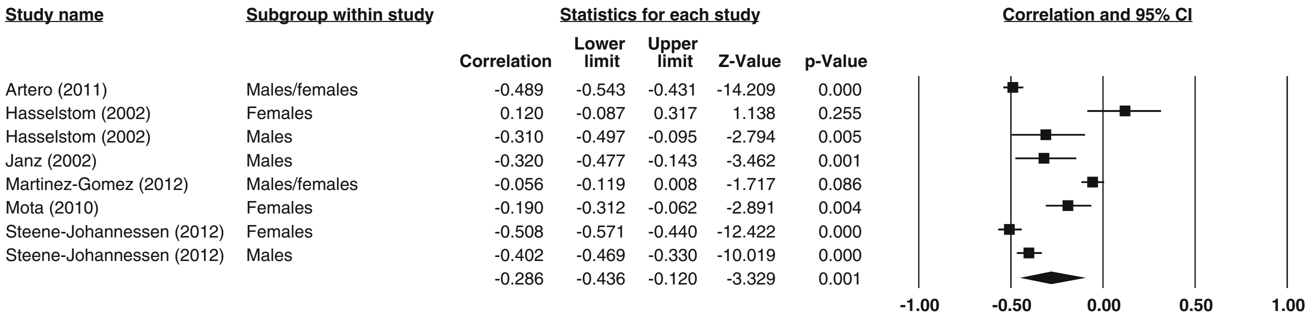
Fourteen studies examined the association between MF and central adiposity, which was most commonly measured by WC. Thirteen studies were classified as having low risk of bias. Overall, ten studies (71 %) found a significant association, including nine (69 %) studies with a low risk of bias, suggesting strong evidence of an inverse

**Table 1** Summary of studies examining the association between health benefits and muscular fitness

| Benefits | Associated with MF | Not associated with MF | Summary coding | |
|---|---|---|---|---|
| | References | References | n/N for benefit (%) | Association (+/−) |
| **Physiological benefits** | | | | |
| Adiposity | | | | |
| Total | [39, 50, 60, 70, 74–77, 81–83, 99, 130–160], 192, 193] | [161–165] | 45/50 (90) | − − |
| Central | [50, 56, 57, 74–76, 99, 135, 143, 158] | [39, 60, 161, 166] | 10/14 (71) | − − |
| Bone health | [33, 51, 53, 54, 94, 167–173] | [52, 55, 174–176] | 12/17 (71) | + + |
| CVD and metabolic risk factors | [30, 32, 39, 56–62, 99, 177–180] | [74, 75, 181–183] | 15/20 (75) | − − |
| Musculoskeletal pain | [64, 66, 109, 184–189] | [65, 73, 108, 110, 190, 191] | 9/15 (60) | ? |
| **Psychological and cognitive benefits** | | | | |
| Self-esteem | [69–73] | [49] | 5/6 (83) | + + |
| Cognitive ability | [35, 117, 118] | [119–121] | 3/6 (50) | ? |

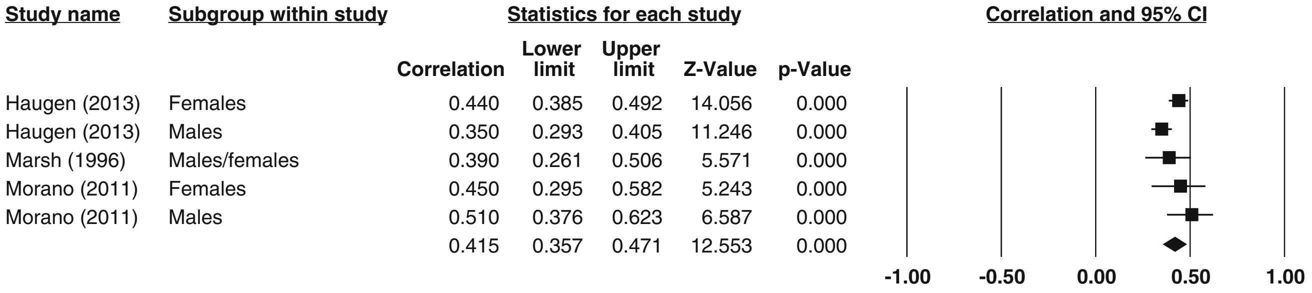
*CVD* cardiovascular disease, *MF* muscular fitness, *n/N* number of studies reporting a statistically significant finding/total number of studies reporting on the benefit

