Sports Medicine (2024) 54:997–1013
https://doi.org/10.1007/s40279-023-01986-y

SYSTEMATIC REVIEW

The Effect of Sedentary Behaviour on Cardiorespiratory Fitness: A Systematic Review and Meta-Analysis

Stephanie A. Prince[1,2] · **Paddy C. Dempsey**[3,4,5,6] · **Jennifer L. Reed**[2,7,8] · **Lukas Rubin**[9,10] · **Travis J. Saunders**[11] · **Josephine Ta**[12] · **Grant R. Tomkinson**[13] · **Katherine Merucci**[14] · **Justin J. Lang**[1,2,13]

Accepted: 14 December 2023 / Published online: 16 January 2024

Abstract

Background Cardiorespiratory fitness (CRF) is an important indicator of current and future health. While the impact of habitual physical activity on CRF is well established, the role of sedentary behaviour (SB) remains less understood.

Objective We aimed to determine the effect of SB on CRF.

Methods Searches were conducted in MEDLINE, Embase, PsycINFO, CINAHL and SPORTDiscus from inception to August 2022. Randomised controlled trials, quasi-experimental studies and cohort studies that assessed the relationship between SB and CRF were eligible. Narrative syntheses and meta-analyses summarised the evidence, and Grading of Recommendations, Assessment, Development and Evaluation (GRADE) certainty was based on evidence from randomised controlled trials.

Results This review included 18 studies that focused on youth (four randomised controlled trials, three quasi-experimental studies, 11 cohort studies) and 24 on adult populations (15 randomised controlled trials, five quasi-experimental studies, four cohort studies). In youth and adults, evidence from randomised controlled trials suggests mixed effects of SB on CRF, but with the potential for interventions to improve CRF. Quasi-experimental and cohort studies also support similar conclusions. Certainty of evidence was very low for both age groups. A meta-analysis of adult randomised controlled trials found that interventions targeting reducing SB, or increasing physical activity and reducing SB, had a significant effect on post-peak oxygen consumption (mean difference = 3.16 mL·kg^{-1}·min^{-1}, 95% confidence interval: 1.76, 4.57).

Conclusions Evidence from randomised controlled trials indicates mixed associations between SB and CRF, with the potential for SB to influence CRF, as supported by meta-analytical findings. Further well-designed trials are warranted to confirm the relationship between SB and CRF, explore the effects of SB independent from higher intensity activity, and investigate the existence of such relationships in paediatric populations.

Clinical Trial Registration PROSPERO CRD42022356218.

Key Points

Evidence from randomised controlled trials indicates mixed associations between sedentary behaviour and cardiorespiratory fitness, with the potential for reduced sedentary behaviour to increase cardiorespiratory fitness, as supported by meta-analytical findings.

Further well-designed trials are warranted to confirm the relationship between sedentary behaviour and cardiorespiratory fitness, explore the effects of sedentary behaviour independent from higher intensity activity and to investigate the existence of such relationships in pediatric populations.

Extended author information available on the last page of the article

1 Introduction

Cardiorespiratory fitness (CRF) is an important measure of health-related fitness and refers to the capability of the cardiovascular and respiratory systems to supply oxygen to muscles for energy production during continuous, large-muscle, whole-body physical activity [1]. Cardiorespiratory fitness is a good indicator of habitual aerobic activity [2–4], and engaging in a greater volume of aerobic activity beyond activities of daily living (e.g. structured exercise and physical training, sports) shown to improve CRF [5, 6]. Importantly, while all physical activity appears to positively influence CRF, some evidence suggests that activity intensity is an important factor [7] with vigorous-intensity physical activity more strongly associated with CRF than light-intensity and moderate-intensity physical activity [1, 8–13].

Cardiorespiratory fitness is a useful prognostic indicator for the health of a population [14, 15] and is predictive of future health outcomes, including cardiometabolic health [16, 17], cardiovascular disease [18, 19], cardiovascular mortality [20, 21], cancer mortality [19, 22] and all-cause mortality [18, 19, 23–26]. Cardiorespiratory fitness is linked to mortality independently of a number of important covariates including age, sex, smoking, alcohol consumption, self-reported physical activity levels, socioeconomic status and comorbidities, making it a powerful predictor of future health states and death [18, 19, 24, 27, 28]. In fact, no other modifiable risk factor has been shown to be a stronger independent predictor of health (e.g. cardiometabolic disease) and longevity than CRF [1, 20, 28, 29].

While habitual physical activity, specifically vigorous intensity physical activity, has long been established as an important contributor to CRF [1, 8], much less is known about the other end of the activity continuum, including sedentary behaviour (SB). Sedentary behaviour is not synonymous with physical inactivity (i.e. insufficient moderate-to-vigorous intensity physical activity [MVPA]), but a distinct behaviour defined by activities undertaken at a low energy expenditure (≤ 1.5 metabolic equivalents of task [METs]) while sitting, lying or reclining [30]. Levels of SB, especially sedentary screen time, have continued to rise [31–34], while CRF has been declining over time [35]. Given that many countries observed increases in population levels of SB during the coronavirus disease 2019 pandemic [36–38] and declines in CRF [39, 40], it is essential to understand the direct relationship between SB and CRF.

Cross-sectional evidence suggests that higher volumes of SB are associated with lower CRF in youth [41–44] and adults [45–49]. A recent systematic review of cross-sectional studies of adults found that device-assessed sedentary time was negatively, though weakly, associated with CRF ($r = -0.16$, 95% confidence interval [CI]: -0.24, -0.09) [48]. Recently, there has been an increase in the number of randomised controlled trials (RCTs) assessing the efficacy of SB interventions to increase CRF either as a primary or secondary outcome [50–53]. No such review has focused on RCTs (to establish causality) or considered the effects of SB independent of physical activity. Therefore, the primary objective of this systematic review was to determine the effect of SB on CRF. A secondary objective was to understand whether the effect of SB on CRF is independent of MVPA.

2 Methods

A systematic review was used to identify all studies that reported on the effects of SB (e.g. sedentary time, sitting time, screen time) on CRF outcomes. To meet the objective of this review, RCTs were the primary study design considered, but quasi-experimental and cohort studies were also explored to supplement RCT findings. The review adheres to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) statement [54] and was prospectively registered on PROSPERO (CRD42022356218).

2.1 Inclusion Criteria

2.1.1 Population

All in-vivo human studies were eligible. Pregnant populations were ineligible.

2.1.2 Exposures

Sedentary behaviour includes activities undertaken at a low energy expenditure (≤ 1.5 METs) while sitting, lying or reclining [30]. Intervention studies were required to include an intervention component that targeted total or type-specific SB or the disruption (break-up) of prolonged SB. Co-interventions (e.g. including a physical activity, diet, weight loss component) were eligible, but were required to provide a quantification of time spent sedentary. A minimum follow-up time of ≥ 7 days was required to exclude studies that assessed immediate/acute effects on CRF. Cohort studies were required to assess exposure to SB at baseline or changes in SB over time and their subsequent effects on CRF.

Sedentary behaviour could be measured either via self-report (e.g. questionnaire, diary/log) or by device (e.g. accelerometer, inclinometer) and could include total time spent sedentary, sitting or in a specific sedentary activity (e.g. screen time, watching television, reading, using a computer or electronic device, playing video games).

2.1.3 Controls

Randomised controlled trials were required to have a no-intervention comparison arm (e.g. usual care, attention control, no intervention). Other studies included historical or comparator controls (e.g. pre-post single-arm trial, multi-arm trial without controls, prospective cohorts, case–control) to establish some element of causality.

2.1.4 Outcomes

Cardiorespiratory fitness could be measured directly or indirectly. Direct measures of CRF include maximal or peak oxygen consumption during exercise testing (hereafter called VO_2peak). Indirect estimates included prediction equations with a variety of inputs, including age, sex, body mass index, height and aerobic exercise performance (i.e. test time, distance, physiological response). Additionally, indirect measures included resting heart rate, maximal heart rate, exercise performance/tolerance (e.g. distance covered, laps, running speed, test duration) and efficiency/economy (heart rate response to exercise, METs). Cardiorespiratory fitness testing could be maximal or submaximal using a variety of modalities such as cycling, running, walking or bench stepping.

2.1.5 Study Designs

Randomised controlled trials were required to have a no-intervention comparison arm. Other study designs included those with historical or comparator controls such as retrospective cohort studies, prospective cohort studies, pre-post studies (quasi-experimental studies) and case–control studies. These study designs provide sufficient detail to examine causal associations for changes in SB and its impact on CRF.

2.1.6 Study Language, Publication Status and Timeframe

No language restrictions were included in the search strategy, but only publications in English, French, Spanish and Czech were included based on authors' language capacity. Only published peer-reviewed studies were eligible. All literature regardless of date of publication was considered.

