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The authors declare no conflicts of interest. The results of the study are presented clearly, honestly, and without fabrication, falsification, or inappropriate data manipulation. The results of the present study do not constitute endorsement by the American College of Sports Medicine.

## ABSTRACT

**Purpose:** To promote greater muscular strength across the life course and in turn, help improve long-term health outcomes, strategies aimed at increasing muscular strength are required. To inform these strategies, this study identified childhood factors associated with muscular strength trajectories. **Methods:** Prospective longitudinal study of 1,280 Childhood Determinants of Adult Health participants who had a range of potentially modifiable factors (e.g., anthropometric measures, physical activity) and health and risk motivation items (e.g., attitudes, beliefs, and intentions on health-related actions) measured in childhood and had their muscular strength assessed up to three times between childhood and midlife. Associations between childhood factors and three predetermined life course muscular strength trajectories (identified previously using group-base trajectory modelling as: above average and increasing; average; below average and decreasing) were examined using log multinomial regression. **Results:** Greater physical fitness, physical activity, fat-free mass, enjoyment of physical activity, physical education, and school sports, and positive attitudes regarding the importance of exercising, staying fit, and body image were associated with a lower likelihood of being in the below average and decreasing muscular strength trajectory (relative risk range: 0.45–0.98). Greater physical fitness, physical activity, and fat-free mass, and attending an independent school were associated with a higher likelihood of being in the above average and increasing muscular strength trajectory (relative risk range: 1.03–1.93). **Conclusions:** As well as providing health benefits in the short term, physical activity, physical fitness, positive health attitudes and healthy weight in childhood may lead to better muscular strength in the long term.

**Key Words:** CHILD, ADOLESCENT. MUSCLE STRENGTH. EPIDEMIOLOGY. COHORT STUDIES, LONGITUDINAL STUDIES

## INTRODUCTION

Muscular strength is defined as the ability of a muscle or muscle group to exert force (1). In childhood, greater muscular strength is associated with improved short- and long-term health outcomes (2-4), including a decreased risk of premature mortality in adulthood (5). Despite recommendations for muscle-strengthening activities three days each week (6) and evidence highlighting a range of health benefits associated with greater muscular strength in childhood (2, 3), in 2017–18, only 15.8% of Australians aged 15–17 years met recommended amounts of muscle-strengthening activities (7) and the muscular fitness levels of children have declined in recent years (8, 9). This is concerning, since childhood muscular strength levels persist, or track, into adulthood (10, 11), and low levels of adult muscular strength associate with increased risk of all-cause and cardiovascular mortality (12). Lifelong engagement in muscle-strengthening activities may help to maintain higher levels of muscular strength into adulthood, which could help prevent adverse health outcomes. Furthermore, knowing how to maintain muscular strength through the life course at the population level might be important in the prevention of sarcopenia, a major risk factor for falls, frailty, functional decline, and loss of independence in older adults (13).

The need for strategies aimed at promoting muscular strength in childhood was made apparent when muscular strength trajectories between childhood and midlife were identified using data from the Australian-based Childhood Determinants of Adult Health (CDAH) Study (11). Participants were broadly grouped as having above average and increasing, (persistently) average, or below average and decreasing muscular strength levels between childhood and midlife (11) using group-based trajectory modelling (14). It was concluded that children with below average muscular strength are likely to have below average muscular strength levels in adulthood unless

strategies aimed at increasing muscular strength levels are introduced (11). To help inform these strategies and promote greater adherence to more favourable muscular strength trajectories, childhood factors associated with muscular strength trajectories need to be identified. Although modifiable and environmental factors associated with childhood muscular fitness have been suggested (15, 16), no study has identified childhood factors that could be targeted to improve muscular strength trajectories. Therefore, using data from the CDAH Study, we aimed to determine the childhood factors associated with muscular strength trajectories (11).

## **METHODS**

### **Participants**

In 1985, a nationally representative sample of Australian schoolchildren (7–15 years) participated in the Australian Schools Health and Fitness Survey (ASHFS). The ASHFS sampling strategy has been detailed elsewhere (17). As part of the ASHFS, measures of muscular fitness, anthropometry and cardiorespiratory fitness (CRF) were collected, and participants completed questionnaires where physical activity, sociodemographic, and health and risk motivation items were reported. Participants were followed up twice in adulthood (2004–06: 26–36 years; 2014–19: 36–49 years) when their muscular strength was remeasured. Included in this study were 1,280 participants who had at least two muscular strength measures. These measures were used to determine muscular strength trajectories in this cohort (11). The ASHFS was approved by the State Directors General of Education and the two adult follow-ups were approved by the Southern Tasmania Health and Medical Human Research Ethics Committee and the Tasmania Health and Medical Human Research Ethics Committee. In childhood, consent was obtained from parents and assent from children; at adult follow-ups, the participant provided written informed consent.

## **Muscular strength trajectories**

The muscular strength trajectories examined in this study were identified in our previous publication, in which we provide a detailed overview of how muscular strength was measured at each of the three life stages and how the muscular strength trajectories were identified using group-based trajectory modelling (11). Briefly, at all three time points, muscular strength was measured as right and left grip strength, shoulder flexion and extension, and leg strength using dynamometers. Measures of muscular strength not attributable to body mass were created (by regressing each muscular strength measure on body mass and using the residuals added to the grand mean) and were then age- and sex-standardised. A combined muscular strength score (including all five age- and sex-standardised measures of muscular strength not attributable to body mass) at each time-point was then created by principal component analysis (11). The three muscular strength trajectories we identified via group-based trajectory modelling (14), using the Stata *traj* command (18), between childhood and mid-adulthood were: below average and decreasing muscular strength, (persistently) average muscular strength, and above average and increasing muscular strength (11).

## **Anthropometric measures**

Body mass was measured using regularly calibrated scales to the nearest 0.5 kg in childhood and to the nearest 0.1 kg using Heine scales (Heine, Dover, NH) in adulthood. Childhood height was measured to the closest 0.1 cm using a KaWe height tape (KaWe Kirchner & Wilhelm, Aspeg, Germany). Body mass index (BMI) was calculated as body mass divided by height squared. Cole's international cut-points for children were used to categorise participants' BMI levels as normal weight or overweight/obese (19). Waist circumference was measured to the nearest 0.1 cm at the

level of the umbilicus using a constant tension tape. The skinfolds of the tricep, bicep, subscapular, and suprailiac were measured to the nearest 0.2 mm using Holtain calipers (Holtain, Crymych, UK). The log of the sum of the four skinfolds was used to calculate body density and fat percentage using age-specific regression estimates (20, 21). Body fat was calculated from body density using the Siri Formula (22). Fat-free mass was estimated as the difference between fat mass and total body mass.

### **Muscular power**

The longest distance (cm) recorded from two attempts at a standing long jump test, where a two-footed take-off and landing was required, was used as one measure of muscular power. This value was regressed on body mass and the residuals were used to create a measure of standing long jump distance not attributable to body mass. Muscular power was also assessed as the time to complete a 50 m run (to the nearest 0.01 of a second), with a lower run time reflecting a better result.

