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A Systematic Analysis of Temporal Trends in the Handgrip Strength of 2,216,320 Children and Adolescents Between 1967 and 2017

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Title

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Running title

Temporal trends in children's handgrip strength

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Abstract

Objective: To estimate national and international temporal trends in handgrip strength for children and adolescents, and to examine relationships between trends in handgrip strength and trends in health-related and sociodemographic indicators.

Methods: Data were obtained through a systematic search of studies reporting temporal trends in the handgrip strength for apparently healthy 9–17 year-olds, and by examining large national fitness datasets. Temporal trends at the country-sex-age level were estimated by sample-weighted regression models relating the year of testing to mean handgrip strength. International and national trends were estimated by a post-stratified population-weighting procedure. Pearson's correlations quantified relationships between trends in handgrip strength and trends in health-related/sociodemographic indicators.

Results: 2,216,320 children and adolescents from 13 high-, 5 upper-middle-, and 1 low-income countries/special administrative regions between 1967 and 2017 collectively showed a moderate improvement of 19.4% (95%CI: 18.4 to 20.4) or 3.8% per decade (95%CI: 3.6 to 4.0). The international rate of improvement progressively increased over time, with more recent values (post-2000) close to two times larger than those from the 1960s/1970s. Improvements were larger for children (9–12 years) compared to adolescents (13–17 years), and similar for boys and girls. Trends differed between countries, with relationships between trends in handgrip strength and trends in health-related/sociodemographic indicators negligible-to-weak and not statistically significant.

Conclusions: There has been a substantial improvement in absolute handgrip strength for children and adolescents since 1967. There is a need for improved international surveillance of handgrip strength, especially in low- and middle-income countries, to more confidently determine true international trends.

PROSPERO registration number: CRD42013003657.

Key points

- There has been a moderate international improvement in handgrip strength for children and adolescents since 1967, with the rate of improvement progressively increasing over time and more recent values (post-2000) close to two times larger than those from the 1960s and 1970s
- Internationally, improvements in handgrip strength were nearly twice as large for children compared to adolescents, yet similar for boys and girls. Nationally, trends varied in magnitude and direction
- Collectively, the relationships between trends in handgrip strength and trends in health-related/sociodemographic indicators were negligible-to-weak and not statistically significant

1 Introduction

Most of the research on the health-related benefits of physical fitness relates to cardiorespiratory fitness.^{1,2} Considerable evidence has recently emerged indicating that muscular strength—the ability of a muscle or muscle group to generate force in a single contraction³—is also a powerful marker of good health.^{4–8} In adults, reduced muscular strength is significantly associated with all-cause, cardiovascular, and non-cardiovascular mortality^{5,9,10} (independent of body size, physical activity levels, and other covariates⁵), cancer,⁹ stroke,⁵ type 2 diabetes,¹¹ hypertension,¹¹ hospitalization,¹² surgical complications,¹³ disability,¹³ functional deficits¹⁴ (in both instrumental activities and activities of daily living^{15,16}), and cognitive declines.^{16,17} Compelling evidence from the Prospective Urban-Rural Epidemiology (PURE) study⁵—a large longitudinal population study of 139,691 adults (35–70 years) across 17 countries over a median of four years—indicated that every 5 kg decrease in handgrip strength was associated with 16–17% higher hazard ratios for all-cause, cardiovascular, and non-cardiovascular mortality. In children and adolescents, muscular strength is significantly associated with current^{7,8} and future^{4,18,19,20} health independent of cardiorespiratory fitness^{21–23} and physical activity.²³ Low muscular strength cut-points for the detection of high cardiometabolic risk^{22,24,25} and poor bone health²⁶ have been used to identify at-risk children and adolescents in need of intervention. This evidence underscores why national^{27–29} and international³⁰ physical activity guidelines now recommend children and adolescents participate in muscle and bone-strengthening activities (in addition to aerobic activity) at least three times per week. For these reasons, temporal trends in muscular strength provide important insights into corresponding trends in population health.

Muscular strength cannot be defined by a single measurement because tests are often specific to the muscle group, the type of muscle action, muscle contraction, contraction velocity, equipment, and joint range of motion. However, handgrip strength—characterized as a maximal isometric grip force task—is a practical, feasible, and scalable functional measure of overall strength for clinical and population screening and surveillance.³¹ It has high-to-very high construct validity with upper-body, lower-body, and overall strength in children, adolescents and adults,^{31,32} high-to-very high test-retest reliability^{33–35}, as well as negligible test-retest learning and fatigue effects.³⁶ The test is safe and there is no evidence of adverse events associated with test administration.³⁷ Handgrip strength testing has also been endorsed by both North American³⁷ and European³⁸ experts for its predictive utility and recommended for school-based fitness testing.

Temporal trends in physical fitness have largely focused on cardiorespiratory fitness, with several large systematic analyses recently published on both pediatric³⁹ and adult populations.⁴⁰ Much less, however, is known about temporal trends in muscular strength for children and adolescents. While reports of trends in handgrip strength for children and adolescents have recently emerged with varying results (e.g., Canada,^{42–44} Mexico,⁴⁵ Mozambique,⁴⁶ Poland,^{47–49} Turkey,⁵⁰ the UK,⁵¹ and the US^{42,43}), there has not yet been a comprehensive study to synthesize national and international trends. Recent studies have also identified a strong negative association between national trends in cardiorespiratory fitness and trends in income inequality (Gini index) among children and adolescents,³⁹ meaning countries with a widening gap between rich and poor residents had less favorable trends (i.e., large declines) in cardiorespiratory fitness. Examining the associations between national trends in handgrip strength and trends in health-

related and sociodemographic indicators could provide further insight into the importance of these indicators and their potential population health implications.

The primary aim of this study was to systematically analyze national (country-specific) and international (pooled global data) temporal trends in handgrip strength for children and adolescents. The secondary aim was to examine relationships between national trends in handgrip strength and trends in health-related and sociodemographic indicators.

2 Methods

2.1 Protocol and Registration

The review protocol was registered with the International Prospective Register of Systematic Reviews (PROSPERO; registration number CRD42013003657). This review followed the Preferred Reporting Items for Systematic reviews and Meta-Analyses (PRISMA) statement.⁵²

2.2 Eligibility Criteria

One large systematic review of temporal trends in children's muscular fitness (i.e., muscular strength [operationalized as handgrip strength] and local muscular endurance [operationalized as sit-ups performance]) was initially undertaken before being divided into two smaller reviews.