2.2 Search Strategy

A comprehensive search strategy was developed in collaboration with a research librarian (KM) from the Health Canada Library with input from review authors. The primary search was created in MEDLINE and tested to ensure the capture of previously identified key papers. An RCT filter was used and adapted from the *Cochrane Handbook for Systematic Reviews of Interventions* [55]. The MEDLINE search was peer reviewed by a Health Canada librarian using the PRESS peer review guidelines [56]. KM completed the searches in MEDLINE® All (via Ovid), Embase (via Ovid) and Scopus. A research librarian from the University of Ottawa (VL) translated and completed the searches in CINAHL (via EBSCOhost) and SPORTDiscus (via EBSCOhost). All searches were run from database inception. The CINAHL and SPORTDiscus searches for non-RCTs were exported on 31 August, 2022. All remaining searches were exported on 29 August, 2022 (Table S1 of the Electronic Supplementary Material [ESM]). Bibliographies of topical systematic reviews evaluating SB and health outcomes that included CRF were scanned for additional studies.

2.3 Article Screening

Articles were imported into EndNote, where duplicates were removed. Screening was conducted in Covidence, which also automatically identified and removed duplicates. Two independent reviewers (two of the following authors: SAP, PCD, JLR, LR, TJS, JT, GRT or JJL) screened the titles and abstracts of all studies to identify potentially relevant articles. The full texts of all studies that either met the inclusion criteria or provided insufficient information in the abstract to exclude were obtained and reviewed. Two independent reviewers (two of the following authors: SAP, PCD, JLR, LR, TJS, JT, GRT or JJL) screened the full texts for inclusion. If conflicts arose, discussion between the reviewers and a possible third reviewer was conducted to achieve a final decision.

Two rounds of article screening were conducted. First, the search strategy used a filter to only include RCTs because this was considered the gold standard of evidence for the research question. Limited RCT evidence was identified resulting in a second expanded search that included articles originally excluded by the RCT filter. This resulted in a second round of screening that captured quasi-experimental studies and cohort studies.

2.4 Data Extraction and Analysis

Data extraction forms were completed in Covidence by two independent reviewers (SAP, PCD, JLR, LR, TJS, JT, GRT or JJL) with conflicts resolved by a third (SAP or JJL). The reviewers were not blinded to the authors or journals when screening or extracting data but did not extract data from their own work.

A narrative synthesis, including summary tables, was used to summarise findings across all studies and grouped by outcome. When enough RCTs were available (more than two studies), pooled effects of SB interventions on each outcome were estimated using a random-effects (Der Simonian Laird method) meta-analysis for mean differences (using post-values or changes, depending on reporting of data in primary studies). When more than one intervention was compared to a single control group, the control group sample was divided by the number of intervention groups. Heterogeneity was assessed using the chi-squared test and I^2 statistic. Publication bias was not assessed as fewer than ten studies were included in each meta-analysis [57, 58]. Leave-one-out sensitivity analyses were conducted to determine if removing an individual study had a meaningful impact on the final effect estimates. Forest plots and meta-analyses were created using Review Manager (RevMan) 5.4 (The Cochrane Collaboration, 2020).

To assess the secondary objective of SB on CRF independent of MVPA, we conducted a subgroup analysis comparing RCTs that did and did not include a physical activity focus/component. Additionally, subgroup analyses explored the population group (i.e. apparently healthy vs condition/disease population), CRF outcome measurement method (i.e. direct vs indirect method), average CRF levels at baseline (age-specific and sex-specific low CRF: ≤ 50th percentile vs high CRF > 50th percentile [59]; female percentiles were used if the sample included both male and female individuals), degree of intervention effectiveness for sedentary behaviour (e.g. intervention had a statistically significant effect on overall sedentary time in hour/day), intervention duration (e.g. ≤ 3 months/3–6 months/ > 6 months) and study risk of bias scores (i.e. low, some, high). Non-RCT interventions were not included in the meta-analysis because of high levels of heterogeneity in the methodology and reporting of results.

2.5 Risk of Bias Appraisal for Individual Studies

The risk of bias of the individual studies was assessed based on study design. Version 2 of the Cochrane Collaboration's Tool for Assessing Risk of Bias (RoB 2) was used for randomised trials [60, 61], the Risk of Bias in Non-randomized Intervention Studies (ROBINS-I) tool for quasi-experimental studies [62] and the Risk Of Bias in Non-randomized Studies—of Exposure (ROBINS-E) tool for observational studies [63]. Risk of bias assessments were carried out by two independent reviewers (SAP, PCD, JLR, LR, TJS, JT, GRT or JJL). Conflicts were resolved by a third reviewer (SAP or JJL).

2.6 Grading of the Overall Evidence

The certainty and strength of the evidence were assessed using a modified Grading of Recommendations, Assessment, Development and Evaluation (GRADE) approach [64]. The certainty of the evidence was categorised as high, moderate, low or very low. Randomised controlled trials provided evidence starting at high certainty, while observational studies began at low certainty. For this systematic review, the GRADE assessment was based solely on the evidence from RCTs. Certainty was determined based on confidence in the effect estimate and adjusted considering limitations in study design or execution, inconsistency of results, indirectness of evidence and imprecision (see Table S2 of the ESM for a summary of decision rules). One reviewer (SAP) assessed the evidence for each outcome, and a second reviewer (JJL) verified the assessment for accuracy. Disagreements were resolved through group discussion and consensus. Evidence profiles are presented using summary of findings tables.

3 Results

3.1 Study Characteristics

Figure 1 provides a detailed flow diagram of the literature search and screening process including reasons for a full-text exclusion. The two search rounds identified 21,769 potentially relevant papers. Of these, 3416 were identified in MEDLINE, 3311 in Embase, 4275 in Scopus, 5240 in CINAHL and 5527 in SPORTDiscus. After deduplication, a combined 14,623 relevant papers remained. Title and abstract review resulted in 221 full-text papers for assessment. Of these, 19 RCTs [50, 51, 65–81], eight quasi-experimental studies [82–89] and 15 cohort studies [11, 90–102] met the study inclusion criteria. A list of excluded full texts and reasons can be found in Table S3 of the ESM. Individual study characteristics can be seen in Tables S4–S6 of the ESM.

Eighteen studies focused on youth (four RCTs, three quasi-experimental studies, 11 cohort studies) and 24 on adults (15 RCTs, five quasi-experimental studies, four cohort studies). Included studies were published between 1999 and 2022; the majority (67%) in the past 5 years. The evidence was obtained from 17 countries/regions, with the USA (28%) and Australia (12%) being the most frequent.

Nineteen RCTs examined the influence of a SB intervention on CRF [50, 51, 65, 67–81, 103]. In youth, three RCTs took place in schools, and one was among children with obesity in a community setting. In adults, most (60%) of the RCT evidence included adults working in sedentary occupations in office settings. Seven had at least one intervention arm that only targeted SB (vs a combination of SB plus physical activity), 16 targeted the reduction in total or domain-specific SB (e.g. school, occupational) and most used an educational intervention. In youth, the intervention duration was similar with a range between 6 and 8 months. In adults, the RCT intervention length ranged from 4 weeks to 3 years, with most (60%) lasting 12 weeks or less. Most RCTs targeted non-clinical populations and included both sexes. The majority of RCTs included CRF as a secondary outcome. In youth, laps completed on the 20-m shuttle run test was the most common measure of CRF, while in adults the most common was VO_2peak ($mL \cdot kg^{-1} \cdot min^{-1}$).