### **Cardiorespiratory fitness (CRF)**

The time it took children (7–15 years) to run/walk 1.6 km was timed (in minutes), with longer run/walk times reflecting lower CRF levels. Physical work capacity at 170 beats per minute ( $PWC_{170}$ ) was also calculated for children 9, 12 and 15 years. Using a Monark 818E bicycle ergometer (Monark Exercise AB, Vansbro, Sweden), this sub-maximal test included three successive three-minute workloads that incrementally increased resistance. Heart rate and watts were recorded in the final minute of each workload. These data were then plotted and extrapolated to calculate  $PWC_{170}$ . The absolute workload achieved in this test is a function of muscle mass,



therefore we created measures of  $PWC_{170}$  not attributable to fat-free mass (by regress  $PWC_{170}$  of fat-free mass and using the residuals added to the grand mean) (16).

### **Flexibility**

The sit and reach test was used to measure flexibility. Participants sat with straight legs and the soles of both feet flat against the front of a sit and reach box. They then reached forward as far as they could. After holding this position for three seconds, a research technician recorded the distanced reached by the participants' fingertip to the nearest complete centimeter, with a positive result meaning a participant could reach past their toes and a negative result meaning a participant could not reach their toes (16). The best of two attempts was used in analyses.

### **Physical activity**

A questionnaire relating to sport and exercise participation, including parental exercise habits, was administered to children 9–15 years. Under the supervision of trained assessors, children completed this questionnaire in groups of four and physical activity levels were determined from their responses. “Non-school physical activity” (sum of active commuting and leisure time physical activity) and “school physical activity” (sum of school physical education and school sport) levels were determined, with total weekly physical activity levels estimated as the sum of all individual physical activity domains (23). In this study, participants were categorized as meeting physical activity recommendations if their total weekly physical activity levels were greater than 420 minutes, a proxy for 60 mins/day (6). Participants were also asked “In most weeks, do you get exercise or activity 3 or 4 times which makes you huff and puff and at least 30 minutes each time?” and responded with either “yes” or “no”.

### **Socioeconomic factors**

Children attended state (public or non-fee paying), Catholic (private or fee-paying) or independent (private or fee-paying) schools. Each child's scholastic level was assigned by each school and responses were grouped as excellent/above average, average, below average/poor. The Australian Bureau of Statistics Socio-economic Index for Areas (SEIFA) and 1981 census data were used to categorise area-level socioeconomic status (SES) based on residential postcode as high, medium-high, medium-low, and low.

### **Health and risk motivation items**

As previously described (24), health and risk motivation items were operationalised as encompassing cognitions (e.g., attitudes, beliefs and intentions) focused on actions that can attain or maintain health. Participants self-reported how important it is to them to have a good figure, exercise regularly, to not be fat, and to know about fitness and how to stay fit. Responses were grouped as "some/little/none" and "high". Participants were asked whether they enjoy physical activity ("yes" or "no") and whether they enjoy school ("all of the time", "most of the time", "some of the time", or "a little of the time/none of the time"). They were also asked whether they enjoy physical education classes and school sports (separately), with responses categorized as "not much/not at all" and "very much/quite a lot/sometimes". Children who responded with "don't have it" or "don't do it" were excluded from analyses.

### **Other covariates**

"How fit do you think you are compared to others your age?" and "How are you at schoolwork compared to others of your age?" was also asked of the participants, with "better than", "same as"

or “worse than” the available responses. Participants self-rated their health, and responses were collapsed as “average/poor/very poor” and “very good/good”. Responses to the question “Does your mother exercise regularly?” and “Does your father exercise regularly?” helped inform parental physical activity levels, with responses grouped as both parents active, one parent active, or both parents inactive.

### **Statistical analyses**

All statistical analyses were performed using Stata (version 16.0, StataCorp, College Station, TX).

### *Demographics*

Participant characteristics are stratified by trajectory group and are presented as mean (standard deviation [SD]) or median (interquartile range) for continuous variables or proportion (number of participants) for categorical variables.

### *Muscular strength trajectories*

To minimize the effect of misclassification associated with trajectories identified using group-based trajectory analysis, only participants attributed to their trajectory class with 70% or greater posterior probabilities were included in the analyses. The 70% threshold has been identified as a minimum rule of thumb recommended at the group level (i.e., the average posterior probability should be at least 0.7 for all trajectory groups) (14), that we have applied at an individual level. Of the 1,280 participants with trajectory data, 170 participants (13.3%) were excluded from primary analyses (below average and decreasing:  $n=54/339$  (15.9%); average:  $n=83/785$  (10.6%); above average and increasing:  $n=33/156$  (21.2%)), leaving 1,110 participants (86.7%) with posterior

probability values  $\geq 0.7$  (below average and decreasing:  $n=285$ ; average:  $n=702$ ; above average and increasing:  $n=123$ ). All univariable associations were repeated on the unrestricted sample ( $n=1280$ ).

### *Factors associated with muscular strength trajectories*

Factors associated with muscular strength trajectories were identified using log multinomial regression models (25). The relative risk (RR) and 95% confidence intervals (CI) of a participant being in a muscular strength trajectory group per one unit increase in a continuous variable or for each level of a categorical variable were quantified. When using a log multinomial regression model, one level of the categorical outcome is redundant, or excluded (25). The ‘average muscular strength’ trajectory group was the excluded outcome group for all analyses. Adapting an approach by Seaman et al (26), inverse probability weighting with multiple imputation of incomplete baseline data was used to account for missing data at follow-up. All models were adjusted for childhood age and sex.

When modelling the association between  $\geq 420$  mins/week of physical activity and each muscular strength trajectory group, we noted that although the association was in the expected direction, it was only marginally statistically significant. We were left wondering, at what level of total weekly physical activity an association with muscular strength trajectory groups first becomes evident in this dataset. Addressing this question helped us better understand how total weekly physical activity was associated with long-term muscular strength levels. We created design variables of total weekly physical activity (i.e., divided total weekly physical activity levels into as many groups as practical, with at least 5 observations in each design variable–muscular strength

trajectory combination) and examined the association between these total physical activity design variables and muscular strength trajectories (using log multinomial regression models) (27). We then examined the pattern of coefficients to assess whether there was a point at which an association became apparent. This weekly total physical activity level cut-off was then used in all further analyses.

Given the large number of factors that were significant at the univariable level and to help preserve sample size, a multivariable model that included all individual factors associated with muscular strength trajectory groups was not feasible. Alternatively, one factor from each of the exposure groups (i.e., fitness; anthropometric measures; physical activity; socioeconomic factors; health and risk motivation items; other covariates) that had the strongest univariable association were carried forward and included in a multivariable model (additionally adjusted for baseline age and sex).

## **RESULTS**

### **Demographics**

Participant characteristics are presented in Table S1 (see Supplemental Digital Content, <http://links.lww.com/MSS/C662>). The average length of follow-up between childhood and young adulthood was 19.8 (0.6) years and between childhood and mid-adulthood was 32.3 (1.3) years.

