1-1-2018

Temporal Trends In The Cardiorespiratory Fitness Of 2,525,827 Adults Representing Eight High- And Upper-Middle-Income Countries Between 1967 And 2016

Nicholas Rye Lamoureux

TEMPORAL TRENDS IN THE CARDIORESPIRATORY FITNESS OF 2,525,827 ADULTS REPRESENTING EIGHT HIGH- AND UPPER-MIDDLE-INCOME COUNTRIES BETWEEN 1967 AND 2016

by

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Bachelor of Science, University of North Dakota, 2016

Master of Science, University of North Dakota, 2018

A Thesis

Submitted to the Graduate Faculty

of the

University of North Dakota

in partial fulfillment of the requirements

for the degree of

Master of Science

Grand Forks, North Dakota

May

2018

This thesis, submitted by Nicholas Rye Lamoureux in partial fulfillment of the requirements for the Degree of Master of Science from the University of North Dakota, has been read by the Faculty Advisory Committee under whom the work has been done and is hereby approved.

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This thesis is being submitted by the appointed advisory committee as having met all of the requirements of the School of Graduate Studies at the University of North Dakota and is hereby approved.

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Dr. Grant McGimpsey

Dean of the School of Graduate Studies

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Date

PERMISSION

Title: Temporal trends in the cardiorespiratory fitness of 2,525,827 adults representing eight high- and upper-middle-income countries between 1967 and 2016

Department: Kinesiology and Public Health Education

Degree: Master of Science

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Nicholas Rye Lamoureux

04/25/2018

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ACKNOWLEDGEMENTS

I would first like to thank my wife, my parents, and all of my family for providing support and encouragement throughout this entire process. This would not have been possible without them

I would first like to thank my advisory committee chair Dr. Grant Tomkinson for the numerous hours he spent providing feedback and guidance throughout the entire process of developing this thesis, and helping shape it into the final product.

For my Parents

ABSTRACT

Objective: To estimate international and national temporal trends in the cardiorespiratory fitness (CRF) of adults, and examine relationships between CRF trends and trends in socioeconomic and health-related indicators.

Methods: Data were obtained from a systematic search of studies that explicitly reported temporal trends in the CRF of apparently healthy adults aged 18–59. Sample-weighted temporal trends were estimated using best-fitting regression models relating the year of testing to mean CRF. Post-stratified population-weighted mean changes in percent and standardized CRF were estimated. Pearson's correlations were used to describe associations between linear trends in CRF and linear trends in socioeconomic and health-related indicators.

Results: 2,525,827 adults representing eight high- and upper-middle-income countries between 1967 and 2016 collectively showed a moderate decline of 7.7% (95%CI: −8.4 to −7.0), [1.6% per decade (95%CI: −1.7 to −1.5)]. Internationally, CRF improved in the 1960s and 1970s, and progressively declined at an increasing rate in subsequent decades. Declines were larger for men than women, and for young adults (<40 years) than middle-aged adults (≥40 years). All countries experienced declines in CRF with a strong negative correlation between obesity trends and CRF trends.

Conclusions: There has been a meaningful decline in the CRF of adults from high- and upper-middle-income countries since 1980, which has progressively increased in magnitude over time, suggestive of a meaningful decline in population health. Continuous national and international surveillance systems are needed in order to monitor trends in health and fitness, especially among low- and middle-income countries for which data do not currently exist.

CHAPTER 1

INTRODUCTION

Cardiorespiratory fitness (CRF) is an important marker of cardiovascular health [1] as it provides a measure of the body's capacity to deliver and utilize oxygen for energy transfer to support muscle activity during physical activity and exercise [2]. CRF — the fourth-leading risk factor for cardiovascular disease [3] — is strongly and inversely related (independent of physical activity level and weight status) in adults to all-cause and cardiovascular disease mortality [4-9], stroke [10] diabetes [11], several cancers [12, 13], and numerous other cardiovascular disease risk factors [14-16]. CRF has been proposed as an important clinical vital sign because of the improved cardiovascular disease mortality risk classification (e.g., net reclassification improvement [NRI], and Framingham and European risk scores) when added to traditional biomarkers [1, 17-20]. Attributable fraction estimates from the Aerobics Center Longitudinal Study of 53,785 men and women showed that CRF was more strongly associated with all-cause mortality than traditional risk factors such as obesity, smoking, hypertension, high cholesterol and diabetes [21]. A recent scientific statement from the American Heart Association (AHA) reported that every metabolic equivalent (MET; 3.5 mL/kg/min) increase in adult CRF was associated with a 10% to 25% decrease in age-adjusted all-cause and/or cardiovascular disease mortality [1]. This evidence provides good support for the monitoring of temporal trends in CRF, which shed meaningful light on temporal trends in population health.

CRF is often expressed as maximal oxygen uptake ($\dot{V}O_{2max}$) or METs, and can be measured using a variety of maximal or sub-maximal field- or laboratory-based running, cycling, or step tests. Although direct (gas-analyzed) measurement of CRF is the criterion, it is impractical for population-based testing. Indirect (non-gas-analyzed) measures on the other hand offer a simple, feasible, practical, reliable and valid alternative [22]. Much of what is known about temporal trends in CRF comes from children and adolescents, where schools have provided opportunities for population-based testing that do not typically exist for adults. Collectively, several large systematic reviews on temporal trends in the CRF of children and adolescents have shown an international decline from the mid-1970s to the early 2000s, followed by a plateau [23-25]. Data on 129,882 children and adolescents aged 6–19 years from 11 countries showed a decline in mean CRF of 4.3% per decade between 1981 and 2000 [26], with a follow-up study showing a decline of 3.6% per decade in 25.4 million 6–19 year olds from 27 countries between 1958 and 2003 [24]. More recently, Tomkinson and colleagues [25] reported that the international decline in CRF has diminished and stabilized with negligible change since 2000 in 965,264 children aged 9–17 years from 19 high- and upper-middle-income countries. Unfortunately, little is known about current national and international trends in the CRF of adults. Furthermore, our recent systematic review identified a strong negative association between country-specific temporal trends in children's CRF and temporal trends in income inequality (Gini index) [25], meaning countries with a widening gap between rich and poor residents had less favorable trends (i.e., large declines) in CRF. Examining the associations between trends in adult CRF and trends in socioeconomic and health-related indicators could provide further insight into the importance of these indicators and their potential population health implications.