3.2 Risk of Bias

Risk of bias for the individual studies is summarised in Tables S7a–c of the ESM. Fourteen of the RCTs (some concerns to high), all quasi-experimental studies (serious or critical), and seven of the cohort studies (high or very high) were identified as having a moderate to high risk of

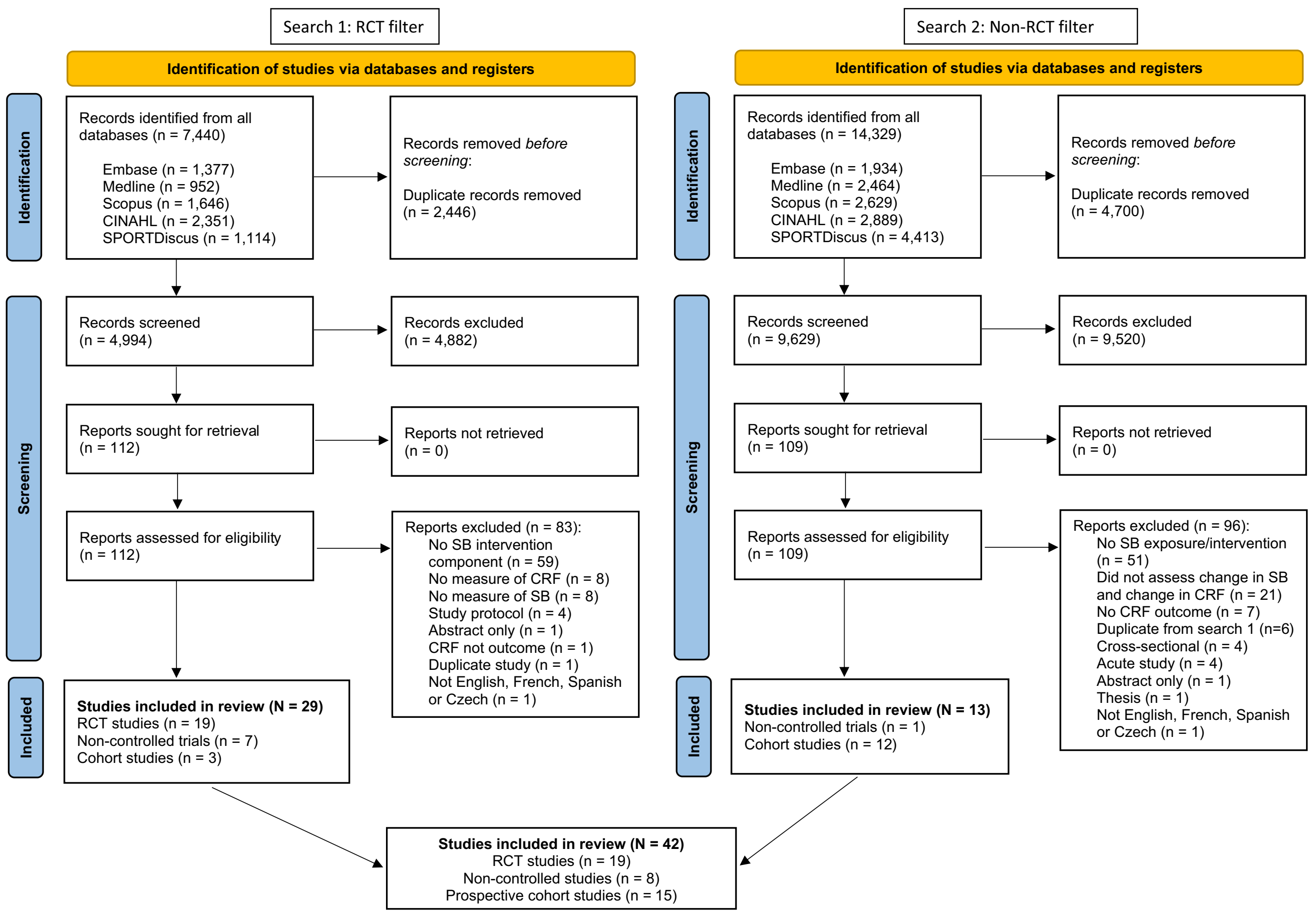

Fig. 1 Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) flow diagram for the identification, screening and inclusion of studies. *CRF* cardiorespiratory fitness, *SB* sedentary behaviour, *RCT* randomised controlled trial

bias. Of the RCTs, the majority had some or a high risk of bias owing to deviations from the intended interventions (72%) and missing outcome data (56%). Among the quasi-experimental studies, most suffered from a serious or critical risk of bias due to confounding (75%) and the measurement of outcomes (50%). Of the cohort studies, the largest sources of bias included a lack of control for important confounding factors (40%) and missing data (47%).

3.3 RCT Evidence

Tables S8 and S9 of the ESM present the individual study findings for the RCTs. Tables 1 and 2 presents the summary of findings and certainty of the evidence for youth and adults, respectively. In youth, there was evidence of mixed effects of SB on CRF with two studies reporting no significant between-group difference [77, 79] and two reporting a significant improvement in CRF [80, 81] in the intervention compared with the control group. A meta-analysis of three RCTs (Fig. 2) found there was no statistically significant effect of SB interventions on post-values for laps completed on the 20-m shuttle run test (mean difference [MD] = 7.9 laps, 95% CI: -0.7, 15.5, $p = 0.07$). The intervention effects reported by Zhou et al. [81] for the two arms that targeted physical activity in an afterschool programme (ASP and ASP plus school physical education) were significantly higher than the school physical education-targeted arm, and the other RCT evidence. Removal of these arms reduced the heterogeneity from 94 to 0%. The quality of evidence from RCTs assessing youth was downgraded to very low because of a risk of bias (one study had a high risk of bias and two with concerns), inconsistency (one trial [81] reported different effects) and indirectness (due to variations in populations and co-interventions).

In adults, seven RCTs [50, 51, 66, 71, 73–75] examined the effects of interventions on $\dot{V}O_2$peak. Figure 3 provides the meta-analyses of mean post-value effects for these interventions stratified by whether the intervention arm focused exclusively on reducing/interrupting SB or was included as a component alongside a physical activity intervention. Overall, interventions had a significantly higher post-$\dot{V}O_2$peak than control groups (MD = 3.16 mL·kg^{-1}·min^{-1}, 95% CI: 1.76, 4.57, $p < 0.0001$). There was no statistically significant difference ($Chi^2 = 2.53$, df = 1, $p = 0.11$) between interventions for which the primary objective was to reduce SB (MD = 2.18 mL·kg^{-1}·min^{-1}, 95% CI: 0.01, 4.36) and interventions that targeted increased physical activity (MD = 4.29 mL·kg^{-1}·min^{-1}, 95% CI: 2.87, 5.70). No statistically significant differences in post-values were observed by a risk of bias (low vs some vs high), population (desk-based workers vs clinical populations), intervention success on reducing SB (reductions in SB statistically significant vs not), SB target (i.e. interrupt vs reduce vs reduce + interrupt), intervention duration (≤ 12 weeks vs > 12 weeks), intervention strategy (i.e. prompts, education, self-monitoring, environment plus prompts, education plus environment, education plus self-monitoring) or $\dot{V}O_2$peak measure (direct vs indirect). Sensitivity analyses found that removing the RCT by Dunning et al. [71] caused the overall effect and SB-only intervention effect to increase (MD = 2.67, 95% CI: 0.78, 4.55). The 10-week trial by Dunning et al. sampled young desk-based workers in South Africa and was designed to reduce SB using prompts. While those in the intervention group sat less compared with the control group (4.9 vs 6.4 h/day, $p = 0.04$), there were no significant changes in CRF. Removing the trial by Larisch et al. [74] reduced the SB-focused intervention effects (MD = 1.41, 95% CI: − 0.61, 3.43), and resulted in a significant difference between the SB-focused interventions and those with a physical activity component or focus ($Chi^2 = 5.24$, df = 1, $p = 0.02$). The 6-month trial by Larisch et al. sampled middle-aged sedentary office workers in Sweden and was designed to both reduce and interrupt SB using education and environmental and organisational-level changes. The SB intervention arm did not significantly reduce SB.

Three adult studies [67, 69, 72] examined the effects of interventions on resting heart rate. Figure 4 provides the meta-analyses of change values for these interventions. Overall, there was no significant effect of SB interventions on changes in the resting heart rate (MD = − 0.12 bpm, 95% CI: − 2.45, 2.20, $p = 0.92$, $I^2 = 0\%$, $p = 0.78$).

While meta-analysis data for $\dot{V}O_2$peak suggest a significant effect of SB on CRF in adults, evidence across all RCTs is mixed with 11 reporting no statistically significant intervention effect [50, 65, 67–74, 76] and three reporting that CRF increased in the intervention [75, 78, 103] compared with a control group. The quality of evidence from RCTs assessing adults was downgraded to very low because of a risk of bias (six studies had a high risk of bias), inconsistency (estimates of effect were mixed, though a VO_2 meta-analysis suggested no significant heterogeneity) and indirectness (largely office workers and clinical populations and variations in co-interventions and physical activity targets).

3.4 Quasi-Experimental and Cohort Evidence

In youth, evidence from quasi-experimental studies and cohort studies (Tables S10 and S12 of the ESM) was similar to RCT evidence, suggesting mixed effects with some showing statistically significant improvements in CRF with reductions in SB [83, 90, 91, 93, 97, 98, 100, 104] and some showing no effect [85, 86, 94, 99, 102, 105]. In adults, evidence from quasi-experimental studies was mixed (Table S11 of the ESM), with one study showing significant improvements in CRF [87], one study showing no effect [82], and two studies being unclear as to the effect of reduced SB or increased physical activity on CRF [84, 88]. Evidence from cohort studies (Table S13 of the ESM) generally suggested that lower SB is associated with greater CRF, even after controlling for physical activity levels.