+ + strong evidence of a positive association, − − strong evidence of an inverse association, ? inconsistent/uncertain



| Study name | Subgroup within study | Correlation | Lower limit | Upper limit | Z-Value | p-Value |
|---|---|---|---|---|---|---|
| Artero (2011) | Males/females | -0.489 | -0.543 | -0.431 | -14.209 | 0.000 |
| Hasselstom (2002) | Females | 0.120 | -0.087 | 0.317 | 1.138 | 0.255 |
| Hasselstom (2002) | Males | -0.310 | -0.497 | -0.095 | -2.794 | 0.005 |
| Janz (2002) | Males | -0.320 | -0.477 | -0.143 | -3.462 | 0.001 |
| Martinez-Gomez (2012) | Males/females | -0.056 | -0.119 | 0.008 | -1.717 | 0.086 |
| Mota (2010) | Females | -0.190 | -0.312 | -0.062 | -2.891 | 0.004 |
| Steene-Johannessen (2012) | Females | -0.508 | -0.571 | -0.440 | -12.422 | 0.000 |
| Steene-Johannessen (2012) | Males | -0.402 | -0.469 | -0.330 | -10.019 | 0.000 |
| | | -0.286 | -0.436 | -0.120 | -3.329 | 0.001 |

**Fig. 2** Forest plot showing the relationship between muscular fitness and adiposity for included studies



| Study name | Subgroup within study | Correlation | Lower limit | Upper limit | Z-Value | p-Value |
|---|---|---|---|---|---|---|
| Haugen (2013) | Females | 0.440 | 0.385 | 0.492 | 14.056 | 0.000 |
| Haugen (2013) | Males | 0.350 | 0.293 | 0.405 | 11.246 | 0.000 |
| Marsh (1996) | Males/females | 0.390 | 0.261 | 0.506 | 5.571 | 0.000 |
| Morano (2011) | Females | 0.450 | 0.295 | 0.582 | 5.243 | 0.000 |
| Morano (2011) | Males | 0.510 | 0.376 | 0.623 | 6.587 | 0.000 |
| | | 0.415 | 0.357 | 0.471 | 12.553 | 0.000 |

**Fig. 3** Forest plot showing the relationship between muscular fitness and perceived sports competence for included studies

association between MF and central adiposity. There was one instance of a positive association being reported between handgrip strength and WC [50]. The associations for central adiposity were also generally low to moderate in magnitude.

A meta-analysis was conducted to determine the pooled effect size between MF and adiposity. All studies reporting partial correlation coefficients between MF and any adiposity variable were included. Using a random effects model, the pooled effect size was $r = -0.29$ (95 % CI $-0.44$ to $-0.12$), $Z = -3.33, p = 0.001$ (Fig. 2). Significant between-study heterogeneity was observed; $Q(7) = 174.89$, $p \leq 0.001$ and $I^2$ (96.00) indicated that 96 % of the observed variance was explained by true systematic effect size differences. Publication bias was considered unlikely with Rosenthal's *fail-safe N* [46] indicating that 686 unpublished studies with an effect size of zero would be required to alter the point estimate to not being statistically significant. However, Duval and Tweedie's *trim and fill* procedure, which attempts to improve the symmetry of smaller studies around the point estimate within the funnel plot, detected an asymmetrical distribution. Consequently, one study was trimmed and the adjusted effect size was slightly weaker ($r = -0.25$, 95 % CI $-0.41$ to $-0.08$).