This study extends our published research on temporal trends in the CRF of children and adolescents [24-26] to adults. The primary aim therefore was to systematically analyze national and international temporal trends in the CRF of adults. The secondary aim was to examine relationships between temporal trends in CRF and temporal trends in broad socioeconomic and health-related indicators across countries. We hypothesized that adult CRF has declined in recent decades and that country-specific temporal trends in income inequality would be inversely associated with temporal trends in CRF.

CHAPTER 2

METHODS

2.1 Protocol and Registration

The review protocol was prospectively registered with the International Prospective Register of Systematic Review (PROSPERO; registration number CRD42013003678). This review was conducted and reported in accordance with the Preferred Reporting Items for Systematic review and Meta-analysis Protocols (PRISMA-P) statement for reporting systematic reviews [27].

2.2 Eligibility criteria

Studies were included if they reported on temporal trends in the CRF of apparently healthy (free from known disease/injury) adults (aged 18 years or older) across at least two time points spanning a minimum of 10 years. All studies must have relied on population-representative surveys of adults, with a minimum sample size of 100 per country-sex-age-test group. CRF must have been measured using indirect laboratory- or field-based measures, with results reported as trends in maximum oxygen uptake ($\dot{V}O_{2max}$) or long-distance running performance (e.g., the time taken to run a long distance or the distance run over long time).

2.3 Information sources

A systematic literature search was conducted on 1st of March 2018 using the EBSCO interface in Cumulative Nursing and Allied Health Literature (CINAHL), Educational Resources Information Center (ERIC), MEDLINE, and SPORTDiscus without date or language restrictions. The search strategy was developed with the assistance of an academic librarian experienced in systematic review searching.

2.4 Search

The search was performed limited to abstract, title and keywords. Search terms within a group were combined with the Boolean OR and were searched in conjunction with other search groups connected by the Boolean AND. Some terms were searched using proximity operators to search for the root word. The first group of search terms identified the fitness measure (physical fitness, or muscular strength, or muscular endurance, or aerobic fitness, or cardio* fitness or cardio* endurance). The second group identified the population (adult*, or men, or man, or woman, or women, or male or female). The third group identified the trend over time (secular, or temporal or historical). Only studies published in English were included. The full search strategies for each database are shown in Supplement 1.

2.5 Study selection

Two researchers searched all databases independently, with all bibliographic records imported into RefWorks (version 2.0; ProQuest LLC, Ann Arbor, MI, USA) and de-duplicated. Both researchers independently screened all potentially relevant titles and abstracts against inclusion criteria, with exclusion by both researchers required for final exclusion. Full text copies were obtained and independently screened by two researchers against inclusion criteria, with consensus required for final inclusion. A third researcher resolved discrepancies if a consensus was not reached. The reference lists of all included studies and personal libraries of the authors were reviewed to identify relevant studies not identified through the database search. In addition, while systematic reviews were not included in the analysis, their reference lists were reviewed for relevant studies. Where necessary, email contact was made with the corresponding authors in order to clarify published results, to avoid 'double counting' previously reported data, or for additional information.

2.6 Data collection process

Descriptive data were extracted into a spreadsheet by a single researcher using a standardized study-specific template [25], and checked for accuracy by a second reviewer.

2.7 Data items

The following study-specific descriptive data were extracted: title, country, years of testing, sex, age or age range, as well as the sample size, mean, and standard deviation data for measured CRF or the absolute, percent, and/or standardized changes in mean CRF (±95% confidence intervals [CIs]). Countries were also classified based on gross national income per capita according to the World Bank criteria (http://data.worldbank.org/about/country-and-lending-groups). $\dot{V}O_{2max}$ data were expressed as relative $\dot{V}O_{2max}$ in mL/kg/min, and long-distance running data were expressed as running speeds in m/s because relative $\dot{V}O_2$ and $\dot{V}O_{2max}$ varies linearly with speed and maximal speed, and therefore speed should appropriately reflect $\dot{V}O_2$ (i.e., the underlying oxygen cost required to complete the distance run) [22, 28].

2.8 Summary measures and synthesis of results

Temporal trends in mean CRF were analyzed using the detailed procedure described elsewhere [24, 25, 29]. Temporal trends at the country-sex-age-test level (e.g., 20- to 24-year-old Japanese women tested on the 1000 m run) were analyzed using best-fitting sample-weighted linear or polynomial (quadratic or cubic) regression models relating the year of testing to CRF. Changes in mean CRF were expressed as percent (% per year) changes. To interpret the magnitude of change, standardized effect sizes (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 and ES≥0.2 considered to be meaningful [30]. Positive changes indicated increases in mean CRF and negative changes indicated declines.