4 Discussion

This systematic review examined the effects of SB on CRF in youth and adults. Evidence from RCTs suggests mixed associations between SB and CRF, but with the potential for SB to influence CRF as evidenced by results from meta-analyses. In adults, results from the meta-analysis of $\dot{V}O_2$peak, which included the most studies and participants, suggest SB interventions could significantly improve CRF. The certainty of evidence was very low, highlighting the need for higher quality RCTs specifically designed and powered to assess this relationship, to improve confidence in the direction and magnitude of effects. Evidence from quasi-experimental studies and cohort studies also suggests mixed associations between SB and CRF.

Previous systematic review evidence for youth was largely based on cross-sectional studies and suggested that SB is negatively associated with CRF [44, 106]. Similarly, previous review evidence from cross-sectional studies involving adults suggested a weak, statistically significant negative association between SB and CRF (r = − 0.16, 95% CI: − 0.24, − 0.09) [48]. Findings from our review build on the evidence base by providing more prospective and intervention evidence to support benefits.

Several but not all quasi-experimental and cohort studies adjusted for physical activity. Randomised controlled trials are the gold standard for assessing this relationship. Interestingly, out of all the SB-only interventions (i.e. interventions that did not primarily target increased MVPA or did not target the displacement of SB by higher intensity physical activity), only one showed a significant between-group change in MVPA. This finding suggests that improved CRF by increased light-intensity physical activity may be feasible,

Table 1 Summary of findings for SB and CRF in youth

Study design	Effect estimates or summary of effect[a]	# of participants (# of studies)	Certainty (quality) of evidence	Interpretation of findings
RCT	**CRF measured via laps completed on the 20-m shuttle run** [77, 79, 81] Pooled mean difference post-values for intervention vs. control: 7.91, 95% CI: − 0.65, 16.47, $p = 0.07$ All three studies targeted reduced screen time (two with a PA component [77, 81]). Two studies observed a significant decrease in screen time vs. control [79, 81], the other did not [77]. Only one [81] saw a significant change in PA. **CRF measured via recovery HR** [80] NS difference between groups (no difference in PA or SB)	**Laps** I: 618, C: 288 (3) **Recovery HR** I: 60, C: 56 (1)	⊕◯◯◯ **Very low certainty** RoB: − 2 points, one study had high RoB, 2 had some concerns Inconsistency: − 1 point, effects from one trial differed, but could likely be explained by intervention target Indirectness: − 2 points, variation in population and co-interventions Imprecision: 0 point, OIS met	There is very low certainty of mixed effects of SB on CRF. Note: 3/4 trials targeted PA, 3/4 trials significantly reduced SB
Quasi-experimental studies	**CRF measured via VO_2peak** [83, 85] One study [83] targeted reduced total SB and found a significant increase in CRF (like the study arms that targeted PA). The other [85] targeted reduced leisure screen time and found that while SB decreased significantly, MVPA also increased significantly and change in CRF was largely correlated with change in MVPA. **CRF measured via resting and recovery HR** [86] Both Black and non-Black students saw improvements in their leisure screen time and PA levels. Resting HR only significantly reduced in non-Black students, while recovery HR significantly improved in Black students only.	**VO_2peak** 120 (2) **Resting/recovery HR** 3813 (1)	NA	Evidence from quasi-experimental studies is mixed (1 positive, 1 mixed, 1 NS).

Table 1 (continued)

Study design	Effect estimates or summary of effect[a]	# of participants (# of studies)	Certainty (quality) of evidence	Interpretation of findings
Cohorts	**CRF measured via V̇O$_2$peak** [93, 94, 97, 99, 102] 3/5 studies (only 1 controlled for PA) observed that reduced screen time or total SB was not significantly associated with CRF [94, 99, 102]. Two studies (1 controlled for PA) found that lower screen time was associated with greater CRF [93, 97]. **CRF measured via laps completed on the 20-metre shuttle run** [90, 91, 100, 104, 105] 3/5 studies (only 1 controlled for PA) observed that reduced SB was significantly associated with greater CRF [90, 91, 104]. One study found no significant association [105]. One study found that greater SB was associated with greater CRF [100]. **CRF measured via running distance** [98] Evidence suggests a significant association between higher TV watching and reduced CRF.	**V̇O$_2$peak** 4171 (5) **Laps** 4071 (5) **Distance** 135 (1)	NA	Evidence from cohort studies is mixed (6 positive, 4 NS, 1 negative). Three studies controlled for PA in the analysis, and the direction of association differed within each one.

C control group, *CI* confidence interval, *CRF* cardiorespiratory fitness, *HR* heart rate, *I* intervention group, *MET* metabolic equivalents of task, *MVPA* moderate-to-vigorous intensity physical activity, *NA* not applicable, *NS* non-significant, *OIS* optimal information size, *PA* physical activity, *RCT* randomised controlled trial, *RoB* risk of bias, *SB* sedentary behaviour, *TV* television

[a]See supplementary Tables 8, 10 and 12 for detailed results

Table 2 Summary of findings for SB and CRF in adults

Study design	Effect estimates or summary of effect	# of participants (# of studies)	Certainty (quality) of evidence	Interpretation of findings
RCT[a]	**CRF measured via VO_2peak** [50, 51, 71, 73, 75, 76, 103] Pooled mean difference post-values for VO_2peak intervention vs. control: 3.16 $mL{\cdot}kg^{-1}{\cdot}min^{-1}$, 95% CI: 1.76 to 4.57, $p < 0.00001$ SB-only: 2.18, 95% CI: 0.01 to 4.36, $p = 0.05$ SB + PA: 4.29, 95% CI: 2.87 to 5.70, $p < 0.00001$ **CRF measured via running distance** [70] NS effect of SB-only intervention on CRF **CRF measured via resting HR** [67–69, 72] Pooled mean difference change values for intervention vs. control in two studies: − 0.12 bpm, 95% CI: − 2.45 to 2.20, $p = 0.92$ (NS effect in either SB-only or SB + PA intervention). Across the four studies, none found a significant group x time interaction (three included a PA replacement for SB). **CRF measured via METs** [65] NS effect of SB + PA intervention on CRF **CRF measured via exercise capacity (Watts)** [78] Significant effect of SB + PA intervention on CRF	**VO_2peak** I: 361, C: 278 (8) **Distance** I: 14, C: 29 (1) **Resting HR** I: 65, C: 66 (4) **METs** I: 10, C: 11 (1) **Watts** I1: 23, I2: 22, C: 17 (1)	⊕◯◯◯ **Very low certainty** RoB: − 2 points, 6 studies had high RoB, 5 had some concerns Inconsistency: − 1 point, while evidence is mixed, VO_2 meta-analyses suggest no significant heterogeneity. Indirectness: − 2 points, variation in populations and co-interventions Imprecision: 0 points, OIS met for VO_2	There is very low certainty of evidence for mixed effects of SB on CRF, but with the potential for SB-focused interventions to improve CRF as evidenced by the VO_2 meta-analysis. Most SB-only interventions remain underpowered.

Table 2 (continued)

Study design	Effect estimates or summary of effect	# of participants (# of studies)	Certainty (quality) of evidence	Interpretation of findings
Quasi-experimental	**CRF measured via VO_2peak** [87–89] SB-only: significant intervention effect on CRF with the intervention group experiencing a significant decrease in SB and increase in CRF. SB + PA: One study found NS effect of the intervention on CRF, second study was successful at improving CRF, but unclear if it was effect of reducing SB or increasing PA because of using a desk cycle ergometer. **CRF measured via 6-min walking distance** [84] SB-only: Unclear association between SB and CRF as no formal statistical analysis undertaken. SB appeared to have decreased and CRF increased, but unclear if PA significantly changed. **CRF measured via METs** [82] SB + PA: PA and CRF significantly improved, but no change in SB.	**VO_2peak** 337 (3) **Distance** 19 (1) **METs** 20 (1)	NA	Evidence from quasi-experimental studies is mixed.
Cohort	**CRF measured via VO2peak** [11, 95, 101] All three studies found a significant association between reduced SB and increased CRF (two controlled for PA). One study [101] found a significant association with leisure SB, but not occupational SB. **CRF measured via 6-min walking distance** [92] NS association between change in SB and change in CRF. Study did not control for PA.	**VO_2peak** 3997 (3) Distance 642 (1)	NA	Evidence from cohort studies generally suggests a significant association between SB and CRF

C control group, *CI* confidence interval, *CRF* cardiorespiratory fitness, *HR* heart rate, *I* intervention group, *MET* metabolic equivalents of task, *NA* not applicable, *NS* non-significant, *OIS* optimal information size, *PA* physical activity, *RCT* randomised controlled trial, *RoB* risk of bias, *SB* sedentary behaviour