### **Factors associated with muscular strength trajectories**

To ensure full disclosure of the factors investigated in this study, the associations between a range of childhood factors and muscular strength trajectories are presented in Table 1 and Table 2. Effect

estimates are visually displayed in Figure S1 and Figure S2 (see Supplemental Digital Content, <http://links.lww.com/MSS/C662>). Enjoyment of physical activity, physical education classes, and school sports; greater importance placed on regular exercise and not being fat; fat-free mass, PWC<sub>170</sub>, standing long jump, and sit and reach; and total physical activity were associated with a lower likelihood of being in the below average and decreasing trajectory. Worse self-rated fitness levels and schoolwork ability compared to others; poor self-rated health; attending a Catholic school; being overweight or obese; sum of skinfolds; and 1.6km and 50m run times (i.e., lower fitness) were associated with a higher likelihood of being in the below average and decreasing trajectory. Greater importance placed on having a good figure and knowing about fitness and how to stay fit; and 1.6km and 50m run times (i.e., lower fitness) were associated with a lower likelihood of being in the above average and increasing trajectory. Attending an independent school; fat-free mass, PWC<sub>170</sub>, standing long jump, and sit and reach; and non-school and total physical activity were associated with a higher likelihood of being in the above average and increasing trajectory. When analyses were repeated on the unrestricted (n=1,280) sample (see Table S2, Supplemental Digital Content, Factors associated with muscular strength trajectory groups, <http://links.lww.com/MSS/C662>), associations remained.

In this dataset, 318 mins/week of total physical activity (~45.4 mins/day) was the point at which a negative association with the below average and decreasing muscular strength group and a positive association with the above average and increasing group became apparent. Children who had  $\geq 318$  mins/week of total physical activity were at decreased risk of being in the below average and decreasing muscular strength group (RR=0.79, 95% CI=0.62, 0.99) and an increased risk of

being in the above average and increasing muscular strength group (RR=1.47, 95% CI=1.002, 2.16), compared with those who participated in <318 mins/week of total physical activity.

Results from the multivariable regression model (see Table S3, Supplemental Digital Content, Multivariable model examining key factors associated with muscular strength trajectory groups, <http://links.lww.com/MSS/C662>) suggested that greater 50 m run time (i.e., lower muscular power) (RR=1.67, 95% CI=1.46, 1.90), attending a Catholic school (RR=1.49, 95% CI=1.16, 1.90), and having worse self-rated fitness levels compared with others (RR=1.92, 95% CI=1.25, 2.95) remained associated with a higher likelihood of being in the below average and decreasing muscular strength trajectory, and enjoying physical activity remained associated with a lower likelihood of being in this same trajectory (RR=0.50, 95% CI=0.33, 0.76). Greater 50 m run time (i.e., lower fitness) remained associated with a lower likelihood (RR=0.42, 95% CI=0.31, 0.56) of being in the above average and increasing muscular strength trajectory and attending an independent school remained associated with a higher likelihood (RR=2.08, 95% CI=1.12, 3.87) of being in this same trajectory. There was no evidence of multicollinearity in this multivariable model as all variance inflation factors were <1.73.

## DISCUSSION

We identified multiple modifiable factors in childhood associated with different muscular strength trajectories between childhood and midlife. These findings could help direct efforts to better children's likelihood of attaining a favourable muscular strength trajectory.

The link between physical activity and muscular fitness levels and adherence to muscle-strengthening activity guidelines in childhood have been highlighted previously (15, 28). We extend current understanding by showing that both the time children spend in and out of school are associated with muscular strength trajectories. In this study, significant associations were found for non-school physical activity and total physical activity (the sum of school and non-school), but not for school physical activity. Participation in muscle-strengthening activities may not have been a focus, or fundamental part of, school curriculums at the time. Ensuring muscle-strengthening activities are promoted in school physical education classes are important (29), especially since adolescent boys have previously identified limited knowledge of how to perform muscular fitness activities and a perceived lack of opportunity to participate in such activities (30). Furthermore, a lack of awareness of the importance and associated health-benefits of greater muscular strength could contribute to the lack of association. In contrast, muscle-strengthening activities may be more appealing to those informed and interested, who actively choose to participate in physical activities, potentially with a muscular fitness focus, out of the school setting. Participating in  $\geq 420$  mins/week of total physical activity was associated with muscular strength trajectories in the expected direction, with associations between total weekly physical activity levels and muscular strength trajectories becoming apparent at  $\geq 318$  mins/week.

Children who enjoyed physical activity, school physical education classes and school sports were less likely to belong to the below average and decreasing muscular strength trajectory group, compared with children who did not enjoy these same activities. These findings highlight children's enjoyment in physical activity as a potential target for strategies aimed at increasing muscular strength levels. Children who reported it being of high importance to exercise regularly



and to not be fat, were less likely to have below average and decreasing muscular strength levels. Greater education for children on the health-benefits associated with exercise could serve as a tool to teach or remind children of the importance of regularly participating in both aerobic and muscle-strengthening activities, as per current guidelines (6). The finding that children not wanting to be fat were less likely to have below average and decreasing muscular strength suggests that children may be aware of the link between greater muscular fitness and body composition (i.e., lower total and central adiposity) (2). This is supported by research that showed physical self-worth to associate with different components of health-related fitness in adolescents, including muscular strength (31). However, it is important that the wide range of health-benefits associated with greater muscular fitness (2, 3), beyond benefits to one's physical appearance, are promoted.

Counterintuitive findings observed in this study were that children who placed greater importance on having a good figure and to know about fitness and how to stay fit, were less likely to have above average and increasing muscular strength levels. The sampling of the baseline cohort included in this study preceded the obesity epidemic (32), which meant a very low proportion (1.63%) of children in this cohort were considered obese. The period at which these childhood measures were collected could also help explain why children who know about fitness and how to stay fit were less likely to belong to the above average and increasing muscular strength group. In 1985, when these measures were collected, aerobic-based activities may have been more focal and the evidence-base much more established, compared with muscle-strengthening activities. As such, these children could have been unaware of the importance of regular participation in muscle-strengthening activities and the plethora of health-benefits associated with muscular fitness (2, 3). Muscle-strengthening activities are often overlooked and physical activity guidelines continue to

underplay the importance of children participating in muscle-strengthening activities (33). More work is required to educate and inform children, their parents, carers, and teachers of the different components of physical fitness, highlighting specifically the health-benefits associated with greater muscular fitness (2, 3) and resistance training (34).

Similar factors associated with muscular strength levels in childhood, including anthropometric and fitness measures (16), were also associated with muscular strength trajectories. Collectively, these findings highlight adiposity and fat-free mass as potential targets that could help identify children, who may not have active role models in their life or be unaware of the importance of being physically active, who could benefit from additional resources to improve their muscular fitness levels. Associations for the different measures of physical fitness (e.g., CRF, muscular power, flexibility) were all in the expected direction, where greater fitness levels were associated with a decreased likelihood of having below average and decreasing muscular strength and a greater likelihood of having above average and increasing muscular strength. These findings highlight lower muscular strength as just one facet of an all-around poor fitness level. This could have implications regarding approaches to improve muscular strength, whereby overall fitness (cardiorespiratory and muscular) could be targeted together rather than single components.