The temporal trends were described as follows: starting with the first year (Y_1) covered by any study-country-sex-age group, every group including Y_1 in its span of years was located, with every change (dx_1, mL/kg/min or % per year) recorded [24, 25, 29]. This process was applied to all years for which change data were available ($Y_1 ... Y_n$), yielding a series of yearly changes. The post-stratified population-weighted mean yearly change was calculated for year (Y_1) [31], which was repeated for Y_2, Y_3, Y_4… until the last year covered by any study, Y_n. This process yielded a series of population-weighted mean yearly changes (dx_1, …, dx_n) that collectively described the temporal pattern of change; a process that was performed for all adults and for different sex, age, and country groups. Population estimates were standardized to the year 1990 — a common testing year across all country-sex-age groups — using United Nations data [32]. The post-stratification population-weighting procedure helped to correct the trends for systematic bias associated with over- and under-sampling, and to standardize the trends to underlying country-sex-age-specific demographics. Temporal trends were estimated using best-fitting population-weighted linear or polynomial regression models relating the year of testing to the yearly changes, and were graphically illustrated using an iterative procedure described by Tomkinson and Olds [24].

Relationships between linear temporal trends in CRF and linear temporal trends in broad socioeconomic and health-related indicators across countries were quantified using Pearson's correlation coefficients, with 95% confidence intervals estimated using Fisher's *z*-transformation. National trends for two broad socioeconomic/health-related indicators (prevalence of obesity [33] and the Human Development Index [HDI][34]) (Table 1) were analyzed using linear regression models (as described above for CRF). While several other socioeconomic/health-related indicators could have been potentially explored (e.g., Gini index — a population measure of the distribution of wealth), these two indicators were selected because temporal trends could be calculated using the same criteria as for CRF (e.g., across at least two time points spanning a minimum of 10 years) across the majority of included countries. Only post-1990 trends in CRF and trends in prevalence of obesity and HDI were correlated. 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 and $ES\geq0.1$ considered to be meaningful.

Table 1. Potential correlates of the post-1990 trends in adult CRF.

Variable	Data source	Description
Prevalence of obesity (%)	*Ng et al. (2014)* Trend data available for 7 countries between 1990 and 2013.	Calculated as the change (per decade) in mean country-specific prevalence of men and women aged ≥20 years (age standardized) classified as obese based on the International Obesity Task Force definition. A positive change indicated an increase in the mean prevalence of obese and a negative change indicated a decline.
Human development index (HDI)	*The United Nations (2016)* Trend data available for 7 countries between 1990 and 2015.	Calculated as the change (per decade) in mean country-specific achievement in a variety of indicators related to standards of living through a scale from 0.456 (low HDI) to 0.889 (very high HDI). A positive change indicated an increase in the mean standard of living and a negative change indicated a decline.

CHAPTER 3

RESULTS

Figure 1 outlines the identification of the included studies. A total of 578 unique records were identified through online bibliographic database searching. After screening titles and abstracts, 19 articles were retained for full-text review, of which 14 were excluded as described in Figure 1. Five references plus three large population-representative datasets (obtained from the personal library of the senior author) suitable for temporal trends analysis were retained for analysis.

Temporal trends in CRF were estimated from 2,525,827 adults aged 18–59 years from eight countries (1,113 country-sex-age-year groups) between 1967 and 2016 (Table 2). These countries represented seven high-income and one upper-middle-income countries, from three continents and approximately 23% of the world's population. Trends were calculated for 60 country-sex-age groups (men: 31; women: 29; young adults [<40 years]: 46; middle-aged adults [≥40 years]: 14), with an average sample size of 42,097 (range: 149 to 387,088) across an average span of 29 years (range: 10 to 47).

Collectively, there was a moderate decline in mean CRF between 1967 and 2016 (change in means [95%CI]: −7.7% [−8.4 to −7.0]) (Figure 2). There was a large collective decline in mean CRF in men (change in means [95%CI]: −10.0% [−10.9 to −9.1]), small declines in women (change in means [95%CI]: −5.3% [−6.2 to −4.4]) and young adults (change in means [95%CI]: −4.7% [−5.7 to −3.7]), and a negligible decline in middle-aged adults (change in means [95%CI]: −2.0% [−3.0 to −1.0])(Figure 3).