### *3.3.2 Bone Health*

Seventeen studies examined the association between MF and measures of bone health. Thirteen studies were cross-sectional, three were longitudinal, and one was experimental. Bone mineral density, bone mineral content, and bone area were the most commonly examined indices of bone health in included studies and one study [51] investigated the effect of muscular strength on fracture risk. Overall, 12 studies (71 %) reported a significant association. Of the nine low-risk-of-bias studies, eight (89 %) reported a statistically significant finding suggesting strong evidence of positive association. The evidence from prospective studies was less conclusive. Of the three longitudinal studies [52–54], two [53, 54] found that MF and bone mass were significantly related. However, in the only randomised controlled trial (RCT) [55], changes in MF were not significantly related to changes in bone mass.

### *3.3.3 Cardiovascular Disease (CVD) and Metabolic Risk Factors*

Twenty studies examined the association between MF and CVD and metabolic risk factors. Fifteen studies were cross-sectional and five were longitudinal. Overall, 15 studies (75 %) found a significant association. Of the 17 low-risk-of-bias studies, 13 (76 %) reported that CVD and metabolic risk factors were significantly associated with MF, suggesting strong evidence of an inverse association. Strong evidence was found for an association between MF and clustered CVD risk with six (86 %) of the seven studies examining this outcome reporting statistically significant findings. MF was also found to be significantly related to insulin resistance [32, 56, 57], inflammatory biomarkers [58–62], and both all-cause mortality and mortality due to CVD [63].

### *3.3.4 Musculoskeletal Pain*

Fifteen studies examined the association between MF and musculoskeletal pain. Nine were cross-sectional and six were longitudinal. These studies generally investigated the role of local muscular endurance of the trunk flexors and extensors in relation to lower back or neck pain. Overall, nine studies (60 %) reported finding a significant inverse association between MF and musculoskeletal pain. Of the eight low-risk-of-bias studies, four (50 %) found that MF and pain symptoms were significantly associated, suggesting inconsistent/uncertain evidence of an inverse association. The results of longitudinal studies were equivocal with three [64–66] of the six studies reporting that MF and musculoskeletal pain were related.

## 3.4 Psychological and Cognitive Benefits

### *3.4.1 Psychological Benefits*

Eight studies, seven cross-sectional and one experimental, investigated the association between MF and psychological benefits. Six were classified as having a low risk of bias. Six studies investigated the association between MF and self-esteem/physical self-perceptions, while the remaining studies investigated other psychological indices including life satisfaction, depressed mood and risk of mental illness and suicide. Of the studies investigating the link between MF and self-esteem/physical self-perceptions, five (83 %) found a significant association for one or a number of constructs. Self-perceptions were examined using instruments developed for the general population. However, the names of certain subscales can vary between instruments. For example, Harter's self-perception profile for adolescents [67] measures perceived *athletic* competence whereas Whitehead's children's self-perception profile [68] measures perceived *sports* competence. Similar subscales were grouped together for this summary. The constructs shown to be consistently related with MF were perceived physical appearance (including perceived body fatness) [69–71], perceived sports competence (including perceived athletic competence and physical ability) [69–71], overall physical self-worth [71, 72] and global self-esteem [71, 73]. Conversely, the single experimental study [49] showed that changes in MF were not related to changes in any physical self-perceptions. The studies investigating other psychological outcomes also generally reported significant findings.

A meta-analysis was conducted to determine the pooled effect size between perceived sports competence and MF, as this was the only construct for which data were available from at least three studies. The random effects model yielded an overall effect size of $r = 0.42$ (95 % CI 0.36–0.47), $Z = 12.55$, $p < 0.001$, indicating a moderate positive association (Fig. 3). Between-study heterogeneity was not significant $Q(4) = 8.35$, $p = 0.08$. However, $I^2$ (52.09) indicated that 52 % of the observed variance could be explained by systematic differences in effect sizes, suggesting moderate heterogeneity. Publication bias was considered unlikely as demonstrated by Rosenthal's *classic* *fail-safe N* [46], which indicated that 471 unpublished studies with an effect size of zero would be required to cause the pooled point estimate to become statistically insignificant. Duval and Tweedie's *trim and fill* procedure [47] detected asymmetry in the distribution of observed effect sizes. Consequently, the adjusted value became slightly weaker ($r = 0.39$, 95 % CI 0.34–0.45).