When comparing themselves to others, children who said their fitness and how good they were at schoolwork was worse than their peers and who rated their health poorly, were more likely to have below average and decreasing muscular strength. These findings highlight the importance of investing time and effort into bettering children's confidence and providing supportive and welcoming environments. Ensuring a balance between skill and challenge has been highlighted as

an important consideration when implementing physical activity programs, as children who are proficient and perceive themselves as skilled, confident and competent are more likely to enjoy themselves and remain physically active (35, 36). Furthermore, previous research has also shown that participation in resistance training not only increases muscular fitness levels (34), but also has psychosocial benefits, including an improvement in the children's sense of self (37).

Associations between different school types and muscular strength trajectories were mixed, potentially driven by socioeconomic differences. Consistency across school types regarding environments, access to equipment, physical education curriculums, sports opportunities, and support networks could help ensure all children have an equal opportunity to participate in physical activities to their greatest ability and give them the best opportunity to become part of a favorable muscular strength trajectory. School-based interventions have been shown to increase childhood muscular fitness levels (38, 39), highlighting how valuable correctly administered activities in the school setting could be for the fitness levels of schoolchildren.

A potential limitation of this study is loss to follow-up. However, all analyses included inverse probability weighting to reduce the likelihood of bias by accounting for missingness (26). Furthermore, owing to the explanatory nature of this paper, the large number of factors significant at the univariable level, and to preserve sample size (especially for the above average and increasing muscular strength group), we did not examine a multivariable model that included all individual factors associated with muscular strength trajectory groups. Instead, we included one key factor from each of our exposure groups (i.e., fitness; anthropometric measures; physical activity; socioeconomic factors; health and risk motivation items; other covariates) in a simplified

multivariable model. We must also acknowledge the influence genetics has on muscular fitness levels (40). However, given a lack of genetic data collected as part of this study, we were unable to explore these associations. As our study examined health and risk motivation factors only once in childhood, we were unable to examine how changes in these variables between childhood and midlife associate with muscular strength across the life course. Furthermore, childhood factors associated with muscular strength trajectories may be different in 1985 compared to 2021. Additional research is required to confirm these findings. A strength of this study is the use of data from the CDAH Study, a large national cohort that has been followed up over 30 years. Childhood factors associated with muscular strength trajectories were measured as part of the ASHFS, which included a nationally representative sample of schoolchildren. Furthermore, the breadth of variables measured as part of the ASHFS allowed us to examine a range of potential factors associated with muscular strength trajectories.

## **CONCLUSIONS**

The findings of this study suggest that as well as providing health benefits in the short term, physical activity, physical fitness, positive health attitudes and healthy weight in childhood are factors that could be targeted in strategies aimed at improving muscular strength in the long term.

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### **Conflict of Interest**

The authors declare no conflicts of interest. The results of the study are presented clearly, honestly, and without fabrication, falsification, or inappropriate data manipulation. The results of the present study do not constitute endorsement by the American College of Sports Medicine.

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## SUPPLEMENTAL DIGITAL CONTENT

### SDC 1: Supplemental Digital Content 1.docx

Table S1. Characteristics of participants

Table S2. Factors associated with muscular strength trajectory groups

Table S3. Multivariable model examining key factors associated with muscular strength trajectory groups

Figure S1. A visual representation of the fitness, anthropometric, physical activity, socioeconomic factors, health and risk motivation items, and other covariates associated with the below average and decreasing muscular strength trajectory group

Figure S2. A visual representation of the fitness, anthropometric, physical activity, socioeconomic factors, health and risk motivation items, and other covariates associated with the above average and increasing muscular strength trajectory group

Table 1. Fitness, anthropometric and physical activity factors associated with muscular strength trajectory groups, adjusted for sex and childhood age (n=1,110).

Characteristic	n	Muscular strength trajectory groups*	
		Below average and decreasing muscular strength	Above average and increasing muscular strength
		RR (95% CI)	RR (95% CI)
Sex	1,110		
Male		1 (REF)	1 (REF)
Female		1.21 (0.98, 1.49)	1.15 (0.81, 1.64)
<b>Fitness</b>			
PWC <sub>170</sub> not attributable to lean body mass, per 10 watts	639	<b>0.94 (0.88, 0.997)</b>	<b>1.13 (1.05, 1.21)</b>
1.6 km run, per 1 min	1,034	<b>1.14 (1.08, 1.20)</b>	<b>0.81 (0.69, 0.95)</b>
Standing long jump not attributable to body mass, per 5 cm	1,110	<b>0.91 (0.90, 0.92)</b>	<b>1.14 (1.10, 1.18)</b>
50 m run, per 1 sec	1,045	<b>1.61 (1.48, 1.77)</b>	<b>0.47 (0.36, 0.59)</b>
Sit and reach, per 5 cm	1,106	<b>0.96 (0.94, 0.97)</b>	<b>1.05 (1.02, 1.08)</b>
<b>Anthropometric measures</b>			
BMI cut-points	1,109		
Normal weight		1 (REF)	1 (REF)
Overweight/obese		<b>1.39 (1.01, 1.91)</b>	0.65 (0.29, 1.45)
Waist circumference, per 10 cm	1,109	1.10 (0.96, 1.27)	1.10 (0.89, 1.35)
Fat-free mass, per 1 kg	671	<b>0.95 (0.92, 0.98)</b>	<b>1.07 (1.05, 1.10)</b>
Sum of skinfolds, per 10 mm	671	<b>1.09 (1.03, 1.16)</b>	0.96 (0.83, 1.12)
<b>Physical activity</b>			
In most weeks, do you get exercise or activity 3 or 4 times which makes you huff and puff and at least 30 minutes each time?	950		
No		1 (REF)	1 (REF)
Yes		0.87 (0.69, 1.10)	1.27 (0.88, 1.83)

Participating in $\geq 420$ mins/week of total physical activity†	958		
No		1 (REF)	1 (REF)
Yes		0.82 (0.64, 1.05)	1.37 (0.94, 2.00)
School physical activity, per 60 mins/week	958	0.97 (0.92, 1.02)	1.03 (0.97, 1.09)
Non-school physical activity, per 60 mins/week	958	0.98 (0.96, 1.003)	<b>1.03 (1.02, 1.05)</b>
Total physical activity, per 60 mins/week	958	<b>0.98 (0.96, 0.999)</b>	<b>1.03 (1.01, 1.05)</b>

\* Average muscular strength trajectory group is the excluded outcome group.

Abbreviations: BMI, body mass index; CI, confidence intervals; PWC<sub>170</sub>, physical work capacity at 170 beats per minute; REF, reference group; RR, relative risk.

† Participants were categorized as meeting physical activity recommendations if their total weekly physical activity levels were greater than 420 minutes, a proxy for 60 mins/day.

Table 2. Socioeconomic factors, health and risk motivation items and other covariates associated with muscular strength trajectory groups, adjusted for sex and childhood age (n=1,110).