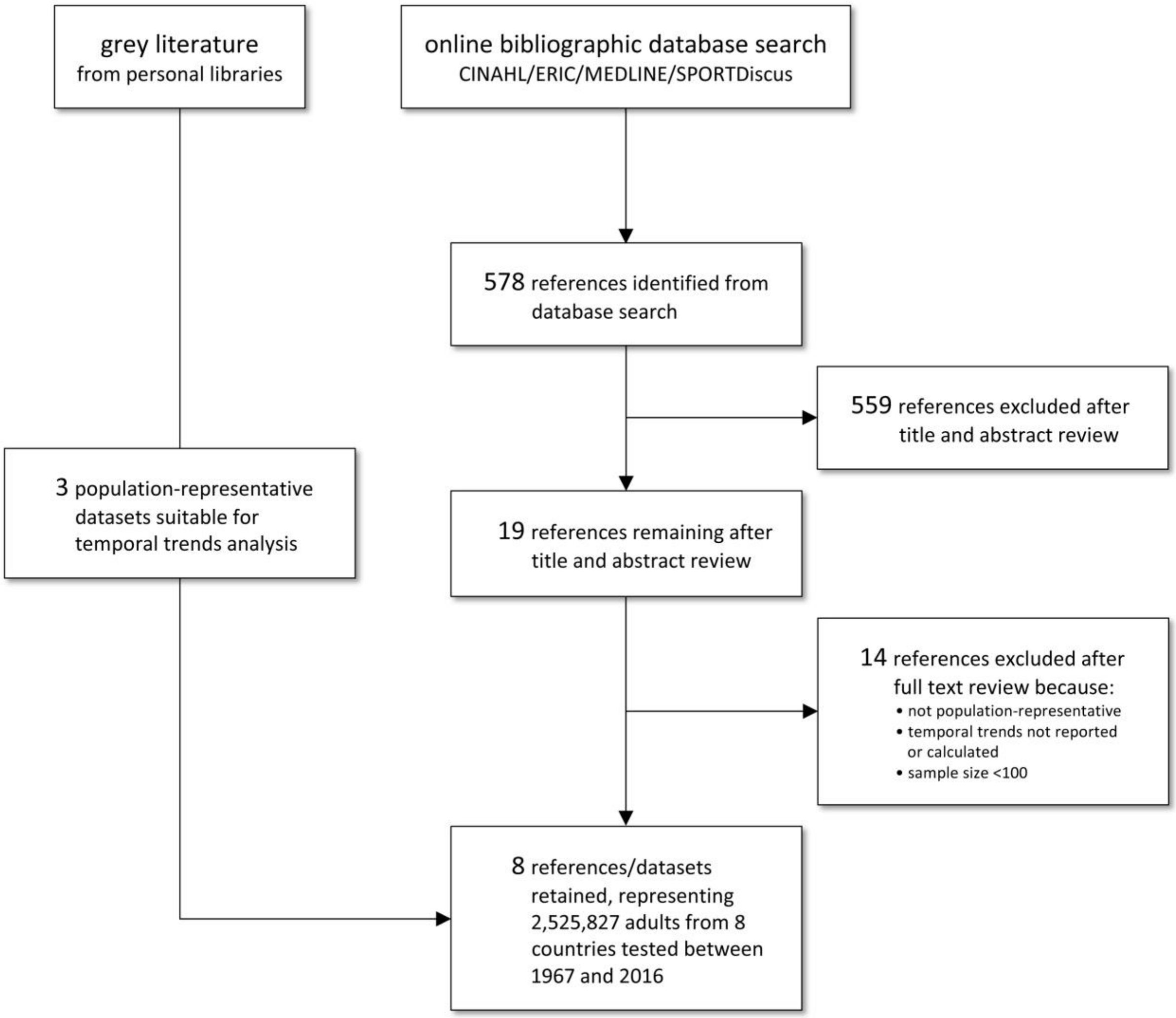

Figure 1. PRISMA flow chart outlining the flow of studies through the review.

Table 2. Summary of the included studies by country.

Country	Sex	Ages (years)	Span of years	Sample size	Country-sex-age-year groups	CRF test(s)
Canada[w1]	M+F	20–59	1981–2009	9,596	8	Bench stepping (CAFT)
China[w2–8]	M+F	18–22	1985–2014	499,229	70	Distance run (800–1000 m)
Finland[w9]	M	20	1975–2004	387,088	3	Timed run (12 min)
Japan[w10–59]	M+F	18–59	1967–2016	1,391,742	956	Distance run, walk (1000–1500 m)
Norway[w60]	M	18	1980–2002	184,638	2	Stationary cycling (Åstrand-
Poland[w61]	M+F	18–19	1979–1999	33,358	12	Distance run (800–1000 m)
Republic of Korea[w62–69]	M+F	19–49	1988–2007	19,207	90	Distance run (1200 m)
Singapore[w70]	M+F	18–19	1981–1991	969	8	Distance run (2400 m)

Note: M=male; F=female; CAFT=Canadian Aerobic Fitness Test.

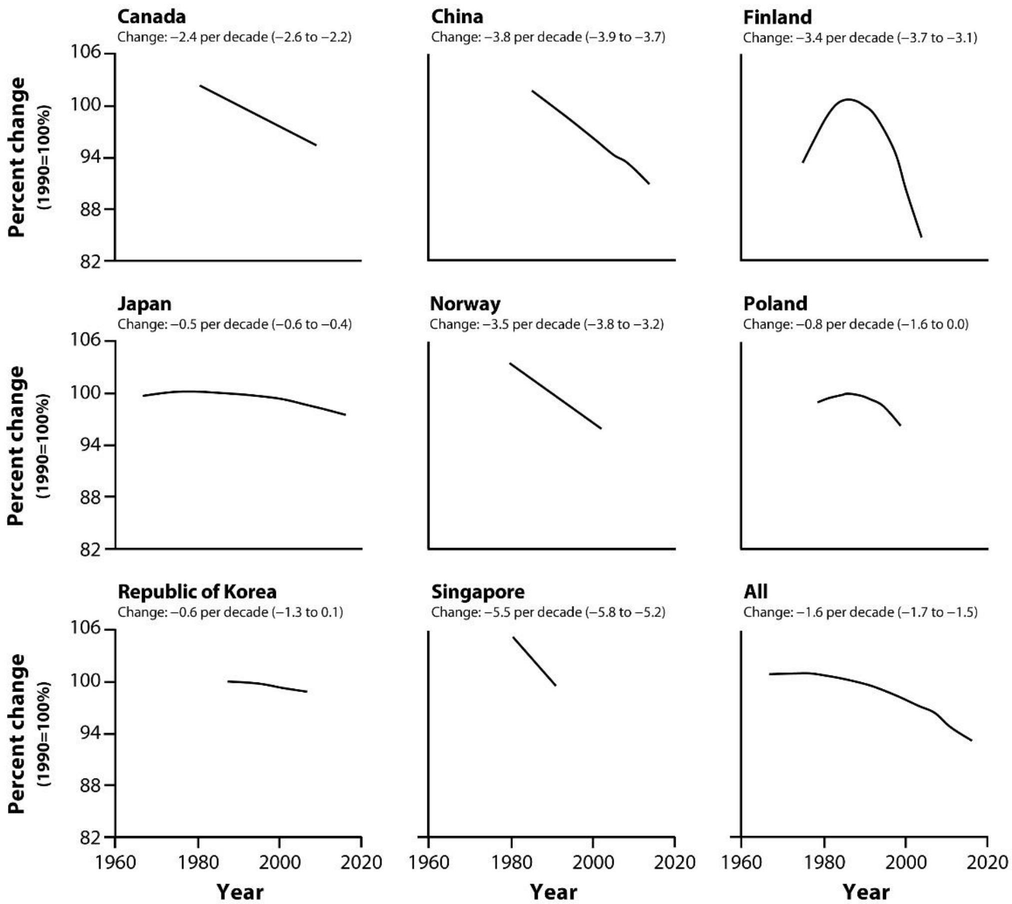

Figure 2. National temporal trends in mean CRF between 1967 and 2016.