[a]See Supplementary Tables 9, 11 and 13 for detailed results

Study or Subgroup	Intervention Mean	Intervention SD	Intervention Total	Control Mean	Control SD	Control Total	Weight	Mean Difference IV, Random, 95% CI
Peralta et al. 2009 (77)	49.3	13.7	16	48.4	12.5	17	17.5%	0.90 [-8.06, 9.86]
Robinson 1999 (79)	19.72	11.4	92	18.18	10.72	100	21.0%	1.54 [-1.60, 4.68]
Zhou et al. 2019 (SPE, 81)	43.81	14.13	162	41.61	14.59	57	20.5%	2.20 [-2.17, 6.57]
Zhou et al. 2019 (ASP, 81)	52.55	16.18	180	41.61	14.59	57	20.5%	10.94 [6.48, 15.40]
Zhou et al. 2019 (SPE + ASP, 81)	64.78	15.75	180	41.61	14.59	57	20.5%	23.17 [18.74, 27.60]
Total (95% CI)			**630**			**288**	**100.0%**	**7.91 [-0.68, 16.51]**

Heterogeneity: Tau² = 88.83; Chi² = 71.91, df = 4 (P < 0.00001); I² = 94%
Test for overall effect: Z = 1.80 (P = 0.07)

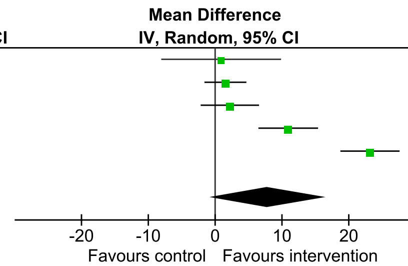

Fig. 2 Meta-analysis comparing post-values of laps completed on the 20-m shuttle run in intervention groups with control groups in youth. *ASP* afterschool programme intervention, *CI* confidence interval, *SD* standard deviation, *SPE* school physical education intervention, *SPE+ASP* school physical education and afterschool programme intervention

Study or Subgroup	Intervention Mean	Intervention SD	Intervention Total	Control Mean	Control SD	Control Total	Weight	Mean Difference IV, Random, 95% CI
3.1.1 SB only								
Carr et al. 2013 (50)	31.1	4.6	23	30	2.6	17	20.1%	1.10 [-1.15, 3.35]
Dunning et al. 2018 (71)	34.6	7.6	11	38	7.2	9	4.2%	-3.40 [-9.90, 3.10]
Kozey-Keadle et al. 2014 (rST, 73)	24.8	5.4	14	23.2	3.6	4	7.8%	1.60 [-2.92, 6.12]
Larisch et al. 2021 (iSED, 74)	40.7	7.2	34	35.9	7.4	57	13.8%	4.80 [1.71, 7.89]
Prince et al. 2018 (51)	23.5	6	17	19.8	5.5	21	10.7%	3.70 [0.00, 7.40]
Subtotal (95% CI)			**99**			**108**	**56.6%**	**2.18 [0.01, 4.36]**
Heterogeneity: Tau² = 2.61; Chi² = 7.19, df = 4 (P = 0.13); I² = 44%								
Test for overall effect: Z = 1.97 (P = 0.05)								
3.1.2 PA + SB								
Balducci et al. 2019 (103)	27.8	5.9	129	23.6	7	132	27.3%	4.20 [2.63, 5.77]
Kozey-Keadle et al. 2014 (Ex-rST, 73)	27.2	6.2	16	23.2	3.6	4	7.5%	4.00 [-0.66, 8.66]
McNeil et al. 2019 (HPA, 75)	23.1	9.2	15	18.3	6.7	7	3.9%	4.80 [-2.01, 11.61]
McNeil et al. 2019 (LPA, 75)	24	7	15	18.3	6.7	7	4.7%	5.70 [-0.40, 11.80]
Subtotal (95% CI)			**175**			**150**	**43.4%**	**4.29 [2.87, 5.70]**
Heterogeneity: Tau² = 0.00; Chi² = 0.25, df = 3 (P = 0.97); I² = 0%								
Test for overall effect: Z = 5.95 (P < 0.00001)								
Total (95% CI)			**274**			**258**	**100.0%**	**3.16 [1.76, 4.57]**

Heterogeneity: Tau² = 1.24; Chi² = 11.38, df = 8 (P = 0.18); I² = 30%
Test for overall effect: Z = 4.41 (P < 0.0001)
Test for subgroup differences: Chi² = 2.53, df = 1 (P = 0.11), I² = 60.5%

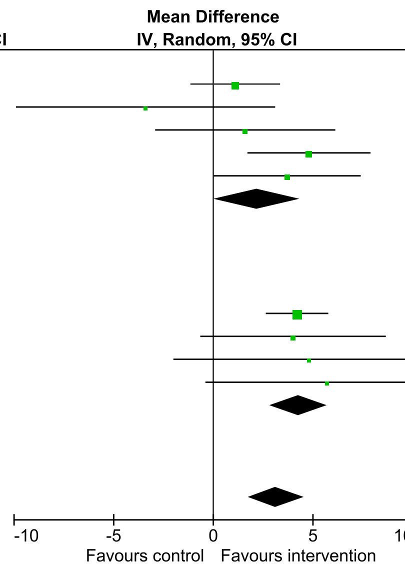

Fig. 3 Meta-analysis comparing post-peak oxygen consumption values (mL·kg^{-1}·min^{-1}) in intervention groups with control groups in adults. Note: Prince et al. 2018 included a physical activity intervention (PA) for both the intervention and control group [51]. *CI* confidence interval, *Ex-rST* increase exercise and reduce sedentary time intervention, *HPA* higher-intensity physical activity intervention, *iSED* sedentary intervention, *LPA* lower-intensity physical activity intervention, *rST* reduce sedentary time intervention, *SB* sedentary behaviour intervention, *SD* standard deviation

Study or Subgroup	Experimental Mean	Experimental SD	Experimental Total	Control Mean	Control SD	Control Total	Weight	Mean Difference IV, Random, 95% CI
Guirado et al. 2022 (72)	-1.5	5.1	17	0.1	13.2	15	10.7%	-1.60 [-8.71, 5.51]
Carter et al. 2020 (69)	-1	7	14	0	5	14	26.6%	-1.00 [-5.51, 3.51]
Bergman et al. 2018 (67)	-0.9	6.3	34	-1.4	6.3	37	62.7%	0.50 [-2.43, 3.43]
Total (95% CI)			**65**			**66**	**100.0%**	**-0.12 [-2.45, 2.20]**

Heterogeneity: Tau² = 0.00; Chi² = 0.48, df = 2 (P = 0.78); I² = 0%
Test for overall effect: Z = 0.10 (P = 0.92)

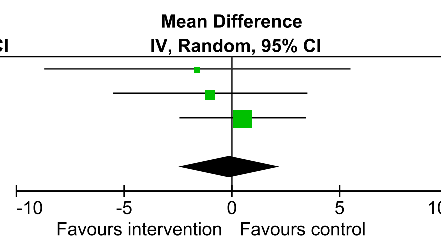

Fig. 4 Meta-analysis comparing changes in the resting heart rate in intervention groups with control groups in adults. *CI* confidence interval, *SD* standard deviation

but the volume of SB reduction may need to be higher than observed. High volumes of SB or prolonged sitting diminish overall skeletal muscle activity and metabolic demand and have deleterious effects on cardiovascular function, including endothelial dysfunction (inability of blood vessels to dilate appropriately), vascular stress, left-ventricular stiffening and blood pressure, which may ultimately be reflected in reduced CRF [107–109]. It is unclear if individuals with sufficient MVPA, but excessive SB, have lower CRF compared with those with sufficient MVPA but low SB.

The RCT by Kozey-Keadle et al. [73] is the only intervention that solely targeted reduced SB and demonstrated a significant improvement in MVPA. Their 12-week RCT assessed whether the combination of aerobic exercise training and reduced SB (EX-rST) resulted in greater improvements in CRF than either reduced SB (rST) or exercise (EX) intervention alone in participants with overweight or obesity. The two groups that targeted reduced SB significantly reduced their SB (r-ST: – 7%, ~ 48 min/day, EX-rST: – 10.3%, ~ 70 min/day). Only the two exercise groups achieved a significant improvement in CRF, possibly suggesting that the addition of exercise MVPA (above incidental physical activity) was likely responsible for the positive changes in CRF. However, these findings and those of our review suggest that SB interventions, which likely have less of an effect on MVPA [110], can maintain and in some cases improve CRF. This is an important finding given the known age-related declines in adult CRF [59, 111, 112], suggesting that incidental/lower intensity physical activity may be sufficient to maintain, but not improve, CRF. This has implications for populations in whom increasing MVPA may be a challenge, but reducing or interrupting SB may be more feasible. Future studies with similar designs of longer duration would help to elucidate the effectiveness of reducing SB in the absence of increases in MVPA.