For this study, studies were included if they explicitly reported on temporal trends in children's maximal strength (operationalized as handgrip strength). Candidate studies, including refereed journal articles and graduate research theses, were eligible if they reported on temporal trends in the handgrip strength (using matched testing protocols) of apparently healthy (free from known disease/injury) age- and sex-matched children and adolescents (aged 9–17 years) across at least

two time points spanning a minimum of five years.³⁹ Temporal trends must have been reported in each study as absolute, percent or standardized changes in means at the country-sex-age level, or as descriptive data (e.g., sample sizes, means and standard deviations) at the country-sex-age-year level in order to calculate temporal trends. At the national level, a minimum of four country-sex-age groups (e.g., 9-year-old Australian boys) was required for inclusion.

2.3 *Information Sources*

A systematic electronic database search was performed on the 30th of October 2018 using the EBSCO interface in Cumulative Nursing and Allied Health Literature (CINAHL), MEDLINE, and SPORTDiscus, without date or language restrictions. The search strategy was developed with the help of an academic librarian experienced in systematic literature searching. Additional studies were located by searching the reference lists of the included studies, topical systematic reviews, and the personal library of the senior author (GRT). Large datasets comprising nationally representative fitness survey data suitable to temporal trends analysis were also considered.

2.4 *Search Strategy*

The electronic database search was limited to keywords, title, and abstract. Search terms within a group were combined with a Boolean OR and were searched concurrently with other search groups using the Boolean AND. Proximity operators (“**”) were used to search for root words. The first group of search terms identified the fitness measure (physical fitness OR muscular fitness OR muscular strength OR muscular endurance OR musculoskeletal fitness OR aerobic fitness OR cardiovascular fitness OR cardiorespiratory fitness). The second group identified the

population (child* OR youth OR young OR adolescen*). The third group identified the trend over time (temporal OR secular OR trend*). The search strategy for databases is shown in Supplement 1.

2.5 Study Selection

All database records were imported into RefWorks (v2.0; ProQuest LLC, Ann Arbor, MI, USA) and de-duplicated. At the first level, two researchers (FLD and TK) independently screened the titles and abstracts against inclusion criteria, with consensus required for further screening. At the second level, full text copies were obtained and independently screened by two researchers against inclusion criteria, with consensus required for final inclusion. A third researcher (GRT) resolved discrepancies if consensus was not reached.

2.6 Data Collection Process

Descriptive data were extracted into a spreadsheet by one researcher using a standardized study-specific template,³⁹ and reviewed by a second researcher for accuracy. If required, additional information was requested from the corresponding authors via email (e.g., to clarify published results or to avoid double counting data).

2.7 Data Items

The following study-specific descriptive data were extracted: title, country, years of testing, sex, age (or age range), and test protocol. If available, the absolute (in kg), percent, and/or standardized changes in mean handgrip strength ($\pm 95\%$ confidence intervals [CIs]) were

extracted; if not, then all sample sizes, means, and standard deviations for measured handgrip were extracted in order to calculate temporal trends.

2.8 *Summary Measures and Synthesis of Results*

Temporal trends were analyzed at the country-sex-age level using best-fitting sample-weighted linear or polynomial (quadratic or cubic) regression models relating the year of testing to mean handgrip strength.^{39,40} Trends in mean handgrip strength were expressed as percent changes (i.e., change in means expressed as a percentage of the overall mean) and as standardized effect sizes (ES) (i.e., change in means divided by the pooled standard deviation). To interpret the magnitude of change, ES of 0.2, 0.5, and 0.8 were used as thresholds for small, moderate, and large, respectively, with $ES < 0.2$ considered to be negligible.⁴¹ Positive temporal trends indicated increases in mean handgrip strength and negative temporal trends indicated declines in mean handgrip strength.

International and national temporal trends (for boys, girls, children [9–12 year-olds], adolescents [13–17 year-olds] and all [9–17 year-old boys and girls]) were calculated using a post-stratified population-weighting procedure that has been described in detail elsewhere.^{39,40,53,54} Population estimates were standardized to the year 2000—a common testing year to the vast majority of country-sex-age groups—using United Nations data.⁵⁵ The post-stratification population-weighting procedure helps correct the trends for systematic bias associated with over- and under-sampling, and standardizes the trends to underlying country-sex-age-specific demographics.

Relationships between national temporal trends in handgrip strength and national temporal trends in pre-specified health-related and sociodemographic indicators were quantified using Pearson's correlation coefficients, with 95% CIs estimated using Fisher's *z*-transformation. National trends for three health-related (childhood and adolescent body mass index [BMI],⁵⁶ moderate-to-vigorous physical activity [MVPA],⁵⁷ and vigorous physical activity [VPA] levels⁵⁷) and three sociodemographic (Gini index,⁵⁸ Human Development Index [HDI],⁵⁹ and urbanization⁶⁰) indicators were analyzed using linear regression models (as described above). Trends in these broad health-related and sociodemographic indicators were examined because they were thought to be meaningfully related to trends in handgrip strength and because it was possible to calculate temporal trends using the same criteria as for handgrip strength (e.g., across at least two time points spanning a minimum of 5 years) for the majority of the included countries. To interpret the magnitude of correlation, ES of 0.1, 0.3, 0.5, 0.7, and 0.9 were used as thresholds for weak, moderate, strong, very strong, and nearly perfect, respectively, with ES < 0.1 considered to be negligible.⁴¹

3 Results

A total of 1,416 unique records were identified through the electronic database search, with 28 retained after the first level of screening (title and abstract review) and six retained after the second level of screening (full-text review) (Figure 1). These six studies were combined with: (a) 12 additional studies identified from the senior author's personal library and the reference lists of included articles (11/12) and topical systematic reviews (1/12), and (b) four large national datasets comprising nationally representative handgrip data suitable for temporal trends analysis, resulting in 22 included studies/datasets (Figure 1).

Insert Figure 1 here

Temporal trends in handgrip strength were estimated from 2,230,658 children and adolescents aged 9–17 years from 18 countries and one special administrative region (Hong Kong) between 1835 and 2017 (Table 1). Trends prior to 1967 were removed because they were only available for 16% (3/19) of countries representing <1% of all data points (e.g., Belgium: 1835–2010; Bulgaria: 1960–1999; USA: 1899–2009). As a result, trends between 1967 and 2017, representing 2,216,320 children (n=914,277) and adolescents (n=1,302,044), were calculated. Trends were available for 13 high-income, 5 upper-middle-income, and 1 low-income countries/special administrative regions¹⁴³ (or 14 very high, 4 high, and 1 low human development countries/special administrative regions),⁵⁹ representing five continents, ~34% of the world's population,⁵⁵ and ~33% of the world's land area.¹⁴⁴ Trends were calculated for 254 country-sex-age groups (children [aged 9–12 years]: 124; adolescents [aged 13–17 years]: 130; boys: 126; girls: 128), with a median sample size of 835 (range 23–75,407) across a median span of 23 years (range 5–50). Trends were available for the following test protocols: maximum of the dominant hand (45% or 10/22 studies), sum of the maxima for both hands (27% or 6/22), maximum of the right hand (14% or 3/22), average of the maxima for both hands (9% or 2/22), and maximum across both hands (5% or 1/22) (Supplement 2). Most test protocols required a straight arm, allowed multiple trials per hand, and used a mechanical handgrip dynamometer adjusted for hand size.