#### 3.4.2 *Cognitive Benefits*

Six studies investigated the association between MF and cognitive benefits (e.g., academic performance), all of which were cross-sectional. Four studies were considered to have a low risk of bias. Of the six included studies, three (50 %) reported a significant association between MF and cognitive ability. Only one of the low-risk-of-bias studies reported a significant association, suggesting inconsistent/uncertain evidence of an association between MF and cognitive benefits.

## 4 Discussion

### 4.1 Overview of Findings

The aim of this systematic review and meta-analyses was to comprehensively evaluate the range of physiological and psychological health benefits associated with MF among children and adolescents. Overall, 110 studies encompassing six health outcomes (i.e., adiposity, bone health, CVD and metabolic risk factors, musculoskeletal pain, psychological health and cognitive ability) were reviewed. Strong evidence for an inverse association with MF was found for adiposity, and CVD and metabolic risk factors. We also found strong evidence for a positive association between MF and bone health and self-esteem (including physical self-concept, perceived physical appearance, and perceived sports competence). The evidence of an association between MF and musculoskeletal pain and cognitive ability was considered to be inconsistent/uncertain.

### 4.2 Physiological Benefits

#### 4.2.1 *Adiposity*

The findings of this review provide strong evidence of an inverse association between MF and both total and central adiposity. The associations were generally low to moderate as demonstrated by the pooled effect size of $r = -0.25$. Excess body fat was consistently associated with poor performance in MF tests that require lifting or propulsion of the body mass. Notably, data from the HELENA (healthy lifestyle in Europe by nutrition in adolescence) study [50], adjusted for multiple confounders, showed consistent moderate inverse associations between jumping-based MF tests and adiposity measured using multiple methods including dual-energy X-ray absorptiometry. Cross-sectional evidence was supported by longitudinal studies which showed reductions in adiposity over time with increases in muscle strength [74–76]. Furthermore, in a large sample of nearly 2,800 US children [77], it was found that both achieving and maintaining 'adequate' MF over a 4-year period resulted in significantly greater odds of being a healthy weight at follow-up.

These data are suggestive of a cause and effect association by which improvements in MF lead to reductions in body fatness. The specific mechanisms through which this may occur are likely to be complex, numerous and interacting. However, as obesity is driven by an energy imbalance [78], with energy surplus being stored as fat tissue, it can reasonably be hypothesised that the protective effects of MF are related to its role in energy expenditure. Skeletal muscle is known to be a highly energetic tissue, contributing substantially to basal metabolic rate [79]. Therefore, improvements in MF may reflect increases in skeletal muscle mass, the metabolic efficiency of muscle (i.e., lipid oxidation and glucose transport capacity), or both, resulting in greater overall daily energy expenditure [50, 79]. Improvements in MF may also make physical activity easier to perform and hence more enjoyable [80], resulting in greater activity energy expenditure over time. However, this association is probably bidirectional with increases in both fitness and fatness likely to impact on physical activity participation [50, 81].

Contrary to the findings of weight-bearing MF tests, the literature consistently showed a positive association between handgrip strength and adiposity. A number of investigators have attributed this to higher levels of lean mass among the overweight youth [50, 82]. However, Artero et al. [83] found that, at least for boys, the higher handgrip strength observed among overweight adolescents could not be explained by differences in fat-free mass, concluding that unmeasured morphological and/or neurological factors might be influencing the association. While it is possible that weight-bearing tests of MF (i.e., standing long jump, vertical jump, etc.) are simply capturing variation in body mass and not necessarily variation in MF, we do not believe this to be the case. Milliken et al. [84] found that vertical jump and standing long jump performance were significant predictors of 1RM leg press, the criterion measure of lower body strength. Therefore, these tests can be considered appropriate for assessing the relationship between MF and health outcomes. Further, longitudinal studies have shown that changes in MF measured both in absolute terms [76] and relative to body weight [74, 75] are inversely associated with adiposity. Despite the apparent contradiction, there appears to be clear evidence of the importance of MF for adiposity among youth, which may occur through both physiological and psycho-behavioural mechanisms.