More recently, there has been a movement to recognise the 'whole day matters' with the composition of movement behaviours (e.g. sedentary time, light-intensity physical activity, MVPA, sleep) within a 24-h period having important implications for health across the lifespan. Evidence suggests that SB and light-intensity physical activity, rather than MVPA, are highly correlated and inter-dependent [113]. Compositional isotemporal substitution modelling recognises behaviours are collinear and co-dependent and provides a means of studying how the reallocation of a fixed duration of time spent in one behaviour with another associates with outcomes. While few studies have used isotemporal substitution modelling with fitness as an outcome, there is evidence to suggest that in youth, reallocating activity behaviours to time spent in SB is associated with lower CRF. However, in adults, reallocating any behaviour towards MVPA has been shown to improve CRF [114]. It is important to remember that most of the evidence is cross-sectional, limiting inferences about the temporal nature of relationships.

The sample sizes in most trials were relatively small with CRF often a secondary outcome. Therefore, most studies were likely underpowered (see optimal information size $N = 134$ per group in Table S2 of the ESM). In fact, none of the adult SB-focused RCTs achieved the estimated optimal information size. While many of the individual trial effects may not have been statistically significant, the mean effect sizes suggested improved CRF. The meta-analyses of $\dot{V}O_2$peak in adults (MD = 3.16 mL·kg^{-1}· min^{-1}) suggest that the effects of interventions on CRF are potentially clinically meaningful, with a 1-MET increase (3.5 mL·kg^{-1}· min^{-1}) associated with reduced risk for all-cause mortality [1, 115]. However, the effects observed in the SB-focused interventions remain below this threshold, though they are consistent with meaningful improvements in clinical populations (e.g. 0.5 MET = 1.75 mL·kg^{-1}· min^{-1}) [116]. Additionally, a threshold of 1.75 mL·kg^{-1}· min^{-1} (0.5 MET) has been considered clinically relevant by some, given a 1-MET change is difficult to achieve for most [117].

4.1 Strengths and Limitations

This review has several strengths including the use of a pre-registered protocol, a comprehensive and peer-reviewed search strategy, the assessment of individual study quality, and the use of a modified GRADE approach to assess the certainty of the evidence and suggest areas of improvement for future studies. In line with previous calls to ascertain the causal associations of SB with outcomes [118], we used a triangulation of evidence (e.g. RCTs, quasi-experiment studies, cohort studies) to obtain a more complete picture of the evidence base. The use of meta-analyses allowed us to combine results from smaller trials; however, the meta-analyses were limited to studies that reported mean changes or post-values using consistent measures and units of CRF. Unfortunately, several of the studies reported adjusted MDs with no post-values or post-values only, with no standard deviations. Furthermore, most of the RCTs were conducted in middle-aged and older adults and targeted sedentary workers or people living with chronic conditions, which increased heterogeneity and limited generalisability. Additionally, most interventions were short in duration (i.e. 12 weeks or less), with few exploring long-term intervention effects (≥ 12 months). While efforts were made to explore sub-group differences, we were limited by the number of included studies.

5 Conclusions

Evidence from RCTs suggests mixed associations between SB and CRF, but with the potential for SB to influence CRF as evidenced by results from meta-analyses. Findings from quasi-experimental and cohort studies align with these conclusions. However, further well-designed trials are necessary to validate the relationship, determine the optimal reduction or replacement of SB required to improve CRF, confirm its independence from changes in higher intensity physical activity and explore this relationship in paediatric populations.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s40279-023-01986-y.

Acknowledgements We thank Valentina Ly from the University of Ottawa for translating and completing the literature search in CINAHL and SPORTDiscus and Lisa Glandon from the Health Canada Library for peer reviewing the primary MEDLINE search strategy. The content and views expressed in this article are those of the authors and do not necessarily reflect those of the Government of Canada.

Funding Open Access funding provided by Public Health Agency of Canada.

Declarations

Funding No funding was required for the conduct of this systematic review and meta-analyses. Paddy C. Dempsey is supported by a National Health and Medical Research Council of Australia Research Fellowship (#1142685).

Conflicts of Interest/Competing Interests Travis J. Saunders has received personal fees for leading a report on the measurement of sedentary behaviour for the Public Health Agency of Canada, and honoraria for presenting on the health impact of physical activity and sedentary behaviour to school groups. Stephanie A. Prince, Paddy C. Dempsey, Jennifer L. Reed, Lukas Rubin, Josephine Ta, Grant R. Tomkinson, Katherine Merucci and Justin J. Lang have no conflicts of interest that are directly relevant to the content of this article.

Ethics Approval Not applicable.

Consent to Participate Not applicable.

Consent for Publication Not applicable.

Data availability All data generated or analysed during this systematic review and meta-analysis are included in the article as table(s), figure(s), and/or Online Supplementary Material(s). Any other data requirement can be directed to the corresponding author upon reasonable request.

Code Availability Not applicable.

Authors' Contributions All authors contributed to the study conception and design. Material preparation and data collection were performed by all authors. Analyses were performed by SAP. The first draft of the manuscript was written by SAP. All authors contributed to data extraction, interpretation and reviewing the manuscript. All authors read and approved the final manuscript.

References

1. Ross R, Blair SN, Arena R, Church TS, Després J-P, Franklin BA, et al. Importance of Assessing cardiorespiratory fitness in clinical practice: a case for fitness as a clinical vital sign: a scientific statement from the American Heart Association. Circulation. 2016;134(24):e653–99.
2. Oja P. Dose response between total volume of physical activity and health and fitness. Med Sci Sports Exerc. 2001;33(6):S428–37.
3. 2018 Physical Activity Guidelines Advisory Committee. 2018 Physical Activity Guidelines Advisory Committee Scientific Report. Washington, DC; 2018.
4. Jackson AS, Sui X, Hébert JR, Church TS, Blair SN. Role of lifestyle and aging on the longitudinal change in cardiorespiratory fitness. Arch Intern Med. 2009. https://doi.org/10.1001/archinternmed.2009.312.
5. Lin X, Zhang X, Guo J, Roberts CK, McKenzie S, Wu WC, et al. Effects of exercise training on cardiorespiratory fitness and biomarkers of cardiometabolic health: a systematic review and meta-analysis of randomized controlled trials. J Am Heart Assoc. 2015;4(7): e002014.
6. Garber CE, Blissmer B, Deschenes MR, Franklin BA, Lamonte MJ, Lee IM, et al. American College of Sports Medicine position stand. Quantity and quality of exercise for developing and maintaining cardiorespiratory, musculoskeletal, and neuromotor fitness in apparently healthy adults: guidance for prescribing exercise. Med Sci Sports Exerc. 2011;43(7):1334–59.
7. Gibala MJ, Little JP. Physiological basis of brief vigorous exercise to improve health. J Physiol. 2020;598(1):61–9.
8. Parikh T, Stratton G. Influence of Intensity of physical activity on adiposity and cardiorespiratory fitness in 5–18 year olds. Sports Med. 2011;41(6):477–88.
9. Burden SJ, Weedon BD, Turner A, Whaymand L, Meaney A, Dawes H, et al. Intensity and duration of physical activity and cardiorespiratory fitness. Pediatrics. 2022. https://doi.org/10.1542/peds.2021-056003.
10. Gralla MH, McDonald SM, Breneman C, Beets MW, Moore JB. Associations of Objectively measured vigorous physical activity with body composition, cardiorespiratory fitness, and cardiometabolic health in youth: a review. Am J Lifestyle Med. 2019;13(1):61–97.
11. Nayor M, Chernofsky A, Spartano NL, Tanguay M, Blodgett JB, Murthy VL, et al. Physical activity and fitness in the community: the Framingham Heart Study. Eur Heart J. 2021;42(44):4565–75.
12. O'Donovan G, Owen A, Bird SR, Kearney EM, Nevill AM, Jones DW, et al. Changes in cardiorespiratory fitness and coronary heart disease risk factors following 24 wk of moderate- or high-intensity exercise of equal energy cost. J Appl Physiol. 2005;98(5):1619–25.
13. Batacan RB Jr, Duncan MJ, Dalbo VJ, Tucker PS, Fenning AS. Effects of high-intensity interval training on cardiometabolic health: a systematic review and meta-analysis of intervention studies. Br J Sports Med. 2017;51(6):494–503.
14. Fowles J, Roy J, Clarke J, Dogra S. Are the fittest Canadian adults the healthiest? Health Rep. 2014;25(5):13–8.
15. Lavie CJ, Sanchis-Gomar F, Ozemek C. Fit is it for longevity across population. J Am Coll Cardiol. 2022;80(6):610–2.