Insert Table 1 here

Collectively, there was a moderate improvement in mean handgrip strength over the 1967–2017 period (change in means [95%CI]: 19.4% [18.4 to 20.4]; ES 0.72 [0.68 to 0.76]) (Figure 2). There was a large international improvement in mean handgrip strength in children (change in

means [95%CI]: 24.4% [22.8 to 26.0]; ES 0.86 [0.81 to 0.91]) that was 1.8-fold larger than the moderate improvement in adolescents (change in means [95%CI]: 13.7% [12.5 to 14.9]; ES 0.56 [0.51 to 0.61]). The moderate international improvement in boys (change in means [95%CI]: 19.4% [18.2 to 20.6]; ES 0.77 [0.72 to 0.82]) was similar to that observed in girls (change in means [95%CI]: 19.0% [17.4 to 20.6]; ES 0.65 [0.60 to 0.70]) (Figure 2).

Insert Figure 2 here

The international rate of improvement was not uniform over time, with the rate of improvement increasing (albeit negligibly) from the 1960s/1970s (change in means [95%CI]: 1.8% per decade [1.5 to 2.1]; ES 0.07 [0.06 to 0.08]), through the 1980s/1990s (change in means [95%CI]: 2.4% per decade [2.1 to 2.7]; ES 0.09 [0.08 to 0.10]), to the 2000s/2010s (change in means [95%CI]: 3.8% per decade [3.4 to 4.2]; ES 0.14 [0.13 to 0.15]) (Figure 2). The rate of improvement peaked in the 2000s/2010s across all age and sex groups, with rates increasing over time in children, adolescents and boys, and rates slowing from the 1960s/1970s to the 1980s/1990s and increasing thereafter in girls (Figure 2).

National trends in handgrip strength ranged from a large improvement for France (11.2% per decade between 1985 and 2008) to a large decline for Turkey (-11.5% per decade between 1983–2013), with trends in other countries typically negligible to small (12/19 or 63%) and positive (i.e., improvements) (11/19 or 58%) (Figure 3). Figure 3 shows that while uniform (linear) and non-uniform (curvilinear) trends were evenly split across countries, some countries experienced a decrease or stabilization of the rate of change (e.g., Belgium, China and Turkey), an increase in the rate of change (e.g., Australia, Italy and the US), or a reversal of the direction of change (e.g., Poland). Within-country trends were very strongly related between sexes (r

[95%CI]: 0.74 [0.43 to 0.89]) but weakly related between age groups (r [95%CI]: 0.19 [-0.36 to 0.64]).

Insert Figure 3 here

Despite not reaching statistical significance at the 95% level, there were weak positive correlations between national trends in handgrip strength and national trends in urbanization, BMI, MVPA, VPA, and HDI. The trend for Gini index was negligible (Table 2).

Insert Table 2 here

4 Discussion

This study estimated temporal trends from 1967 to 2017 in handgrip strength for 2.2 million children and adolescents from 19 countries/special administrative regions. The main findings were that: (a) there was a moderate international improvement in handgrip strength since 1967, equivalent to an improvement of ~20%, ~0.7 standard deviations or ~3–9 kg for 9–17-year-olds using Eurofit's dominant hand protocol;¹⁴⁵ (b) the international rate of improvement progressively increased with more recent rates of increase close to two times larger than those from the 1960s/1970s; (c) international improvements were observed for all age and sex groups, with the rate of increase over the entire period nearly twice as large for children compared to adolescents, and similar for boys and girls; (d) national trends varied in magnitude and direction; and (e) national trends in health and sociodemographic indicators were, at best, weakly and not significantly correlated with national trends in handgrip strength. Because handgrip strength demonstrates high-to-very high construct validity,^{31,32} our finding of improved handgrip strength is suggestive of improved overall strength capacity; specifically however, it reflects an improved ability of children and adolescents to perform everyday high intensity gripping tasks. This may be meaningful to public health given previous findings of significant cross-sectional and

longitudinal relationships between handgrip strength and health indicators among children and adolescents.^{4,7,8,18–26}

It has previously been argued that trends in cardiorespiratory fitness among children and adolescents have probably been caused by a network of environmental, social, behavioral, psychosocial and physiological factors.^{39,40,54} Trends in the handgrip strength among children and adolescents are potentially explained by a similar causal network. Consider first the potential impact of body size on muscular strength.^{8,146,147} Temporal trends in body size and biological maturation are thought to be influenced by improved living conditions, better nutrition, and reduced infectious disease.¹⁴⁸ Numerous public health initiatives (e.g., health promotion campaigns, clean water technologies, food fortification, pasteurization) have contributed to improved environmental and nutritional conditions for children and adolescents across the study period,^{149,150} although it is difficult to estimate the effect of such factors on trends in handgrip strength. Several recent studies have found that temporal trends in handgrip strength were independent of trends in body size, operationalized as height and mass,⁵¹ height, mass and BMI,⁴⁷ and fat mass and fat-free mass.¹⁴⁸ Our trends, therefore, likely reflect trends in both muscle function and body size. Underlying trends in muscle function are expected given that handgrip strength demonstrates high-to-very high construct validity, although these validity coefficients reduce to low-to-moderate when controlled for body mass.^{31,32} International increases in childhood and adolescent BMI are well established,⁵⁶ reflecting both increases in fat mass and fat-free mass.¹⁵¹ Increases in fat-free mass should result in a general increase in handgrip strength given that the capacity to generate force by a muscle is proportional to its cross-sectional area.¹⁵² Given BMI increased over the period 1975–2016 in all 19 included

countries/special administrative regions,⁵⁶ concurrent increases in handgrip strength would be expected, although Figure 3 shows between-country variation in both direction and magnitude. Our analysis revealed that the relationship between trends in handgrip strength and trends in BMI was weak and not statistically significant, suggesting that trends in other factors are likely also involved.