### *4.2.2 Bone Health*

Youth has been identified as a critical stage for determining lifelong skeletal health [79]. During puberty in particular, bone tissue is highly responsive to osteogenic stimuli [55]. This has led researchers to investigate the potential of optimising peak bone mass during youth for the primary prevention of osteoporosis in adulthood [85, 86]. A high bone mass during youth is also protective against the risk of immediate fracture [87], especially as participation in 'risky' physical activities is highest during this time [79]. While peak bone mass is predominantly determined by genes [88], a number of modifiable determinants including physical activity, calcium intake and MF have been identified [89–91]. The findings of our review support the latter, with the majority of low-risk-of-bias studies demonstrating a significant association between MF and bone health. However, as the majority of studies were cross-sectional, we are unable to form strong conclusions regarding the prospective association between MF and bone health. In one of the few longitudinal studies, Cheng et al. [52] found that MF was not a predictor of bone mass among a sample of Asian adolescents. However, bone mass is in part racially determined [92, 93] and consequently these findings may not be generalisable to different ethnic groups. In a school-based RCT, Weeks et al. [55] found that changes in bone mass measured at multiple sites could be explained by changes in lean mass but not by changes in MF. Alternatively, a 20-year follow-up study found site-specific associations between curl-ups performance during adolescence and bone mineral density in adulthood [54].

One consistent finding between studies was of the importance of lean mass in explaining bone mass variation. Lean mass was found to be a strong predictor of bone mass, in some cases independently explaining more than 60 % of the observed variance [33, 94]. Associations between MF and bone mass on the other hand were considerably weaker. As improvements in muscular performance would be expected to accompany increases in lean mass, MF may be most useful as an inexpensive and reproducible surrogate for lean mass, enabling the identification of youth with a heightened risk of poor skeletal health [33]. Alternatively, MF may be a proxy for past physical activity, indirectly influencing bone mineralisation through increasing lean mass during pubertal growth [95]. More longitudinal and experimental studies are required to ascertain the relative contribution of physical activity and MF—and their interaction with lean mass—to improvements in bone health. Regardless, the rationale for increasing peak bone mass during youth through activities that both require and develop MF appears sound.

### *4.2.3 CVD and Metabolic Risk Factors*

While the clinical symptoms of CVD typically manifest in adulthood, evidence suggests that the genesis of CVD occurs in youth; with elevated levels and clustering of known risk factors evident in childhood [96, 97]. As CVD risk factors track from youth to adulthood [98], adolescence represents an opportunity to mitigate population-level health burden through preventive strategies. The studies included in this review provide strong evidence for the importance of MF during youth for CVD risk and extend on the inconclusive findings from an earlier systematic review [31]. In addition to clustered CVD risk, studies also demonstrated that MF was associated with insulin resistance [32, 56, 57], inflammatory biomarkers [58–62] and both all-cause and CVD-related mortality [30].

CRF is known to be a strong predictor of CVD risk [2], but importantly, MF was found to be associated with CVD risk independent of CRF and other confounders [56, 57]. This was confirmed longitudinally among Danish adolescents taking part in the European Youth Heart Study [39], suggesting that there is both a combined and additive effect of MF on CVD outcomes. The association was found to be non-linear with the greatest benefits achieved by increasing MF levels from low to moderate, with little additional benefit received thereafter [56, 57, 99]. Interestingly, the protective effect of MF was found to be most distinct amongst overweight youth [56, 57]. This finding is encouraging as overweight youth are a group already at increased risk of CVD and metabolic disorders in later life [100, 101]. Increasing MF in overweight youth, particularly from low to moderate levels, may be an effective strategy for improving the health trajectory of this 'at-risk' group. Additionally, overweight youngsters tend to experience greater self-efficacy and enjoyment in MF-based activities compared with those that demand a greater cardio-respiratory capacity [102]. Intervention programmes involving a 'muscular' focus (e.g., resistance training) may therefore result in greater adherence and satisfaction among overweight youth, as demonstrated in previous studies [103, 104]. Future research should determine the clinical significance of changes in MF during youth for CVD and metabolic outcomes in later life [39].