Note: data are standardized to the year 1990=100%, with higher values (>100%) indicating better CRF and negative values (<100%) indicating poorer CRF; the solid lines represent the national changes in mean CRF, 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.

Internationally, the changes in mean CRF was not uniform over time, with the rate of change shifting from negligible improvements in the 1960s and 1970s (change in means [95%CI]: 0.4% per decade [0.2 to 0.6]), to negligible declines in the 1980s and 1990s (change in means [95%CI]: −1.8% per decade [−2.0 to −1.6]), and to small declines in the 2000s and 2010s (change in means [95%CI]: −2.5% per decade [−2.8 to −2.2]) (Figure 2). This trend was consistent across different sex and age groups (Figure 3).

All countries experienced declines in CRF, ranging from large declines in China and Finland to negligible declines in Poland and the Korean Republic (Figure 2). While most country trends were approximately uniform (linear), Figure 2 indicates non-uniform (curvilinear) trends in Finland and Poland evidenced by improvements in the 1970s and early 1980s followed by declines from the mid-to-late 1980s onwards.

Country-specific temporal trends for men and women were reasonably consistent, with women almost always experiencing smaller declines in CRF than men (e.g., Canada, China, Japan, and Poland) or improvements instead of declines (e.g., Republic of Korea) (Figure 3). Similarly, country-specific declines in CRF were consistently larger in young adults than in middle-aged adults (Figure 3).

There was a very strong negative correlation between trends in adult obesity and trends in CRF (r [95%CI]: −0.77 [−0.96 to −0.03]), indicating that countries with the largest increases in obesity over the period 1990–2013 had the largest declines in CRF (Figure 4). The correlation between trends in HDI and trends in CRF was weak and positive (r [95%CI]: 0.15 [−0.68 to 0.81]).

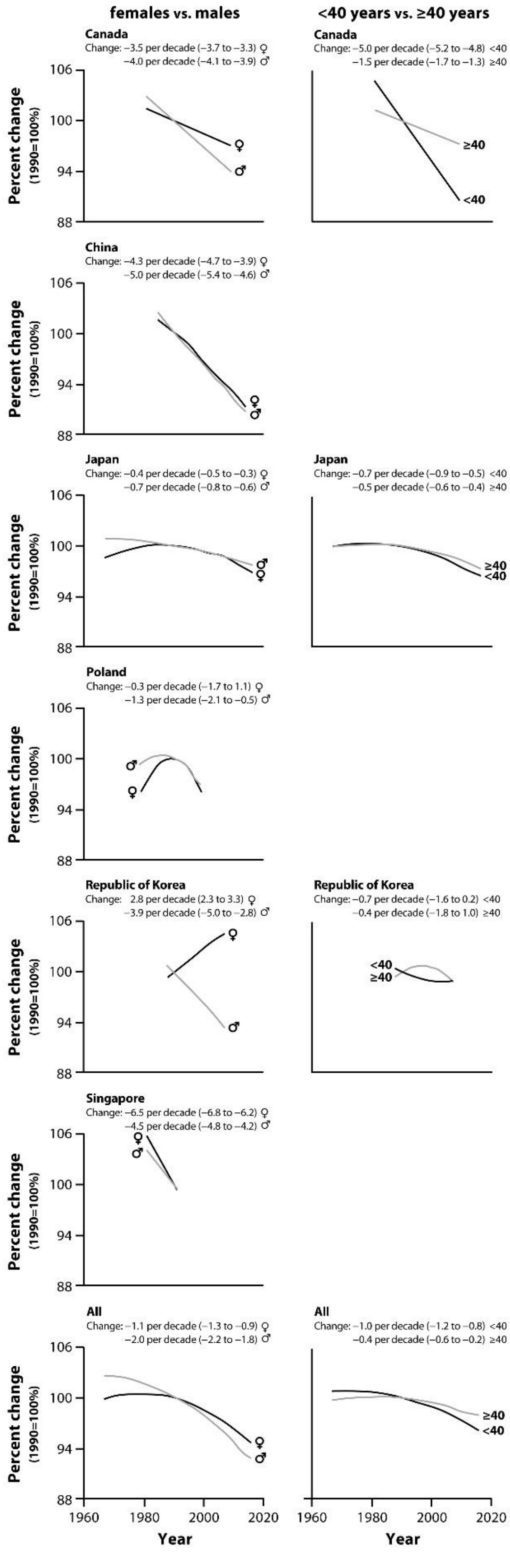

Figure 3. National temporal trends in mean CRF at the age and sex level between 1967 and 2016. Note: data are standardized to the year 1990=100%, with higher values (>100%) indicating better CRF and negative values (<100%) indicating poorer CRF; the black lines represent the national changes in mean CRF for females (♀; left panels) and those aged <40 years (right panels), the grey lines represent the national changes in mean CRF for males (♂**;** left panels) and those aged ≥40 years (right panels), 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