Temporal trends in handgrip strength are also likely influenced by concurrent trends in biological maturation.^{148,153} To our knowledge, only one study has examined temporal trends in handgrip strength while statistically controlling for trends in maturation. Moliner-Urdiales et al.¹⁵⁴ observed declines in handgrip strength for Spanish youth between 2001 and 2007 independent of changes in fat mass, fat-free mass, age and pubertal status (assessed by the Tanner-Whitehouse scale). However, several studies have reported that trends in handgrip strength have coincided with trends in maturation. For example, Saczuk et al.⁴⁸ found that the trend towards earlier maturation in Polish girls between 1986 and 2006 coincided with improved handgrip strength. Whereas, Malina et al.⁴⁵ suggested that earlier maturation explained part of the sex-related temporal differences in the handgrip strength among Mexican youth. While trends in maturation have varied over time and between countries, estimates indicate that the age of menarche advanced by ~0.3 years per decade over most of the 20th century, and the age at which boys' voices break by ~0.2 years per decade.¹⁵⁵ Over the 50-year period between 1967 and 2017, this equates to 1.0 and 1.5 years for boys and girls, respectively. Tomkinson et al.¹⁴⁵ found that handgrip strength improved with each year of age by ~16% in boys and ~15% in girls between the ages of 9 and 12, and by ~11% in boys and ~3% in girls between the ages of 13 and 17. Between 1967 and 2017, we found that mean handgrip strength improved internationally by

~24% and ~14% in children and adolescents, respectively. When corrected for trends in biological maturation, the underlying improvement in handgrip strength is reduced to ~1–8% in children (i.e., 24% minus 16% in boys and 24% minus 1.5 multiplied by 15% in girls) and ~3–9% in adolescents (i.e., 14% minus 11% in boys and 14% minus 1.5 multiplied by 3% in girls). Advances in biological maturation could help explain why improvements in handgrip strength were larger for children compared to adolescents.

In a recent systematic review, Smith et al.¹⁵⁶ reported that muscular fitness was positively related to objectively measured MVPA, VPA, and organized sport participation. However, they acknowledged that associations between handgrip strength and MVPA, VPA, and organized sport participation were less consistent than for other strength measures (e.g., standing broad jump, push-ups, composite strength).¹⁵⁶ Because of the difficulty in obtaining accurate measurements and temporal differences in sampling and methodology, trend data on the physical activity levels of children and adolescents are scarce. Currently there is no compelling evidence for international increases in MVPA, VPA, or organized sport participation,^{57,157–159} and to our knowledge, no study has examined temporal trends in handgrip strength while statistically controlling for trends in physical activity levels. Recently however, Sandercock and Cohen⁵¹ reported that the decline in 10-year-old English children's handgrip strength between 2008 and 2014 coincided with a decline in self-reported physical activity. Our findings suggested only weak, non-statistically significant, correlations between trends in handgrip strength and self-reported trends in MVPA/VPA indicating that trends in absolute handgrip strength poorly reflect trends in MVPA/VPA. Perhaps this describes the fact that childhood and adolescent physical

activities do not typically involve exposure to gripping tasks that stimulate an increase in finger flexor strength (i.e., handgrip strength).

In the absence of concurrent trend data, it is difficult to explain why the improvements in handgrip strength were generally larger for children than adolescents. Apart from advances in biological maturation, which are more likely to have influenced trends in handgrip strength for children rather than adolescents (see above), it is possible that age-related temporal differences in body size (i.e., BMI) and MVPA/VPA are involved. Although we were unable to estimate age-related temporal differences in BMI or MVPA/VPA, a secondary analysis of the relationships between trends in handgrip strength and trends in BMI and MVPA/VPA showed moderate-to-large age-related differences. For example, trends in children's handgrip strength were strongly correlated with BMI (r [95%CI]: 0.55 [0.03 to 0.84]), and strongly but not significantly correlated with MVPA (r [95%CI]: 0.56 [-0.24 to 0.91]) and VPA (r [95%CI]: 0.59 [-0.20 to 0.91]); in contrast, they were negligibly-to-moderately but not significantly correlated in adolescents (r [95%CI]: BMI, 0.21 [-0.36 to 0.67]); VPA, -0.34 [-0.84 to 0.48]; and VPA, -0.08 [-0.74 to 0.66]). This suggests that childhood trends in handgrip strength, but not adolescent trends, are good markers of trends in BMI and MVPA/VPA. Assuming these ecological correlations are causal, this temporal connection suggests that strategies (e.g., national and international physical activity guidelines²⁷⁻³⁰) promoting the development of fat-free muscle mass and MVPA/VPA (including gripping activities) might be a better population approach to improving handgrip strength in children than in adolescents. It is also possible that any given increase in BMI or MVPA/VPA results in a larger increase in handgrip strength in children than in adolescents. In a large nationally representative sample of Canadian children and adolescents

aged 6–17 years, the positive relationship between BMI and handgrip strength was stronger/steeper in children than adolescents.¹⁶⁰ In addition, trends in handgrip strength were strongly associated with trends in HDI among children (r [95%CI]: 0.59 [0.09 to 0.85]) but negligibly associated among adolescents (r [95%CI]: 0.03 [−0.51 to 0.55]). This suggests that trends in the economic and development status of a country are associated with trends in children's strength levels, perhaps because of better quality and/or quantity of opportunities for organized sport and physical activity. For instance, country-specific human development was a strong-to-very strong positive correlate of physical activity opportunities at the school and community/environment levels, and a moderate positive correlate of organized sport and physical activity, among children and adolescents across 49 countries.¹⁶¹ Age-related differences in motivation levels may also be involved.

This study represents the most comprehensive analysis to date investigating the national and international temporal trends in handgrip strength for children and adolescents. We used a detailed statistical approach, including weighted regression and a post-stratification population weighting procedure, which helped adjust our trends for sampling bias by incorporating the underlying population demographics. Furthermore, a sensitivity analysis showed that the removal of countries with very large samples ($n > 300,000$ e.g., China, Japan, and Poland, which collectively comprised 93% of all data points) (Table 1) had a negligible effect ($ES < 0.2$) on the international trends, providing support that these countries did not substantially bias the reported international trend in handgrip strength.