		Muscular strength trajectory groups*	
		Below average and decreasing muscular strength	Above average and increasing muscular strength
Characteristic	n	RR (95% CI)	RR (95% CI)
Socioeconomic factors			
School type	1,110		
State		1 (REF)	1 (REF)
Catholic		1.33 (1.05, 1.67)	1.05 (0.69, 1.61)
Independent		0.74 (0.45, 1.22)	1.93 (1.11, 3.33)
Area-level SES	934		
High		1 (REF)	1 (REF)
Medium-high		0.90 (0.66, 1.22)	0.79 (0.48, 1.30)
Medium-low		0.93 (0.70, 1.24)	0.76 (0.48, 1.20)
Low		1.07 (0.70, 1.65)	1.02 (0.50, 2.08)
Scholastic level assigned by school	1,046		
Excellent/Above average		1 (REF)	1 (REF)
Average		1.00 (0.80, 1.26)	0.80 (0.55, 1.17)
Below average/Poor		1.12 (0.81, 1.54)	0.87 (0.50, 1.49)
Health and risk motivation items			
Do you enjoy physical activity?	953		
No		1 (REF)	1 (REF)
Yes		0.49 (0.34, 0.71)	2.32 (0.56, 9.55)
Do you enjoy school physical education classes?	892		
Not much/not at all		1 (REF)	1 (REF)
Very much/quite a lot/sometimes		0.45 (0.30, 0.68)	1.29 (0.41, 4.05)

Do you enjoy school sports?	903		
Not much/not at all		1 (REF)	1 (REF)
Very much/quite a lot/Sometimes		<b>0.52 (0.34, 0.80)</b>	1.00 (0.37, 2.71)
How important is it to you to have a good figure?	954		
Some/little/none		1 (REF)	1 (REF)
High		1.03 (0.82, 1.30)	<b>0.62 (0.42, 0.91)</b>
How important is it to you to exercise regularly?	956		
Some/little/none		1 (REF)	1 (REF)
High		<b>0.74 (0.59, 0.94)</b>	0.90 (0.60, 1.33)
How important is it to you to not be fat?	956		
Some/little/none		1 (REF)	1 (REF)
High		<b>0.75 (0.60, 0.95)</b>	0.84 (0.58, 1.22)
How important is it to you to know about fitness and how to stay fit?	953		
Some/little/none		1 (REF)	1 (REF)
High		1.14 (0.89, 1.45)	<b>0.64 (0.44, 0.93)</b>
Do you enjoy school?	958		
All of the time		1 (REF)	1 (REF)
Most of the time		1.14 (0.73, 1.77)	1.45 (0.70, 3.00)
Some of the time		1.33 (0.85, 2.06)	0.97 (0.45, 2.06)
A little of the time/None of the time		1.42 (0.85, 2.39)	1.24 (0.52, 3.00)
<b>Other covariates</b>			
How fit do you think you are compared to others your age?	957		
Better than		1 (REF)	1 (REF)
Same as		<b>1.75 (1.23, 2.51)</b>	0.76 (0.51, 1.14)
Worse than		<b>3.67 (2.44, 5.53)</b>	0.49 (0.20, 1.17)
How is your health usually?	958		

Very good/good		1 (REF)	1 (REF)
Average/poor/very poor		<b>1.98 (1.58, 2.49)</b>	0.71 (0.41, 1.22)
How good are you at schoolwork compared to others of your age?	956		
Better than		1 (REF)	1 (REF)
Same as		1.14 (0.87, 1.49)	1.23 (0.78, 1.92)
Worse than		<b>1.83 (1.25, 2.67)</b>	0.77 (0.31, 1.91)
Parental exercise	903		
Both parents active		1 (REF)	1 (REF)
One parent active only		0.96 (0.69, 1.33)	1.16 (0.70, 1.94)
Both parents inactive		1.01 (0.73, 1.40)	0.76 (0.45, 1.29)

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\* Average muscular strength trajectory group is the excluded outcome group.

Abbreviations: CI, confidence intervals; REF, reference group; RR, relative risk; SES, socioeconomic status.



**Online-only supplement**

Table S1. Characteristics of participants (n=1,110).

Characteristic	Below average and decreasing muscular strength		Average muscular strength		Above average and increasing muscular strength	
	n	Statistic*	n	Statistic*	n	Statistic*
Childhood						
Sex	285		702		123	
Male		44.6 (127)		51.7 (363)		44.7 (55)
Female		55.4 (158)		48.3 (339)		55.3 (68)
Age, y	285	11.4 (2.6)	702	11.4 (2.5)	123	11.6 (2.5)
<b>Fitness</b>						
Combined muscular strength score	176	-1.6 (1.2)	426	0.4 (1.0)	71	2.5 (1.2)
PWC <sub>170</sub> not attributable to lean body mass, watts	167	89.3 (32.5)	407	95.0 (36.8)	65	99.0 (38.2)
1.6 km run, mins	266	9.4 (1.9)	663	8.9 (1.7)	105	8.6 (1.6)
Standing long jump not attributable to body mass, cm	285	137.1 (27.4)	702	150.4 (29.3)	123	160.9 (29.7)
50 m run, secs	269	9.4 (1.1)	668	9.0 (1.0)	108	8.6 (0.8)
Dominant grip strength not attributable to body mass, kg	176	20.0 (7.2)	430	24.0 (8.2)	71	27.8 (9.6)
Sit and reach, cm	282	2.7 (7.5)	701	5.3 (7.3)	123	7.2 (7.9)

**Anthropometric measures**

BMI cut-points	285		701		123	
Normal weight		89.1 (254)		92.7 (650)		95.1 (117)
Overweight/obese		10.9 (31)		7.3 (51)		4.9 (6)
Waist circumference, cm	284	64.2 (8.5)	702	63.4 (7.9)	123	64.4 (8.3)
Fat free mass, kg	176	32.6 (8.9)	425	33.9 (8.9)	70	35.5 (9.6)
Sum of skinfolds, mm	176	40.7 (22.6)	425	34.1 (15.1)	70	34.9 (18.8)

**Physical activity**

In most weeks, do you get exercise or activity 3 or 4 times which makes you huff and puff and at least 30 minutes each time?	241		600		109	
No		60.2 (145)		55.3 (332)		53.2 (58)
Yes		39.8 (96)		44.7 (268)		46.8 (51)
Participating in $\geq 420$ mins/week of total physical activity†	244		603		111	
No		67.6 (165)		63.2 (381)		55.9 (62)
Yes		32.4 (79)		36.8 (222)		44.1 (49)
School physical activity, mins/week	244	95 (50, 167.5)	603	110 (60, 180)	111	120 (60, 210)
Non-school physical activity, mins/week	244	157.5 (62.5, 330)	603	180 (60, 375)	111	210 (74, 480)