16. García-Hermoso A, Ramírez-Vélez R, García-Alonso Y, Alonso-Martínez AM, Izquierdo M. Association of cardiorespiratory fitness levels during youth with health risk later in life. JAMA Pediatr. 2020;174(10):952.
17. Ruiz JR, Castro-Piñero J, Artero EG, Ortega FB, Sjöström M, Suni J, et al. Predictive validity of health-related fitness in youth: a systematic review. Br J Sports Med. 2009;43(12):909–203.
18. Kodama S, Saito K, Tanaka S, M M, Yachi Y, Asumi M, et al. Cardiorespiratory fitness as a quantitative predictor of all-cause mortality and cardiovascular events in healthy men and women. JAMA. 2009;301(19):2024.
19. Steell L, Ho FK, Sillars A, Petermann-Rocha F, Li H, Lyall DM, et al. Dose-response associations of cardiorespiratory fitness with all-cause mortality and incidence and mortality of cancer and cardiovascular and respiratory diseases: the UK Biobank cohort study. Br J Sports Med. 2019;53(21):1371–8.
20. Gupta S, Rohatgi A, Ayers CR, Willis BL, Haskell WL, Khera A, et al. Cardiorespiratory fitness and classification of risk of cardiovascular disease mortality. Circulation. 2011;123(13):1377–83.
21. Berry JD, Willis B, Gupta S, Barlow CE, Lakoski SG, Khera A, Rohatgi A, et al. Lifetime risks for cardiovascular disease mortality by cardiorespiratory fitness levels measured at ages 45, 55, and 65 years in men. The Cooper Center Longitudinal Study. J Am Coll Cardiol. 2011;57(15):1604–10.
22. Schmid D, Leitzmann MF. Cardiorespiratory fitness as predictor of cancer mortality: a systematic review and meta-analysis. Ann Oncol. 2015;26(2):272–8.
23. Lee DC, Artero EG, Sui X, Blair SN. Mortality trends in the general population: the importance of cardiorespiratory fitness. J Pscyhopharmacology. 2010;24:27–35.
24. Blair SN, Kohl HW, Paffenbarger RS, Clark DG, Cooper KH, Cooper, Gibbons LW. Physical fitness and all-cause mortality: a prospective study of healthy men and women. JAMA. 1989;262(17):2395–401.
25. Kokkinos P, Faselis C, Samuel IBH, Lavie CJ, Zhang J, Vargas JD, et al. Changes in cardiorespiratory fitness and survival in patients with or without cardiovascular disease. J Am Coll Cardiol. 2023;81(12):1137–47.
26. Kokkinos P, Faselis C, Samuel IBH, Pittaras A, Doumas M, Murphy R, et al. Cardiorespiratory fitness and mortality risk across the spectra of age, race, and sex. J Am Coll Cardiol. 2022;80(6):598–609.
27. Laukkanen JA, Zaccardi F, Khan H, Kurl S, Jae SY, Rauramaa R. Long-term change in cardiorespiratory fitness and all-cause mortality: a population-based follow-up study. Mayo Clin Proc. 2016;91(9):1183–8.
28. Kaminsky LA, Imboden MT, Ozemek C. It's time to (again) recognize the considerable clinical and public health significance of cardiorespiratory fitness. J Am Coll Cardiol. 2023;81(12):1148–50.
29. Lee D, Sui X, Ortega F, Kim Y, Church T, Winett R, et al. Comparisons of leisure-time physical activity and cardiorespiratory fitness as predictors of all-cause mortality in men and women. Br J Sports Med. 2011;45(6):504–10.
30. Tremblay MS, Aubert S, Barnes JD, Saunders TJ, Carson V, Latimer-Cheung AE, et al. Sedentary Behavior Research Network (SBRN)—Terminology Consensus Project process and outcome. Int J Behav Nutr Phys Act. 2017;14(1):75.
31. Yang L, Cao C, Kantor ED, Nguyen LH, Zheng X, Park Y, et al. Trends in sedentary behavior among the US population, 2001–2016. JAMA. 2019;321(16):1587–97.
32. Prince SA, Melvin A, Roberts KC, Butler GP, Thompson W. Sedentary behaviour surveillance in Canada: trends, challenges and lessons learned. Int J Behav Nutr Phys Act. 2020;17:34. https://doi.org/10.1186/s12966-020-00925-8.
33. Chau JY, Merom D, Grunseit A, Rissel C, Bauman AE, van der Ploeg HP. Temporal trends in non-occupational sedentary behaviours from Australian Time Use Surveys 1992, 1997 and 2006. Int J Behav Nutr Phys Act. 2012;9(1):76.
34. López-Valenciano A, Mayo X, Liguori G, Copeland RJ, Lamb M, Jimenez A. Changes in sedentary behaviour in European Union adults between 2002 and 2017. BMC Public Health. 2020;20(1):1206.
35. Lamoureux NR, Fitzgerald JS, Norton KI, Sabato T, Tremblay MS, Tomkinson GR. Temporal Trends in the cardiorespiratory fitness of 2,525,827 adults between 1967 and 2016: a systematic review. Sports Med. 2019;49(1):41–55.
36. Moore SA, Faulkner G, Rhodes RE, Brussoni M, Chulak-Bozzer T, Ferguson LJ, et al. Impact of the COVID-19 virus outbreak on movement and play behaviours of Canadian children and youth: a national survey. Int J Behav Nutr Phys Act. 2020. https://doi.org/10.1186/s12966-020-00987-8.
37. Colley RC, Bushnik T, Langlois K. Exercise and screen time during the COVID-19 pandemic. Health Rep. 2020;31(6):3–11.
38. Stockwell S, Trott M, Tully M, Shin J, Barnett Y, Butler L, et al. Changes in physical activity and sedentary behaviours from before to during the COVID-19 pandemic lockdown: a systematic review. BMJ Open Sport Exerc Med. 2021;7(1): e000960.
39. Kidokoro T, Tomkinson GR, Lang JJ, Suzuki K. Physical fitness before and during the COVID-19 pandemic: results of annual national physical fitness surveillance among 16,647,699 Japanese children and adolescents between 2013 and 2021. J Sport Health Sci. 2023;12(2):246–54.
40. Jurak G, Morrison SA, Kovač M, Leskošek B, Sember V, Strel J, et al. A COVID-19 crisis in child physical fitness: creating a barometric tool of public health engagement for the Republic of Slovenia. Front Public Health. 2021. https://doi.org/10.3389/fpubh.2021.644235.
41. Aires L, Pratt M, Lobelo F, Santos RM, Santos MP, Mota J. Associations of cardiorespiratory fitness in children and adolescents with physical activity, active commuting to school, and screen time. J Phys Act Health. 2011;8(Suppl. 2):S198-205.
42. Sandercock GRH, Ogunleye AA. Independence of physical activity and screen time as predictors of cardiorespiratory fitness in youth. Pediatr Res. 2013;73(5):692–7.
43. Santos R, Mota J, Okely AD, Pratt M, Moreira C, Coelho-e-Silva MJ, et al. The independent associations of sedentary behaviour and physical activity on cardiorespiratory fitness. Br J Sports Med. 2014;48(20):1508–12.
44. Carson V, Hunter S, Kuzik N, Gray CE, Poitras VJ, Chaput J-P, et al. Systematic review of sedentary behaviour and health indicators in school-aged children and youth: an update. App Physiol Nutr Metab. 2016;41(6 (Suppl. 3)):S240–65.
45. Prince SA, Blanchard CM, Grace SL, Reid RD. Objectively-measured sedentary time and its association with markers of cardiometabolic health and fitness among cardiac rehabilitation graduates. Eur J Prev Cardiol. 2016;23(8):818–25.
46. Kulinski JP, Khera A, Ayers CR, Das SR, De Lemos JA, Blair SN, et al. Association between cardiorespiratory fitness and accelerometer-derived physical activity and sedentary time in the general population. Mayo Clin Proceed. 2014;89(8):1063–71.
47. Wientzek A, Tormo Díaz MJ, Castaño JMH, Amiano P, Arriola L, Overvad K, et al. Cross-sectional associations of objectively measured physical activity, cardiorespiratory fitness and anthropometry in European adults. Obes. 2014;22(5):E127–34.
48. Silva FM, Duarte-Mendes P, Rusenhack MC, Furmann M, Nobre PR, Fachada MÂ, et al. Objectively measured sedentary behavior and physical fitness in adults: a systematic review and meta-analysis. Int J Environ Res Public Health. 2020;17(22):8660.