Despite the strengths of this study, there are several limitations. First, because we estimated trends in handgrip strength from descriptive data rather than raw data, we were unfortunately unable to statistically remove the effects of factors (e.g., body size) known to influence muscular strength. Previously, absolute handgrip strength has been both positively¹⁶² and negatively¹⁶³ associated with cardiometabolic health in children and adolescents, whereas strength relative to body mass appears to be a more consistent positive predictor.^{23,164} Because our study was unable to estimate temporal trends in relative handgrip strength, caution should be taken when inferring corresponding trends in population health. Nevertheless, absolute handgrip strength in adolescence is reliably associated with other health outcomes (e.g., bone health),^{165,166} and the predictive value of absolute and relative handgrip strength for cardiometabolic risk is comparable.¹⁶⁷ Therefore, there is currently no reason to assume the pooled international improvement in absolute handgrip strength represents a decline in population health. Second, the international trends are largely representative of high- and upper-middle-income countries/special administrative regions (18/19 or 95%), which limits the generalizability of our results to low-income and middle-income countries that may be experiencing a physical activity transition.¹⁶⁸ Third, we have low confidence in our country-level correlations (Table 2) because: (a) of the small number of included countries; (b) the homogeneity in the available trend data between countries; (c) the time span over which trends in handgrip strength were calculated did not always match the time span over which the trends in health-related/sociodemographic indicators were calculated; (d) the correlations between trends in handgrip strength and trends in MVPA/VPA were limited to only European countries; and (e) there is potential for ecological fallacy. Fourth, handgrip data were collected using different sampling strategies and sampling frames and were not always nationally representative. In the absence of nationally representative

data, trends were estimated using state/provincial and community level data as they provided the best-available insight into national trends. Furthermore, trends were estimated from available country-sex-age-specific data, which may not be representative of all sex and age groups within a country. Fifth, while differences in test protocols (e.g., dynamometer, number of trials, optimal grip span adjustment, elbow angle, etc.) will affect the variability of the test results, they should not have affected our temporal trends because the included study-level trends were estimated using matched protocols (Supplement 3). Finally, temporal trends in mean handgrip strength could be systematically biased if concurrent trends in skewness occurred, although this is unlikely given that Tremblay et al.⁴⁴ reported negligible differences between trends in mean and median handgrip strength in nationally representative samples of Canadian youth tested between 1981 and 2009.

We have previously made recommendations to facilitate data pooling and to improve national and international surveillance of cardiorespiratory fitness.^{145,169,170} Here, in order to best track temporal trends in the muscular fitness (e.g., handgrip strength) of children and adolescents, we recommend that:

- 1 researchers or governments routinely measure handgrip strength (e.g., every 5–10 years) using (where possible) nationally representative data. Care should be taken to minimize temporal variability in sampling and testing procedures;
- 2 to better synthesize national and international temporal trends, researchers should report temporal trends as absolute, percent, and standardized changes in means at the sex-age level or as descriptive data at the sex-age-year level to allow temporal trends to be

calculated. In addition, they should accurately report the sampling strategy/frame, test protocol, and years of testing;

- 3 to better understand true underlying causal mechanisms, temporal trends should be adjusted for trends in factors known to influence handgrip strength (e.g., body size, biological maturation), with subsequent changes to trend estimates quantified. For example, allometric scaling has been used to adjust trends in handgrip strength for trends in body size (i.e., height and mass),⁵¹ and adjusting for trends in measures of fat mass and fat-free mass may help explain a significant extra proportion of the residual variance;¹⁵⁴
- 4 temporal trends should be examined alongside trends in other health-related outcomes (e.g., traditional cardiovascular risk factors) in order to better understand the effect of trends in muscular fitness on trends in health-related outcomes; and
- 5 temporal trends in measures of centrality (e.g., means, medians) should be complemented by trends in measures of variability (e.g., standard deviations, coefficients of variation), and asymmetry (e.g., skewness) to identify whether the trends were uniform or non-uniform across the distribution, especially given the recent identification of health-related criterion-referenced cut-points for handgrip strength.^{22,24–26}

5 Conclusion

This study found a moderate international improvement in absolute handgrip strength for children and adolescents since 1967, with the rate of improvement progressively increasing over time, with more recent values being two times larger than those in the 1960s/1970s. Generally, improvements in the international handgrip strength were nearly twice as large for children than adolescents, yet similar for boys and girls. Trends in handgrip strength varied between countries,

with the national trends being negligibly-to-weakly but not significantly related to national trends in health and sociodemographic indicators. There is a need for improved national and international surveillance of handgrip strength, especially among low- and middle-income countries, in order to more confidently determine true international trends among children and adolescents. In addition, researchers should continue to explore the relationships between absolute handgrip strength and health-related outcomes in children and adolescents to help contextualize our findings.

Disclaimer

The content and views expressed in this article are those of the authors and do not necessarily reflect those of the Government of Canada.

Data availability statement

The datasets analyzed in this review are available from the corresponding author on reasonable request.

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Author Contributions

GRT and FLD developed the research question and designed the study. GRT and FLD had full access to all the data in the study and take responsibility for the integrity of the data. GRT and FLD led the statistical analysis, synthesis of results, and writing of the report. All authors contributed to the interpretation of results, editing and critical reviewing of the final report, and approved the final report.

Compliance with Ethical Standards

Faith L. Dooley, Tori Kaster, John S. Fitzgerald, Tanis J. Walch, Madison Annandale, Katia Ferrar, Justin J. Lang, Jordan J. Smith, and Grant R. Tomkinson declare they have no conflicts of interest

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Tables

Table 1. Summary of the included studies by country.

Country	Sex	Age (years)	Span of years	Sample size	Sampling strategy	Sample base	HDI
Australia ⁶¹	F (49.5%) M (50.5%)	9–12	1985–1999	2,912	P	N/S/O	0.939 (very high)
Belgium ^{62–63}	F (47.7%) M (52.3%)	9–17	1835–2010	27,868	P/NP	S/O	0.916 (very high)
Bulgaria ^{64–67}	F (50.7%) M (49.3%)	9–17	1960–1999	28,058	P	N/O	0.813 (very high)
Canada ^{68–71}	F (49.7%) M (50.3%)	9–17	1967–2009	6,884	P/NP	N/O	0.926 (very high)
China ^{72–75}	F (49.9%) M (50.1%)	9–17	2000–2014	656,162	P	N	0.752 (high)
Estonia ⁶³	F (53.4%) M (46.6%)	10–17	1992–2002	4,338	P/NP	S/O	0.871 (very high)
France ⁶³	F (52.1%) M (47.9%)	11,13,14	1985–2008	572	P/NP	O	0.901 (very high)
Greece ⁶³	F (48.7%) M (51.3%)	13–15	1990–2008	2,188	P/NP	N/O	0.870 (very high)
Hong Kong ^{76–80}	F (48.6%) M (51.4%)	9–12	2000–2015	17,653	P	N	0.933 (very high)
Italy ⁶³	F (50.9%) M (49.1%)	12–16	1992–2008	5,643	P/NP	S/O	0.880 (very high)
Japan ^{81–131}	F (49.4%) M (50.6%)	9–17	1967–2017	1,043,672	P	N	0.909 (very high)
Mexico ¹³²	F (49.8%) M (50.2%)	9–17	1968–2000	2,463	NP	O	0.774 (high)
Mozambique ¹³³	F (53.0%) M (47.0%)	9–17	1992–2012	3,283	P	O	0.437 (low)
Poland ^{63,134–137}	F (49.1%) M (50.9%)	9–17	1979–2011	367,320	P/NP	N/S/O	0.865 (very high)
Spain ⁶³	F (51.3%) M (48.7%)	9–17	1984–2010	19,948	P/NP	S/O	0.891 (very high)
Thailand ¹³⁸	F (51.0%) M (49.0%)	9–12	1990–2003	15,235	P	N	0.755 (high)
Turkey ¹³⁹	F (30.8%) M (69.2%)	11–12	1983–2013	1,195	NP	O	0.791 (high)
UK ^{63,140}	F (57.6%) M (42.4%)	9–13,15,17	1981–2014	17,842	P/NP	N/S/O	0.922 (very high)
USA ^{69,70,141,142}	F (46.8%) M (53.2%)	9–17	1899–2009	7,153	NP	S/O	0.924 (very high)