CHAPTER 4

DISCUSSION

This analysis estimated that the CRF of adults: (a) improved internationally in the 1960s and 1970s and declined thereafter, with the magnitude of decline progressively increasing until it reached a peak in the 2000s and 2010s; (b) declined across all included high- and middle-income countries, with both the rate and pattern of change varying among countries; and (c) declined to a greater extent in men than in women, and in younger adults than in middle-aged adults. It also indicated that countries with the largest increases in adult obesity experienced the largest declines in CRF. Given the strong and independent link between CRF and cardiovascular disease and all-cause mortality, these declines in CRF raise a concern and suggest that the current and future health of today's adults is probably worse than that of their peers from decades past. For example, assuming a mean $\dot{V}O_{2max}$ of 45 mL/kg/min for young men [35, 36] and a 7.7% decline over the period 1967–2016, the reported international decline is equal to ~1 MET decline, which is associated with up to a 25% decrease in age-adjusted all-cause and/or cardiovascular disease mortality [1].

We have previously argued that temporal declines in CRF are influenced by a network of environmental, social, behavioral, physical, psychosocial and physiological variables [23–25]. Theoretically, declines in physiological variables such as $\dot{V}O_{2max}$ (leading to a reduced maximum rate at which oxygen can be delivered and utilized in energy transfer), mechanical efficiency (leading to an increased oxygen cost for any given exercise intensity) and the fractional utilization of oxygen (leading to a reduction in the length of time sustained for any given exercise intensity), as well as declines in psychosocial variables (e.g., motivation, ability to tolerate discomfort and pacing [with respect to long-distance running]), are likely involved. While no population-representative trend data for these variables are available, analysis of analysis of 2,006 Swedish adults aged 20–65 years between 1990 and 2000 showed that median absolute CRF ($\dot{V}O_{2max}$ in L/min estimated from the heart rate response to submaximal work on a stationary cycle) remained stable while median relative CRF ($\dot{V}O_{2max}$ in mL/kg/min) declined [37]. These data suggest that little change in true cardiovascular function (i.e., absolute $\dot{V}O_{2max}$) has occurred in adults over time, and that increased body mass — the ratio scaling factor used to remove the influence of body size on absolute $\dot{V}O_{2max}$ — is largely responsible for the decline in relative CRF. However, despite the fact that direct measures of CRF were not used to track trends in CRF in this study, the indirect measures that were used demonstrate strong-to-very strong validity against gas-analyzed $\dot{V}O_{2max}$, with coefficients of determination (R^2) ranging from 0.58 to 0.85 [38-41], suggesting that the reported declines in CRF reflect declines in underlying $\dot{V}O_{2max}$ and/or relative oxygen transport capability.

Physiological changes are in turn affected by physical changes such as increased fatness, as well as behavioral changes such as decreased physical activity levels or increased sedentary time, which may result in reduced cardiovascular function [2, 26, 36]. Consider first increases in fatness, for which an international increase is well established [33, 42]. There are both mechanistic and correlational arguments to support why increases in fatness will influence declines in CRF. First, because fat constitutes an additional load, increased fatness will decrease relative $\dot{V}O_{2max}$ approximately on a pro rata basis [43], and in contrast to a passive load, it will result in additional metabolic maintenance costs (e.g., breathing, thermoregulation) [44]. Second, increases in fatness have coincided with declines in CRF. Consistent with evidence in children

[29, 45], this study found that increased adult obesity was very strongly and negatively correlated with decreased adult CRF. Assuming the observed ecological correlation is causal, this temporal connection suggests that anti-obesity strategies (e.g., reduced energy intake relative to expenditure, increased energy expenditure) might be a suitable population approach to slowing the decline in CRF. Third, using a matching analysis (where people tested at one time point are matched for sex, age and fatness with people tested years later), increases in fatness have been estimated to explain 35% to 70% of the declines in CRF [46, 47]. Unfortunately the residual variability remains unexplained. Importantly, recent increases in adult fatness have coincided with increases in adult fat-free mass [48], both of which affect the balance between energy supply and energy demand. While increased fat-free mass will improve the metabolic potential of the exercising muscles (e.g., improved capacity for glycogen storage, increased muscular strength resulting from increased cross-sectional area, increased number of mitochondria), such a benefit to energy supply will likely be outweighed by the increase in energy demand resulting from increased fat mass.

Of course temporal trends in behaviors are also probably involved [24–25]. Because of the difficulty in obtaining accurate measurements and temporal differences in sampling and methodology, trend data on adult physical activity levels are scare. At this time there is no compelling evidence for international increases in physical activity levels or declines in sedentary behaviors [49, 50]. Adult trend data from high-income countries suggest that leisure-time physical activity has increased [51-53] and occupational physical activity has declined [52, 54, 55]. Similarly in children and adolescents, physical activity levels and sport participation appear to have remained stable [56, 57] or increased [58]. Because CRF assesses an individual's physiological response to their total physical activity profile, declines in adult CRF are therefore suggestive of declines in overall physical activity levels.

In order to improve CRF, the World Health Organization [59] recommends that adults participate in at least 150 minutes of moderate intensity aerobic exercise (continuous, rhythmic, dynamic, large muscle group exercise such as walking, running, cycling, swimming) each week, or at least 75 minutes of vigorous intensity aerobic exercise each week, or an equivalent combination thereof. For additional health benefits, adults are encouraged to double the recommended weekly dose [59].