Total physical activity, mins/week	244	280 (160, 513.5)	603	320 (180, 562)	111	361 (200, 650)
<b>Socioeconomic factors</b>						
School type	1,110		702		123	
State		68.4 (195)		73.9 (519)		66.7 (82)
Catholic		26.3 (75)		19.4 (136)		22.0 (27)
Independent		5.3 (15)		6.7 (47)		11.4 (14)
Area-level SES	238		589		107	
High		31.1 (74)		27.5 (162)		33.6 (36)
Medium-high		24.8 (59)		29.7 (175)		24.3 (26)
Medium-low		35.3 (84)		35.7 (210)		32.7 (35)
Low		8.8 (21)		7.1 (42)		9.4 (10)
Scholastic level assigned by school	271		659		116	
Excellent/Above average		47.2 (128)		46.7 (308)		50.9 (59)
Average		38.8 (105)		40.4 (266)		35.3 (41)
Below average/Poor		14.0 (38)		12.9 (85)		13.8 (16)
<b>Health and risk motivation items</b>						
Do you enjoy physical activity?	242		600		111	
No		7.4 (18)		2.7 (16)		1.8 (2)
Yes		92.6 (224)		97.3 (584)		98.2 (109)
Do you enjoy school physical education classes?	216		569		107	

		Not much/not at all	6.0 (13)		1.6 (9)		2.8 (3)
		Very much/quite a lot/sometimes	94.0 (203)		98.4 (560)		97.2 (104)
Do you enjoy school sports?	231			568		104	
		Not much/not at all	5.6 (13)		2.1 (12)		3.9 (4)
		Very much/quite a lot/sometimes	94.4 (218)		97.9 (556)		96.2 (100)
How important is it to you to have a good figure?	243			600		111	
		Some/little/none	48.6 (118)		47.8 (287)		60.4 (67)
		High	51.4 (125)		52.2 (313)		39.6 (44)
How important is it to you to exercise regularly?	243			602		111	
		Some/little/none	37.0 (90)		27.7 (167)		32.4 (36)
		High	63.0 (153)		72.3 (435)		67.6 (75)
How important is it to not be fat?	243			602		111	
		Some/little/none	44.9 (109)		36.1 (217)		43.2 (48)
		High	55.1 (134)		64.0 (385)		56.8 (63)
How important is it to you to know about fitness and how to stay fit?	243			599		111	
		Some/little/none	32.9 (80)		33.4 (200)		42.3 (47)
		High	67.1 (163)		66.6 (399)		57.7 (64)
Do you enjoy school?	244			603		111	

All of the time	8.6 (21)	10.5 (63)	7.2 (8)
Most of the time	37.7 (92)	38.5 (232)	48.7 (54)
Some of the time	43.0 (105)	40.6 (245)	33.3 (37)
A little of the time/none of the time	10.7 (26)	10.5 (63)	10.8 (12)
<b>Other factors</b>			
How fit do you think you are compared to others your age?	244	602	111
Better than	13.1 (32)	25.4 (153)	28.8 (32)
Same as	70.1 (171)	69.8 (420)	65.8 (73)
Worse than	16.8 (41)	4.8 (29)	5.4 (6)
How is your health usually?	244	603	111
Very good/good	70.9 (173)	86.4 (521)	85.6 (95)
Average/poor/very poor	29.1 (71)	13.6 (82)	14.4 (16)
How good are you at schoolwork compared to others of your age?	243	602	111
Better than	25.5 (62)	31.7 (191)	23.4 (26)
Same as	63.4 (154)	62.3 (375)	71.2 (79)
Worse than	11.1 (27)	6.0 (36)	5.4 (6)
Parental exercise	233	567	103
Both parents active	18.9 (44)	18.3 (104)	20.4 (21)

One parent active only		36.9 (86)		37.0 (210)		42.7 (44)
Both parents inactive		44.2 (103)		44.6 (253)		36.9 (38)
Young adulthood						
Age, y	273	31.3 (2.6)	655	31.2 (2.6)	120	31.5 (2.7)
Combined muscular strength score	263	−2.2 (1.1)	634	0.4 (1.0)	115	3.1 (1.0)
Mid-adulthood						
Age, y	225	44.0 (2.9)	562	43.8 (2.8)	101	43.9 (3.1)
Combined muscular strength score	189	−2.1 (1.0)	472	0.3 (0.9)	89	2.9 (0.9)

\* Statistics are mean (standard deviation) or median (interquartile range) for continuous variables or proportion (number of participants) for categorical variables.

† Participants were categorized as meeting physical activity recommendations if their total weekly physical activity levels were greater than 420 minutes, a proxy for 60 mins/day.

Abbreviations: BMI, body mass index; PWC<sub>170</sub>, physical working capacity at heart rate of 170 beats per minute; SD, standard deviation; SES, socio-economic status.

Proportions may not total 100 due to rounding.

Table S2. Factors associated with muscular strength trajectory groups, adjusted for sex and childhood age (n=1,280).

Characteristic	n	Muscular strength trajectory groups*	
		Below average and decreasing muscular strength	Above average and increasing muscular strength
		RR (95% CI)	RR (95% CI)
Sex	1,280		
Male		1 (REF)	1 (REF)
Female		1.12 (0.93, 1.36)	1.18 (0.87, 1.61)
<b>Fitness</b>			
PWC <sub>170</sub> not attributable to lean body mass, per 10 watts	738	<b>0.94 (0.89, 0.99)</b>	<b>1.14 (1.07, 1.21)</b>
1.6 km run, per 1 min	1,198	<b>1.14 (1.09, 1.19)</b>	<b>0.81 (0.71, 0.93)</b>
Standing long jump not attributable to body mass, per 5 cm	1,280	<b>0.91 (0.90, 0.92)</b>	<b>1.13 (1.10, 1.16)</b>
50 m run, per 1 sec	1,210	<b>1.60 (1.48, 1.74)</b>	<b>0.48 (0.39, 0.59)</b>
Sit and reach, per 1 cm	1,276	<b>0.96 (0.95, 0.97)</b>	<b>1.04 (1.02, 1.07)</b>
<b>Anthropometric measures</b>			
BMI cut-points	1,279		
Normal weight		1 (REF)	1 (REF)
Overweight/obese		<b>1.46 (1.09, 1.95)</b>	0.61 (0.29, 1.29)
Waist circumference, per 10 cm	1,279	1.08 (0.94, 1.24)	1.06 (0.87, 1.29)
Fat-free mass, per 1 kg	777	<b>0.95 (0.92, 0.98)</b>	<b>1.06 (1.04, 1.08)</b>
Sum of skinfolds, per 10 mm	777	<b>1.09 (1.03, 1.15)</b>	0.93 (0.80, 1.09)
<b>Physical activity</b>			
In most weeks, do you get exercise or activity 3 or 4 times which makes you huff and puff and at least 30 minutes each time?	1,092		
No		1 (REF)	1 (REF)
Yes		0.87 (0.70, 1.08)	1.27 (0.92, 1.76)