Note: UK=United Kingdom; USA=United States of America; M=male; F=female; P=probability sampling (i.e., random selection); NP=non-probability sampling (i.e., non-random selection); N=national sampling; S=state/provincial sampling; O=other sampling (i.e., city, local area, or school-level sampling); HDI=Human Development Index (2017 estimate) with HDI values of 0.800, 0.700 and 0.550 used as thresholds for very high, high and medium human development, respectively;⁵⁹ Hong Kong is a special administrative region of the People's

Republic of China, and because it maintains a separate governing and economic system, national temporal trends in handgrip strength were estimated separately from China.

Table 2. Potential health-related and sociodemographic correlates of the trends in handgrip strength for children and adolescents.

Variable	Data source	Description	Correlation (95% CI)
<i>Health</i>			
Body mass index (BMI)	NCD-RisC ⁵⁶ Trend data available for 19/19 (100%) countries/special administrative regions between 1975 and 2016.	Calculated as the change (per decade) in mean country-level BMI of boys and girls aged 5–19 years (age standardized). With increasing handgrip strength, a positive correlation (next column) indicated an increase in mean BMI and a negative correlation indicated a decline.	0.18 (–0.30 to 0.59)
Moderate-to-vigorous physical activity (MVPA) and vigorous physical activity (VPA)	Inchley et al. ⁵⁷ Data originally obtained from Health Behaviour in School-aged Children (HBSC) World Health Organization (WHO) collaborative cross-national study. Trend data available for 10 European countries (10/19 or 53% of all countries) between 2002 and 2014.	Calculated as the change (per decade) in mean country-level percentage of boys and girls aged 11-, 13-, and 15-years old that achieved at least 60 minutes of MVPA everyday or VPA at least four times per week. With increasing handgrip strength, a positive correlation indicated an increase in the mean percentage of moderately-to-vigorously or vigorously active children and a negative correlation indicated a decline.	MVPA 0.14 (–0.54 to 0.71) VPA 0.15 (–0.53 to 0.71)
<i>Sociodemographic</i>			
Gini index	World Bank ⁵⁸ Trend data available for 17/19 (89%) countries/special administrative regions between 1990 and 2017.	Summarizes the change (per decade) in the distribution of income among individuals in a country where 0 represents perfect equality and 100 implies perfect inequality. With increasing handgrip strength, a positive correlation indicated a trend towards perfect inequality and a negative correlation a trend towards perfect equality..	0.04 (–0.45 to 0.51)

Human development index (HDI)	United Nations ⁵⁹ Trend data available for 18/19 (95%) countries/special administrative regions between 1990 and 2017.	Calculated as the change (per decade) in mean country-level human development (i.e., achievements in health, education and income). With increasing handgrip strength, a positive correlation indicated an increase in the mean human development and a negative correlation indicated a decline.	0.15 (−0.34 to 0.58)
Urbanization	World Bank ⁶⁰ Trend data available for 19/19 (100%) countries/special administrative regions between 1967 and 2017.	Calculated as the change (per decade) in the percentage of people living in urban areas. With increasing handgrip strength, a positive correlation indicated an increase in urbanization and a negative correlation indicated a decline.	0.27 (−0.21 to 0.65)

Figure captions

Figure 1. PRISMA flow chart outlining the flow of studies through the review.

Figure 2. International temporal trends in mean handgrip strength between 1967 and 2017.

Note: data were standardized to the year 2000=100%, with higher values (>100%) indicating better handgrip strength and negative values (<100%) indicating poorer handgrip strength; the solid lines represent the international changes in mean handgrip strength, and the shaded areas represent the 95% CIs, with upward sloping lines indicating increases over time and downward sloping lines indicating declines over time; mean (95%CI) percent changes (per decade) are shown at the top of each panel.

Figure 3. National temporal trends in mean handgrip strength between 1967 and 2017.

Note: data were standardized to the year 2000=100%, with higher values (>100%) indicating better handgrip strength and negative values (<100%) indicating poorer handgrip strength; the solid lines represent the national changes in mean handgrip strength, and the shaded areas represent the 95% CIs, with upward sloping lines indicating increases over time and downward sloping lines indicating declines over time; mean (95%CI) percent changes (per decade) are shown at the top of each panel; for this study, national temporal trends in mean handgrip strength for China and Hong Kong (a special administrative region of the People's Republic of China) were estimated separately.