Temporal differences in CRF between the sexes and different age groups

Figure 3 (two bottom panels) indicates that the collective decline in mean CRF was larger for men than for women and for young adults than for middle-aged adults. These temporal differences have previously been identified in adults [37, 60] and children [25]. Ekblom et al. [37] found that over the period 1990–2000 median CRF ($\dot{V}O_{2max}$ in mL/kg/min) declined in men but not women, and declined with increasing age in both men and women. Similarly, Willis et al. [60] found that while mean CRF ($\dot{V}O_{2max}$ in mL/kg/min estimated from maximal treadmill walking/running) increased in 52,785 men aged 20–74 years between 1970 and 2009, CRF declined somewhat after 2000, with the largest declines observed in young men aged 20–34 years. In our recent analysis of 965,264 children aged 9–17 years from 19 high-income and upper middle-income countries between 1981 and 2014, we found that the decline in mean CRF (mL/kg/min estimated from 20 m shuttle run test performance) was larger for boys than for girls [25].

These temporal differences are difficult to explain in the absence of concurrent data collected on the same adults as those examined in this study. Data from the International Obesity Task Force [33] indicate that recent increases in age-standardized adult obesity (in the countries included in this study at least) have been somewhat larger for men (1.7% per decade) than for women (~1.1% per decade) and for young adults (~1.6% per decade) than for middle-aged adults (~1.2% per decade). Similarly, Ekblom et al. [37] found that both BMI and the prevalence of overweight and obesity increased in men aged 20–59 years, with the largest increases found in young men aged 20–29 years; no changes were found in women. While the temporal coincidence of these patterns is potentially circumstantial, it does at least suggest a strong association between fatness and CRF, although the direction of the causal relationship is not clear.

It is also possible that these sex-related temporal differences in CRF are due to temporal differences in physical activity participation [25]. While good trend data are hard to identify, evidence from elite sport indicates that sex-related temporal differences in physical activity participation exist. For example, female participation at the Olympic Games has steadily risen since its inception in 1900, with females comprising 45% of all athletes in 2016, increasing from 26% in 1988 and 11% in 1960 [61]. This diminishing gender gap in elite sport may reflect that international sport participation has increased for all females. Perhaps the recent promotion of gender equality policies and programs that aim to empower women and girls [62] has helped to reduce the gender gap in CRF through sport participation and other physical activity areas. Sex-related differences in motivation levels may also be involved.

Strengths and limitations

This study systematically reviewed and analyzed data from eight unique datasets/studies to estimate international and national temporal trends in the CRF of 2,525,827 adults from eight high- and upper-middle-income countries. The inclusion of only population-representative temporal data on adults who were tested using validated measures of CRF, coupled with the use of weighted regression and a post-stratification population weighting procedure, resulted in high confidence that the reported declines are in fact real. A sensitivity analysis showed that the removal of countries with very large sample sizes (China, Japan, and the Republic of Korea) had a negligible effect (ES<0.1) on the collective trend in CRF, providing support that the reported international trend in CRF was not biased by these countries.

While this is the first systematic review of temporal trends in adult CRF, it used a detailed statistical approach that has been previously adopted in similar reviews on children's CRF [23–25], thus widening the lens on the international trends picture and allowing for direct comparisons between children and adults. For example, figure 4 shows the international temporal trends in mean CRF for children and adults from high- and upper-middle-income countries between 1981 and 2014. Comparative trend data were taken from Tomkinson et al. [25]. Examination of figure 4 reveals that there has been a moderate decline in CRF for both children (ES=−0.71) and adults (ES=−0.64) since 1981, although the shapes of the temporal trends have differed. In children, the rate of decline slowed from 1981 to 2000 and stabilized near zero thereafter; in adults, the rate of decline progressively increased with every decade. These data suggest that the current decline in adult CRF might diminish in subsequent decades when today's children (whose CRF levels have remained reasonably stable for the past decade and a half) become adults. Alternatively, because the transition from adolescence to adulthood represents a period of significant change where activities of daily life are restructured, these temporal differences might indicate a widening of the gap in CRF levels between adolescence and adulthood over time, resulting in a relatively larger decline in CRF in early adulthood. While the underlying reasons for these age-related temporal differences are not clear, as with temporal differences between men and women and young and middle-aged adults, differential trends in fatness, physical activity and sedentary behaviors are probably involved. Data from Olds et al. [63] indicate that childhood overweight and obesity has stabilized since the mid-to-late 1990s in some high-income countries, which may help explain the recent plateau in children's CRF.

It is possible that the country-level CRF data have not always been collected under precisely the same conditions, resulting in systematic differences in testing conditions (e.g., climate, altitude, practice, and running surfaces) and measurement errors (e.g., methodological drift and diurnal variation). However, the inclusion of only large randomized population-representative datasets would have minimized sampling- and methodology-related issues, meaning the reported trends were unlikely to be systematically biased. This study was also limited to the examination of temporal trends in mean values, which could be systematically biased if concomitant trends in skewness occurred. Consistent with data on children [45, 64], Santtila et al. [65] indicated that the decline in the 12-minute distance run performance of 20-year-old Finnish men was skewed towards the low fitness end of the distribution [65]. On the one hand, this suggests that the reported declines in mean CRF are inflated; on the other hand, the trends in skewness reported by Santtila et al. [65] are the likely artifact of expressing CRF as the distance run in 12 minutes, which should have been attenuated when expressed in running speed (m/s) or relative $\dot{V}O_{2max}$

(mL/kg/min) (as in this study) because these data are normally distributed and more appropriate for parametric statistical analysis.