Participating in $\geq 420$ mins/week of total physical activity†	1,102		
No		1 (REF)	1 (REF)
Yes		0.89 (0.71, 1.12)	1.21 (0.86, 1.68)
School physical activity, per 60 mins/week	1,102	0.96 (0.91, 1.01)	1.00 (0.94, 1.07)
Non-school physical activity, per 60 mins/week	1,102	0.99 (0.97, 1.01)	<b>1.03 (1.01, 1.05)</b>
Total physical activity, per 60 mins/week	1,102	0.99 (0.97, 1.01)	<b>1.02 (1.004, 1.05)</b>
<b>Socioeconomic factors</b>			
School type	1,280		
State		1 (REF)	1 (REF)
Catholic		<b>1.27 (1.02, 1.58)</b>	1.11 (0.76, 1.61)
Independent		0.67 (0.41, 1.09)	<b>1.91 (1.15, 3.15)</b>
Area-level SES	1,076		
High		1 (REF)	1 (REF)
Medium-high		0.99 (0.75, 1.33)	0.67 (0.43, 1.04)
Medium-low		1.00 (0.77, 1.31)	0.69 (0.46, 1.02)
Low		1.25 (0.85, 1.84)	0.97 (0.53, 1.78)
Scholastic level assigned by school	1,209		
Excellent/Above average		1 (REF)	1 (REF)
Average		1.01 (0.83, 1.24)	0.85 (0.61, 1.18)
Below average/Poor		1.10 (0.81, 1.48)	0.93 (0.57, 1.50)
<b>Health and risk motivation items</b>			
Do you enjoy physical activity?	1,096		
No		1 (REF)	1 (REF)
Yes		1.12 (0.93, 1.36)	1.18 (0.87, 1.61)
Do you enjoy school physical education classes?	1,032		
Not much/not at all		1 (REF)	1 (REF)
Very much/quite a lot/sometimes		<b>0.53 (0.35, 0.81)</b>	0.96 (0.42, 2.20)



Do you enjoy school sports?	1,036		
Not much/not at all		1 (REF)	1 (REF)
Very much/quite a lot/Sometimes		<b>0.56 (0.37, 0.84)</b>	0.95 (0.40, 2.29)
How important is it to you to have a good figure?	1,096		
Some/little/none		1 (REF)	1 (REF)
High		1.01 (0.82, 1.25)	<b>0.61 (0.44, 0.86)</b>
How important is it to you to exercise regularly?	1,099		
Some/little/none		1 (REF)	1 (REF)
High		<b>0.74 (0.59, 0.91)</b>	0.93 (0.65, 1.33)
How important is it to you to not be fat?	1,099		
Some/little/none		1 (REF)	1 (REF)
High		<b>0.77 (0.62, 0.95)</b>	0.78 (0.56, 1.09)
How important is it to you to know about fitness and how to stay fit?	1,096		
Some/little/none		1 (REF)	1 (REF)
High		1.15 (0.91, 1.45)	<b>0.64 (0.46, 0.90)</b>
Do you enjoy school?	1,102		
All of the time		1 (REF)	1 (REF)
Most of the time		1.07 (0.71, 1.60)	1.32 (0.72, 2.42)
Some of the time		1.32 (0.89, 1.97)	0.85 (0.45, 1.61)
A little of the time/None of the time		1.45 (0.91, 2.31)	1.18 (0.57, 2.48)
<b>Other covariates</b>			
How fit do you think you are compared to others your age?	1,100		
Better than		1 (REF)	1 (REF)
Same as		<b>1.58 (1.16, 2.17)</b>	0.81 (0.57, 1.16)
Worse than		<b>3.06 (2.11, 4.43)</b>	<b>0.39 (0.17, 0.93)</b>
How is your health usually?	1,102		
Very good/good		1 (REF)	1 (REF)

Average/poor/very poor		<b>1.70 (1.43, 2.23)</b>	0.77 (0.49, 1.22)
How good are you at schoolwork compared to others of your age?	1,099		
Better than		1 (REF)	1 (REF)
Same as		1.17 (0.92, 1.50)	1.09 (0.74, 1.59)
Worse than		<b>1.70 (1.17, 2.47)</b>	0.82 (0.38, 1.74)
Parental exercise	1,036		
Both parents active		1 (REF)	1 (REF)
One parent active only		0.94 (0.70, 1.28)	1.01 (0.65, 1.57)
Both parents inactive		0.98 (0.73, 1.33)	0.76 (0.48, 1.18)

\* Average muscular strength trajectory group is the excluded outcome group.

Abbreviations: BMI, body mass index; CI, confidence intervals; PWC<sub>170</sub>, physical work capacity at 170 beats per minute; REF, reference group; RR, relative risk; SES, socioeconomic status.

† Participants were categorized as meeting physical activity recommendations if their total weekly physical activity levels were greater than 420 minutes, a proxy for 60 mins/day.

Table S3. Multivariable model examining key factors associated with muscular strength trajectory groups, adjusted for all listed factors, sex and childhood age (n=903).

Characteristic	Muscular strength trajectory groups*	
	Below average and decreasing muscular strength	Above average and increasing muscular strength
	RR (95% CI)	RR (95% CI)
50 m run, per 1 sec	<b>1.67 (1.46, 1.90)</b>	<b>0.42 (0.31, 0.56)</b>
BMI cut-points		
Normal weight	1 (REF)	1 (REF)
Overweight/obese	1.28 (0.93, 1.75)	0.69 (0.27, 1.77)
Participating in $\geq 318$ mins/week of total physical activity		
No	1 (REF)	1 (REF)
Yes	0.89 (0.72, 1.10)	1.46 (0.97, 2.19)
School type		
State	1 (REF)	1 (REF)
Catholic	<b>1.49 (1.16, 1.90)</b>	0.96 (0.58, 1.59)
Independent	0.75 (0.42, 1.37)	<b>2.08 (1.12, 3.87)</b>
Do you enjoy physical activity?		
No	1 (REF)	1 (REF)
Yes	<b>0.50 (0.33, 0.76)</b>	1.73 (0.40, 7.53)
How fit do you think you are compared to others your age?		
Better than	1 (REF)	1 (REF)
Same as	1.28 (0.90, 1.82)	1.21 (0.76, 1.91)
Worse than	<b>1.92 (1.25, 2.95)</b>	1.18 (0.74, 0.90)

\* Average muscular strength trajectory group is the excluded outcome group.

Abbreviations: BMI, body mass index; CI, confidence intervals; REF, reference group; RR, relative risk.