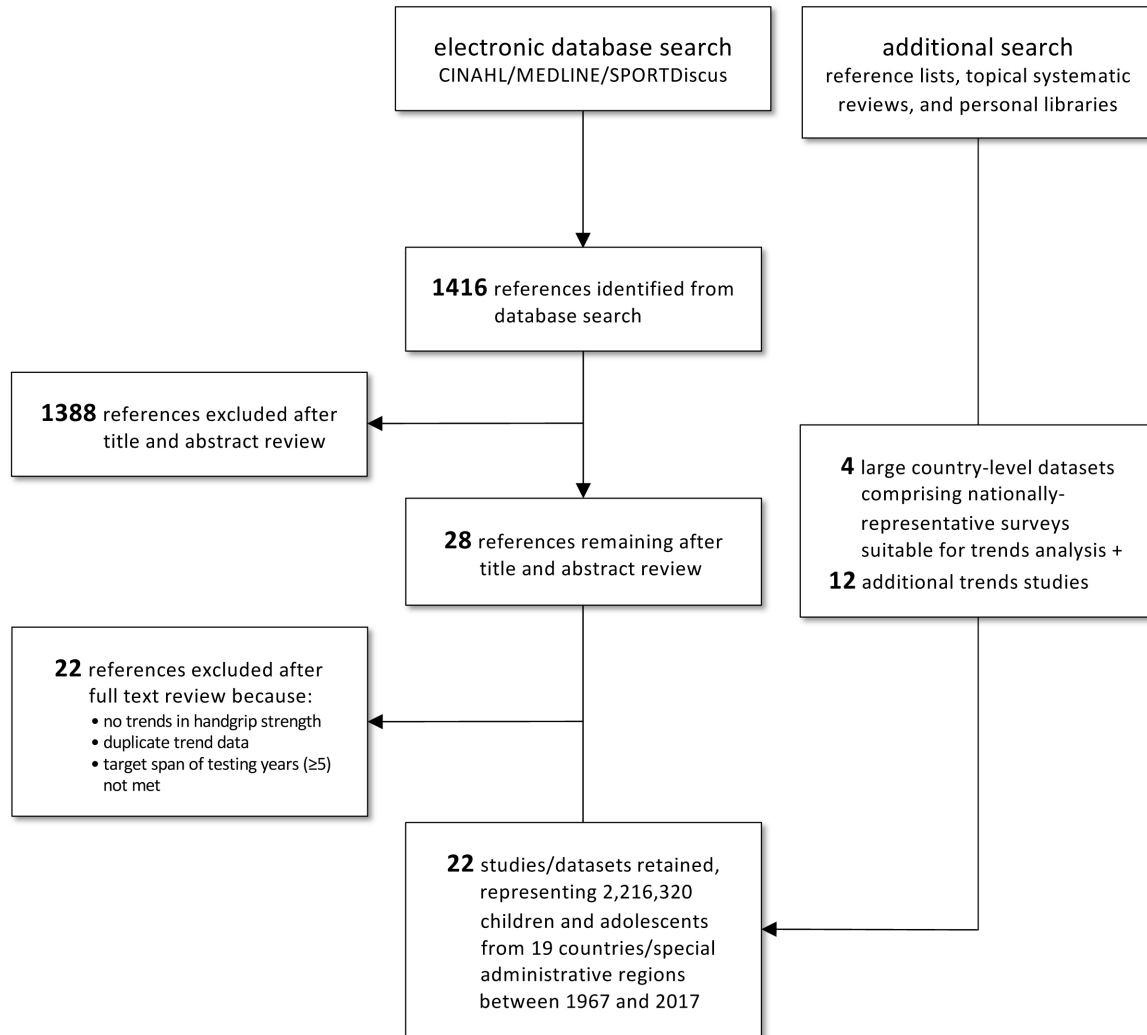


Figure 1.

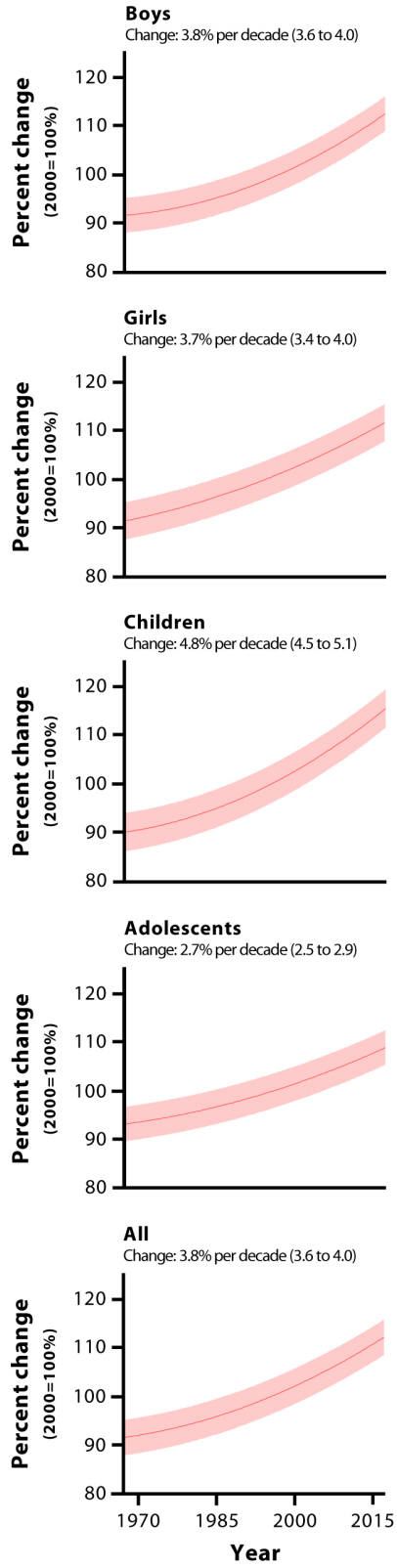


Figure 2.