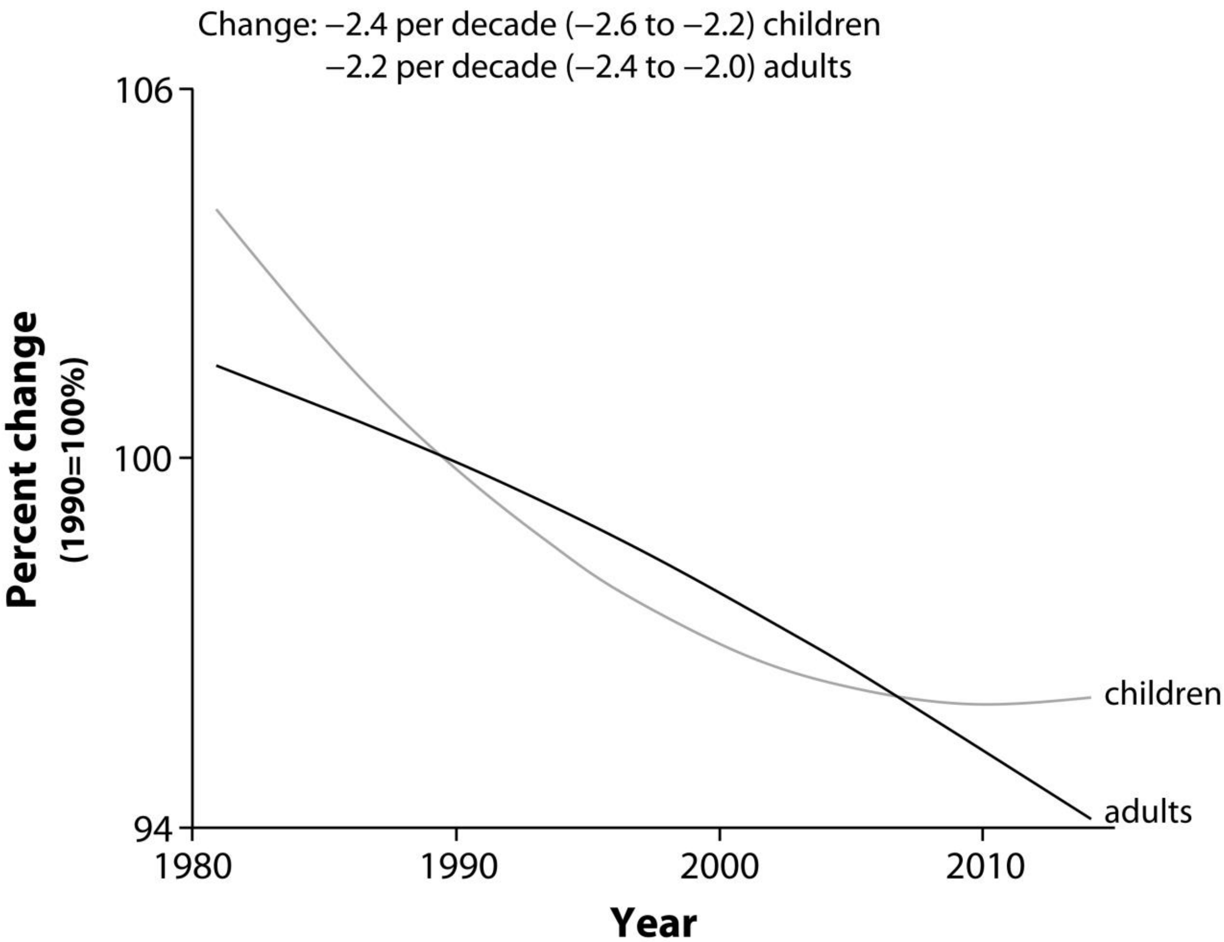

Figure 4. International temporal trends in mean CRF for children (9–17 years) and adults (18–59 years) from high- and upper-middle-income countries between 1981 and 2014.

Note: data are standardized to the year 1990=100%, with higher values (>100%) indicating better CRF and negative values (<100%) indicating poorer CRF; the black trend line represents the international change in mean CRF for adults (18–59 years) and the grey trend line the international change in mean CRF for children (9–17 years), with upward sloping lines indicating increases over time and downward sloping lines indicating declines over time; trend data for children are from Tomkinson et al. [25].

It is also important to remember that the reported trends are representative of only eight high- and upper-middle-income countries, and it is not known whether similar trends exist for other high- and upper-middle-income countries or for low-income countries that may be experiencing a physical activity transition [66]. In addition, the reported trends were estimated from available country-sex-age-specific trend data, which may not be representative of trends across all adults within the included countries or all measurement years. Finally, given that the international trends in CRF were estimated using different CRF tests, each of which imposes different physiological and psychosocial demands, it could be that the trends (percent and standardized) for one test do not equate to the trends for another. It is likely however that the reported trends are largely reflective of declines in construct CRF because the included tests demonstrate strong-to-very strong criterion validity.

Conclusion

This study indicates that there has been a meaningful international decline in the CRF of adults from high- and upper-middle-income countries since 1980, which has progressively increased in magnitude every decade thereafter. Declines in adult CRF were experienced by all included countries, with declines larger for men than for women, and for young adults than for middle-aged adults. Although it is not known why the sex- and age-related temporal differences exist, temporal differences in adult obesity and physical activity levels may be involved. Another key finding was that country-level declines in adult CRF coincided with increases in adult obesity, with the smallest national declines in CRF observed in countries with the smallest increases in obesity. Given the etiology of the decline in CRF is of more than just theoretical interest, it is important that trends in CRF and other cardiovascular disease risk factors (e.g., obesity, physical inactivity, sedentary behavior) be tracked if we want to develop appropriate strategies to reverse the current decline in CRF. Consistent with CRF data in children and adolescents, there are currently no available trend data for adults from low- and middle-income countries. In an effort to enhance knowledge, we advocate for the development of continuous national and international surveillance systems, especially among low- and middle-income countries, in order to monitor trends in health and fitness and to guide national and international action.

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