### *4.2.4 Musculoskeletal Pain*

A sharp increase in musculoskeletal pain symptoms has been observed during the time around puberty [105] and pain symptoms during youth have been shown to predict pain in adulthood [106]. Furthermore, the prevalence of back pain among children and adolescents may be as high as 25 % [107]. The findings of studies included in this review were equivocal, indicating that the association between MF and musculoskeletal pain remains unclear, which is consistent with the findings of an earlier review [31]. While some studies found that increased trunk muscle strength and local muscular endurance were protective against back and neck pain, others found no association. One study reported that greater back strength increased the risk of low back pain [108] while another reported that both reduced and greater back muscular endurance were associated with back pain [109]. It is important to note that cross-sectional studies cannot determine causality and reverse causation is equally plausible—low activity levels and poor MF may cause back pain or vice versa [110]. Evidence from longitudinal studies should confirm or refute causality but at present they too appear somewhat equivocal. The available evidence currently supports the potential for an inverse association between MF and musculoskeletal pain. However, more high-quality longitudinal investigations are required to confirm previous findings and explain the contradictory reports identified within other studies.

## 4.3 Psychological and Cognitive Benefits

### *4.3.1 Psychological Benefits*

Poor mental health is a significant public health issue for youth [111], and mental illness is expected to be the leading disease burden globally by 2020 [112]. Identifying the determinants of mental health problems is important for informing public health strategies, particularly those with a preventive focus. Global self-esteem, an important element of well-being [113], is typically considered to be at the apex of a hierarchical framework made up of domain-specific constructs (i.e., physical self-worth), which are further subdivided into specific self-perceptions [71]. The findings of this review suggest evidence of an association between MF and physical self-perceptions, namely perceived physical appearance (including perceived body fatness) and perceived sports competence (including perceived physical ability and athletic competence). Furthermore, there is evidence for an association between MF and overall physical self-worth and global self-esteem. According to Harter's competence motivation theory, actual competence precedes perceived competence in the causal pathway [114]. Perceptions of competence are hypothesised to influence physical activity participation through decreased motivation to be active. As suggested by Stodden et al. [115], this can result in a self-perpetuating cycle of disengagement among less capable youth. Successful sports performance is largely dependent on fitness-related attributes, therefore the moderate association found between MF and perceived sports competence is not overly surprising. However, this association reinforces the argument for developing adequate fitness, particularly during childhood, in order to improve opportunities for success and increase the likelihood of lifelong physical activity. Increasing physical activity can be considered an important public health objective not only for the known physical health benefits but also for its role in the prevention and treatment of psychological ill health [116]. The finding that a low level of muscular strength during adolescence was associated with a greater risk of psychiatric diagnosis and suicide in later life [30] highlights the relevance of MF for positive psychological health.

### *4.3.2 Cognitive Benefits*

There was considerable heterogeneity between measures used to assess cognitive ability, making comparisons between these particular studies problematic. As such, these findings must be interpreted with caution. In addition, as all of the studies reviewed herein were cross-sectional, no evidence on causality can be provided. The evidence for an association between MF and cognitive ability was considered inconsistent/uncertain. While Dwyer et al. [117] found significant associations between MF and 'scholastic ability' among 7- to 15-year-old youths; this was a subjective rating made on a simple 5-point scale and therefore may not represent true academic ability. Coe et al. [35] and Du Toit et al. [118] also reported significant associations between MF and academic performance, but analyses were not adjusted for important covariates. Alternatively, the studies that controlled for potential confounders such as age and sex [119–121] found no association between MF and academic ability. Previous research has linked CRF and physical activity to cognitive ability [122, 123]; however, it is unknown whether physical activity and CRF improve cognitive functioning or whether they are simply markers of motivated and high-achieving youth [121]. Potential mechanisms for this association have been hypothesised and include neuroplastic responses from increased blood flow and the release of brain derived neurotrophic factor [124]. Alternatively, CRF may influence executive control enabling better performances in complex cognitive tasks [125]. While there appears to be support for the importance of CRF, the available evidence is unclear on the link between MF and cognitive ability.