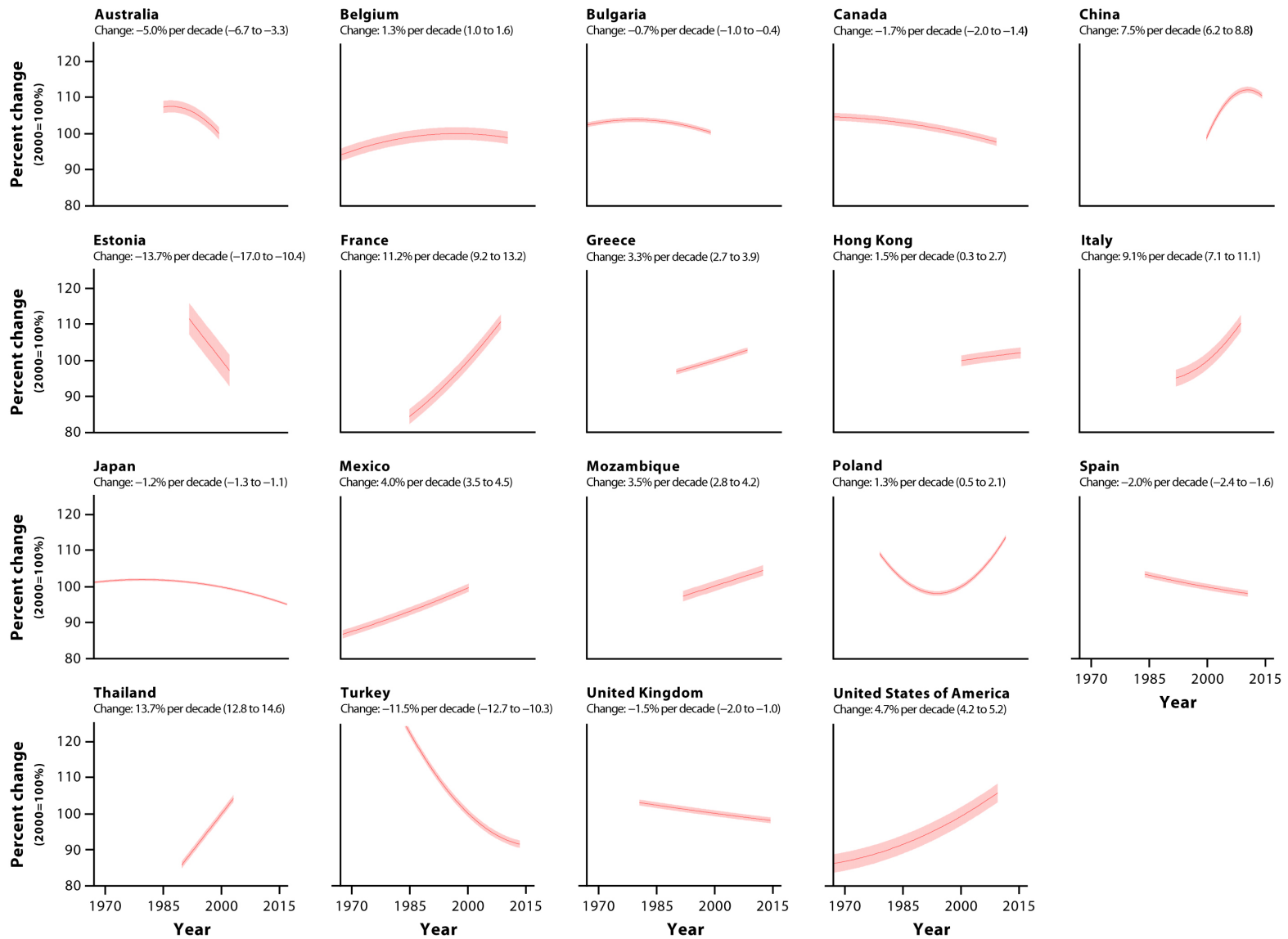


Figure 3.

Supplementary Material

Article title: A systematic analysis of temporal trends in the handgrip strength of 2,216,320 children and adolescents between 1967 and 2017; **Journal name:** Sports Medicine; **Author names and affiliations:** Faith L. Dooley (University of North Dakota), Tori Kaster (University of North Dakota), John S. Fitzgerald (University of North Dakota), Tanis J. Walch (University of North Dakota), Madison Annandale (University of South Australia), Katia Ferrar (University of South Australia), Justin J. Lang (Public Health Agency of Canada and Children's Hospital of Eastern Ontario Research Institute), Jordan J. Smith (University of Newcastle), and Grant R. Tomkinson (University of North Dakota and University of South Australia); **E-mail address of the corresponding author:** grant.tomkinson@und.edu.

Supplement 1. Search strategy for databases.

Search terms

(physical fitness OR muscular fitness OR muscular strength OR muscular endurance OR musculoskeletal fitness OR aerobic fitness OR cardiovascular fitness OR cardiorespiratory fitness) AND (child* OR youth OR young OR adolescen*) AND (temporal OR secular OR trend*).

Databases

CINAHL (1991 to 30 October 2018): 208 studies identified.

MEDLINE (1974 to 30 October 2018): 793 studies identified.

SPORTDiscus (1956 to 30 October 2018): 415 studies identified.

Article title: A systematic analysis of temporal trends in the handgrip strength of 2,216,320 children and adolescents between 1967 and 2017; **Journal name:** Sports Medicine; **Author names and affiliations:** Faith L. Dooley (University of North Dakota), Tori Kaster (University of North Dakota), John S. Fitzgerald (University of North Dakota), Tanis J. Walch (University of North Dakota), Madison Annandale (University of South Australia), Katia Ferrar (University of South Australia), Justin J. Lang (Public Health Agency of Canada and Children's Hospital of Eastern Ontario Research Institute), Jordan J. Smith (University of Newcastle), and Grant R. Tomkinson (University of North Dakota and University of South Australia); **E-mail address of the corresponding author:** grant.tomkinson@und.edu.

Supplement 2. Handgrip strength test protocols for the 22 included studies/datasets.

Web reference(s)	Country	Which hand was used?	How was handgrip strength calculated?	What was the elbow position?	How many trials were allowed per hand?	Which dynamometer was used?	Was the dynamometer adjusted for hand size?
61	Australia	Both	Average of maxima	Bent	1	Mechanical	Yes
62	Belgium	Right	Maximum	NA	NA	Mechanical	NA
63	Belgium/Estonia/France/Greece/Italy/Poland/Spain/UK	Dominant	Maximum	Straight	2	NA	Yes
64–67	Bulgaria	Right	Maximum	NA	NA	NA	NA
68	Canada	Both	Sum of maxima	Straight	2	Mechanical	Yes
69	Canada/USA	Both	Sum of maxima	NA	NA	NA	NA
70	Canada/USA	Both	Sum of maxima	NA	NA	NA	NA
71	Canada	Both	Sum of maxima	Straight	2	Mechanical	Yes
72–75	China	Dominant	Maximum	Straight	2	Mechanical	Yes
76–80	Hong Kong	Both	Sum of maxima	Straight	3	Mechanical	Yes
81–131	Japan	Both	Average of maxima	Straight	2	Mechanical	Yes
132	Mexico	Both	Sum of maxima*	NA	3	Mechanical	Yes

133	Mozambique	Dominant	Maximum	Straight	2	Mechanical	Yes
134	Poland	Right	Maximum	NA	2	Hydraulic	NA
135	Poland	Dominant	Maximum	Straight	2	NA	Yes
136	Poland	Dominant	Maximum	Straight	3	NA	Yes
137	Poland	Dominant	Maximum	Straight	3	NA	Yes
138	Thailand	Dominant	Maximum	Straight	2	NA	Yes
139	Turkey	Dominant	Maximum	Straight	2	Mechanical	Yes
140	UK	Dominant	Maximum	NA	3	Mechanical	Yes
141	USA	Dominant	Maximum	Bent	NA	NA	NA
142	USA	Both	Maximum	Straight	2	Mechanical	NA

Note: NA=Not available;*=temporal data were available for maximum of right hand, maximum of left hand, and sum of the maxima for both hands, with trends estimated in this study using the sum of the maxima for both hands.