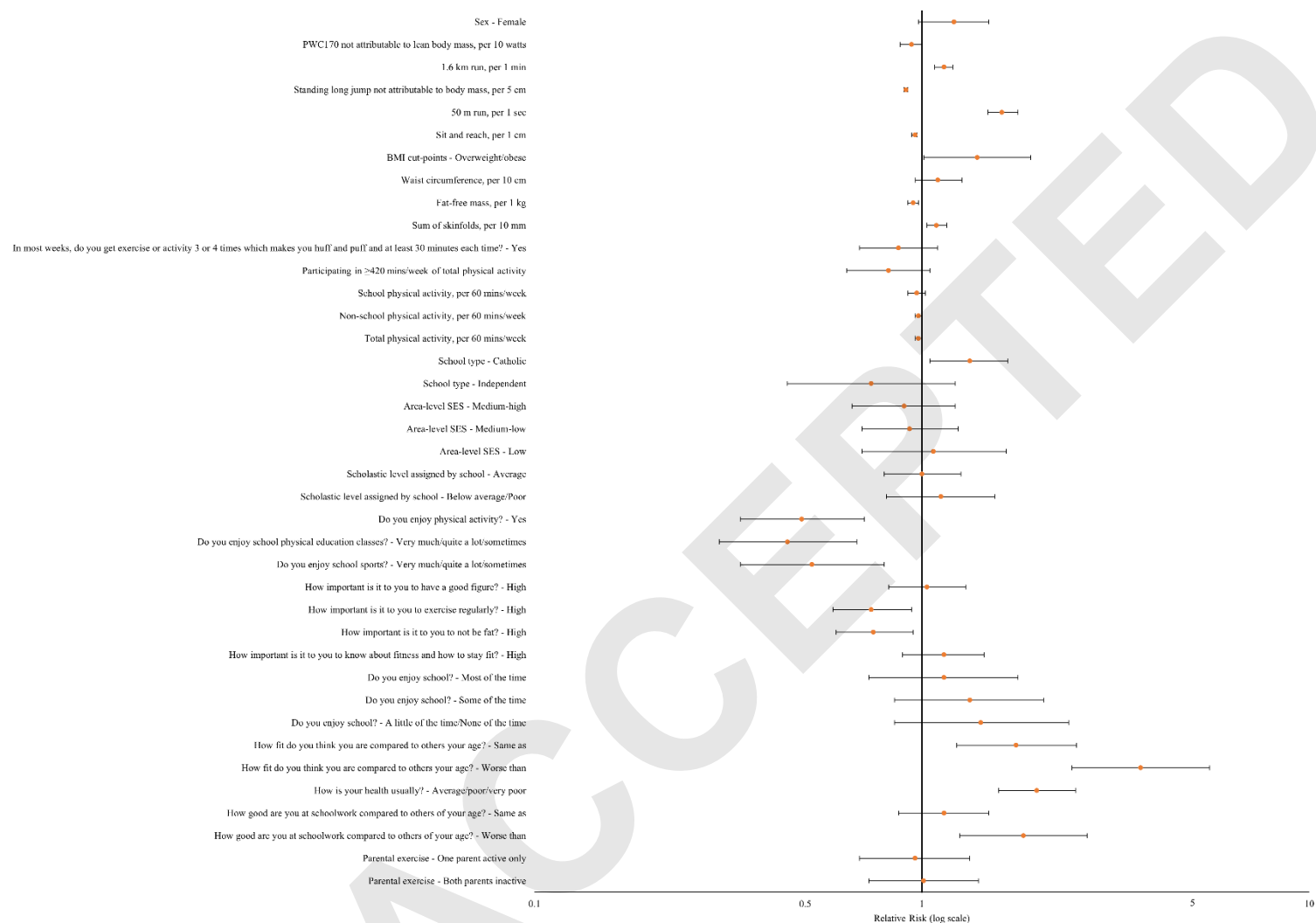


Figure S1. A visual representation of the fitness, anthropometric, physical activity, socioeconomic factors, health and risk motivation items, and other covariates associated with the below average and decreasing muscular strength trajectory group, adjusted for sex and childhood age (estimates presented in Table 1 and Table 2).

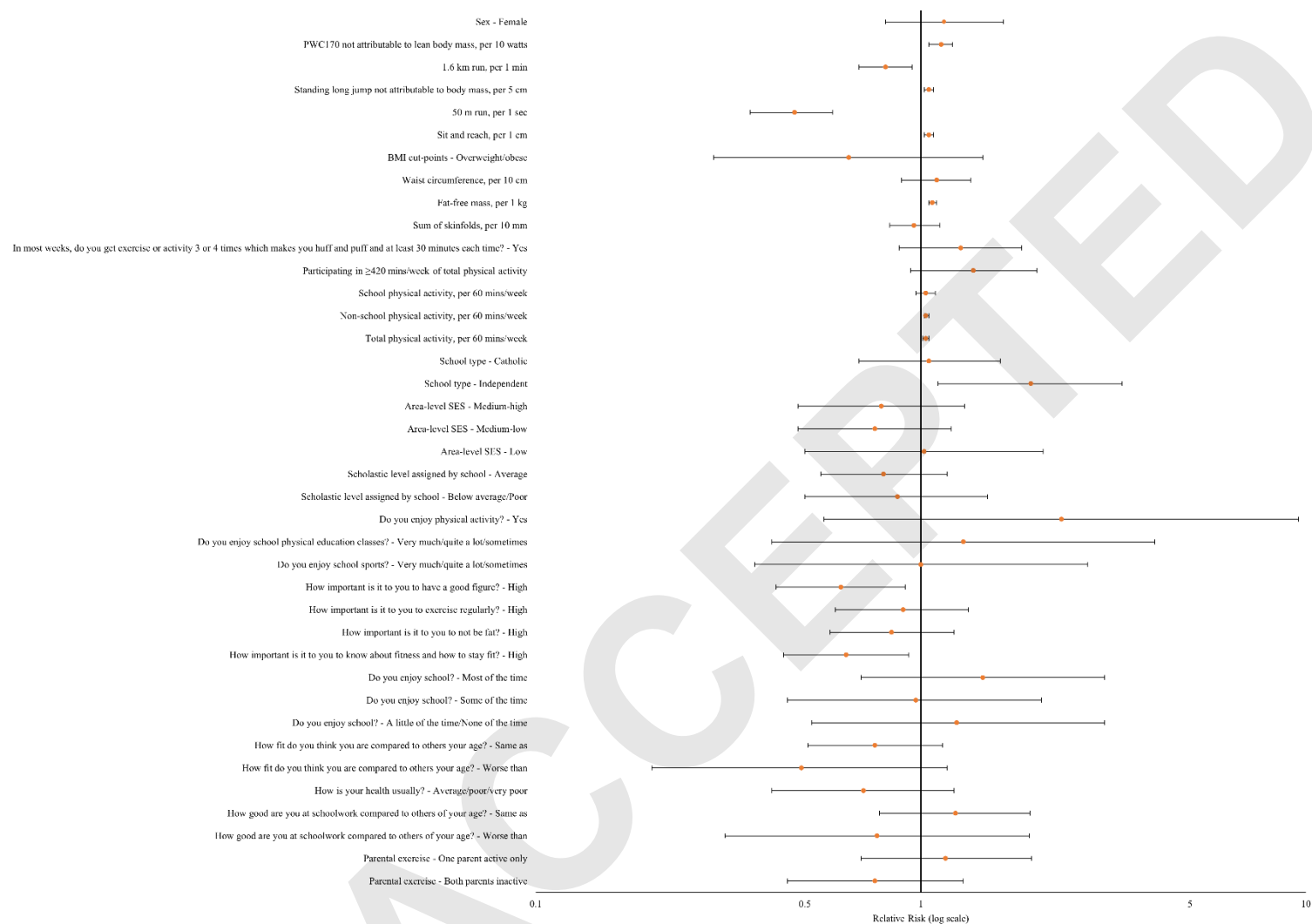


Figure S2. A visual representation of the fitness, anthropometric, physical activity, socioeconomic factors, health and risk motivation items, and other covariates associated with the above average and increasing muscular strength trajectory group, adjusted for sex and childhood age (estimates presented in Table 1 and Table 2).