## 4.4 Strengths and Limitations

Although other reviews on this topic are available [2, 31], they have focused on the benefits and 'predictive validity' of health-related fitness in general. While longitudinal data can provide stronger evidence for the link between MF and health, it is important to acknowledge and review evidence from cross-sectional studies. To the authors' knowledge, this is the first review to provide a systematic and comprehensive evaluation of the range of physiological and psychological benefits associated with MF among children and adolescents. Furthermore, our review provides an update of the evidence reported within earlier reviews. Strengths of our review include the large number of included studies covering a variety of relevant domains and additional coding for risk of bias in the quantitative synthesis. However, the former also introduced some limitations. Discussion of the broad range of potential benefits of MF precluded a more detailed examination of potential moderators of the observed associations. Whether or not the associations were moderated by age, sex or ethnicity is likely to be of importance to researchers, physical educators and health professionals. However, this was beyond the scope of our review. Further, it must be noted that we did not review the benefits of MF for the prevention of sports-related injuries. Previous research has indicated that resistance training as part of a preparatory conditioning programme is effective for reducing the risk of injury during sports participation [11]. Additionally, as inactive children are at greater risk of injury in both physical education and leisure-time physical activity contexts [126], resistance training may also assist those not participating in organised sport to safely engage in physical activity. However, in order for our review to be generalisable to the wider youth population we excluded studies specifically targeting young athletes during the screening process.

### 4.5 Future Research

The paucity of longitudinal and experimental studies prevented us from drawing stronger conclusions on causal relationships for a number of outcomes. Experimental studies have measured changes in MF and the outcomes included in this review [103, 127–129]. However, these studies often focus on examining time and group effects, and usually fail to investigate the *association* between changes in MF and changes in the outcome. In this respect, the importance of MF specifically for these outcomes can be deduced but not confirmed. More high-quality longitudinal and experimental studies are required to investigate causality and to determine the clinical significance of changes in MF for health-related outcomes. In particular, further study of the effects of MF on psychological well-being is needed. Large-scale longitudinal studies examining the effect of resistance training or changes in MF on aspects of cognitive ability (i.e., executive function) are also warranted. Few studies included in our review reported standardised coefficients, preventing more comprehensive meta-analyses of the associations between MF and potential benefits. Future studies should report standardised coefficients to allow for simpler comparisons of study findings and to enable more thorough meta-analyses of the associations between MF and health outcomes. Finally, as was evident in studies examining the relationship between MF and adiposity, the association can change, and even reverse, depending on whether an 'absolute' or 'relative' (i.e., divided by body mass) measure of MF is used. In future studies, investigators should consider the type of MF test used and decide on the most appropriate method for expressing MF in their analyses. As performance in many weight-bearing MF tests is highly correlated with body mass/adiposity [130], analyses of the relationship between MF and the health outcome of interest should adjust for this variable in order to ascertain the independent contribution of MF.

## 5 Conclusions

This systematic review comprehensively evaluated the range of potential benefits of MF among children and adolescents. We conclude that:

1. there is strong evidence for a positive association between MF and bone health and self-esteem, although the associations are low to moderate;
2. there is strong evidence of an inverse association between MF and total and central adiposity, and CVD and metabolic risk factors, although the associations are also low to moderate; and
3. the associations between MF and musculoskeletal pain and cognitive ability are inconsistent/uncertain.

The findings of this review lend support to current physical activity guidelines that recommend youth regularly engage in muscle-strengthening physical activities [12]. School- and community-based youth programmes should include activities that develop muscular strength, local muscular endurance and muscular power in addition to other health- and skill-related components of physical fitness. These findings are of relevance to physical educators, healthcare professionals, policy makers, and researchers interested in paediatric health.

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