49. Vaara JP, Vasankari T, Wyss T, Pihlainen K, Ojanen T, Raitanen J, et al. Device-based measures of sedentary time and physical activity are associated with physical fitness and body fat content. Front Sports Act Liv. 2020. https://doi.org/10.3389/fspor.2020.587789.
50. Carr LJ, Karvinen K, Peavler M, Smith R, Cangelosi K. Multicomponent intervention to reduce daily sedentary time: a randomised controlled trial. BMJ Open. 2013;3(10): e003261.
51. Prince SA, Reed JL, Cotie LM, Harris J, Pipe AL, Reid RD. Results of the Sedentary Intervention Trial in Cardiac Rehabilitation (SIT-CR Study): a pilot randomized controlled trial. Int J Cardiol. 2018;269:317–24.
52. KozeyKeadle S, Lyden K, Staudenmayer J, Hickey A, Viskochil R, Braun B, et al. The independent and combined effects of exercise training and reducing sedentary behavior on cardiometabolic risk factors. Appl Physiol Nutr Metab. 2014;39(7):770–80.
53. Balducci S, Haxhi J, Sacchetti M, Orlando G, Cardelli P, Vitale M, et al. Relationships of changes in physical activity and sedentary behavior with changes in physical fitness and cardiometabolic risk profile in individuals with Type 2 diabetes: The Italian Diabetes and Exercise Study 2 (IDES_2). Diabetes Care. 2022;45(1):213–21.
54. Page MJ, McKenzie JE, Bossuyt PM, Boutron I, Hoffmann TC, Mulrow CD, The PRISMA, et al. statement: an updated guideline for reporting systematic reviews. BMJ. 2020;372:n71.
55. Lefebvre CGJ, Briscoe S, Littlewood A, Marshall C, Metzendorf M-I, Noel-Storr A, et al. Technical supplement to Chapter 4: aearching for and selecting studies. In: Higgins JPT TJ, Chandler J, Cumpston MS, Li T, Page MJ, Welch VA, editors. Cochrane Handbook for systematic reviews of interventions. Version 6. Cochrane; 2019.
56. McGowan J, Sampson M, Salzwedel DM, Cogo E, Foerster V, Lefebvre C. PRESS peer review of electronic search strategies: 2015 Guideline Statement. J Clin Epidemiol. 2016;75:40–6.
57. Sutton AJ, Duval SJ, Tweedie RL, Abrams KR, Jones DR. Empirical assessment of effect of publication bias on meta-analyses. BMJ. 2000;320(7249):1574–7.
58. Higgins JPT TJ, Chandler J, Cumpston M, Li T, Page MJ, Welch VA (editors). Chapter 13: Assessing risk of bias due to missing results in a synthesis. 2023. Available from: https://training.cochrane.org/handbook/current/chapter-13. [Accessed 6 Dec 2023].
59. Hoffmann MD, Colley RC, Doyon CY, Wong SL, Tomkinson GR, Lang JJ. Normative-referenced percentile values for physical fitness among Canadians. Health Rep. 2019;30(10):14–22.
60. Sterne JAC, Savović J, Page MJ, Elbers RG, Blencowe NS, Boutron I, et al. RoB 2: a revised tool for assessing risk of bias in randomised trials. BMJ. 2019. https://doi.org/10.1136/bmj.l4898.
61. Collaboration TC. RoB 2: a revised Cochrane risk-of-bias tool for randomized trials. 2022. Available from: https://methods.cochrane.org/bias/resources/rob-2-revised-cochrane-risk-bias-tool-randomized-trials. [Accessed 18 May 2022].
62. Sterne JA, Hernán MA, Reeves BC, Savović J, Berkman ND, Viswanathan M, et al. ROBINS-I: a tool for assessing risk of bias in non-randomised studies of interventions. BMJ. 2016. https://doi.org/10.1136/bmj.i4919.
63. ROBINS-E Development Group (Higgins JMR, Rooney A, Taylor K, Thayer K, Silva R, Lemeris C, et al. Risk Of Bias In Non-randomized Studies - of Exposure (ROBINS-E). 2022. Available from: https://www.riskofbias.info/welcome/robins-e-tool. [Accessed 11 May 2023].
64. Schunemann H, Brozek J, Guyatt G, Oxman A, editors. GRADE Handbook. 2013.
65. Aguinaga S, Marquez DX. Impact of Latin dance on physical activity, cardiorespiratory fitness, and sedentary behavior among latinos attending an adult day center. J Aging Health. 2019;31(3):397–414.
66. Balducci S, Conti F, Sacchetti M, Russo CR, Argento G, Haxhi J, et al. Study to weigh the effect of exercise training on BONE quality and strength (SWEET BONE) in type 2 diabetes: study protocol for a randomised clinical trial. BMJ Open. 2019;9(11): e027429.
67. Bergman F, Wahlström V, Stomby A, Otten J, Lanthén E, Renklint R, et al. Treadmill workstations in office workers who are overweight or obese: a randomised controlled trial. Lancet Public Health. 2018;3(11):e523–35.
68. Carr LJ, Leonhard C, Tucker S, Fethke N, Benzo R, Gerr F. Total worker health intervention increases activity of sedentary workers. Am J Prev Med. 2016;50(1):9–17.
69. Carter SE, Draijer R, Maxwell JD, Morris AS, Pedersen SJ, Graves LEF, et al. Using an e-health intervention to reduce prolonged sitting in UK office workers: a randomised acceptability and feasibility study. Int J Environ Res Public Health. 2020;17(23):1–21.
70. Cheng SWM, Alison J, Stamatakis E, Dennis S, McNamara R, Spencer L, et al. Six-week behaviour change intervention to reduce sedentary behaviour in people with chronic obstructive pulmonary disease: a randomised controlled trial. Thorax. 2022;77(3):231–8.
71. Dunning JR, McVeigh JA, Goble D, Meiring RM. The effect of interrupting sedentary behavior on the cardiometabolic health of adults with sedentary occupations a pilot study. J Occup Environ Med. 2018;60(8):760–7.
72. Guirado T, Metz L, Pereira B, Brun C, Birat A, Boscaro A, et al. A 12-week cycling workstation intervention improves cardiometabolic risk factors in healthy inactive office workers. J Occup Environ Med. 2022;64(8):E467–74.
73. Kozey-Keadle S, Staudenmayer J, Libertine A, Mavilia M, Lyden K, Braun B, et al. Changes in sedentary time and physical activity in response to an exercise training and/or lifestyle intervention. J Phys Act Health. 2014;11(7):1324–33.
74. Larisch L-M, Bojsen-Moller E, Nooijen CFJ, Blom V, Ekblom M, Ekblom O, et al. Effects of two randomized and controlled multi-component interventions focusing on 24-hour movement behavior among office workers: a compositional data analysis. Int J Environ Res Public Health. 2021;18(8):4191.
75. McNeil J, Brenner DR, Stone CR, O'Reilly R, Ruan Y, Vallance JK, et al. Activity tracker to prescribe various exercise intensities in breast cancer survivors. Med Sci Sports Exerc. 2019;51(5):930–40.
76. Patel AK, Banga C, Chandrasekaran B. Effect of an education-based workplace intervention (move in office with education) on sedentary behaviour and well-being in desk-based workers: a cluster randomized controlled trial. Int J Occup Safe Ergon. 2022;28(3):1655–63.
77. Peralta LR, Jones RA, Okely AD. Promoting healthy lifestyles among adolescent boys: the Fitness Improvement and Lifestyle Awareness Program RCT. Prev Med. 2009;48(6):537–42.
78. Reich B, Niederseer D, Loidl M, Fernandez La Puente de Battre MD, Rossi VA, Zagel B, et al. Effects of active commuting on cardiovascular risk factors: GISMO—a randomized controlled feasibility study. Scand J Med Sci Sports. 2020;30:15–23.
79. Robinson TN. Reducing children's television viewing to prevent obesity: a randomized controlled trial. JAMA. 1999;282(16):1561–7.
80. Sacher PM, Kolotourou M, Chadwick PM, Cole TJ, Lawson MS, Lucas A, et al. Randomized controlled trial of the MEND

program: a family-based community intervention for childhood obesty. Obes. 2010;18(Suppl. 1):S62–8.
81. Zhou Z, Li S, Yin J, Fu Q, Ren H, Jin T, et al. Impact on physical fitness of the chinese champs: a clustered randomized controlled trial. Int J Environ Res Public Health. 2019;16(22):4412.
82. Aguiñaga S, Marques IG, Kitsiou S, Balbim GM, Gerber BS, Buchholz SW, et al. BAILAMOS With mHealth Technology! Improving physical activity and well-being in middle-aged and older Latinxs: a pre–post feasibility study. Health Educ Behav. 2021;48(5):575–83.
83. Epstein LH, Paluch RA, Gordy CC, Dorn J. Decreasing sedentary behaviors in treating pediatric obesity. Arch Pediatr Adoles Med. 2000;154(3):220–6.
84. Freene N, van Berlo S, McManus M, Mair T, Davey R. A behavioral change smartphone app and program (ToDo-CR) to decrease sedentary behavior in cardiac rehabilitation participants: prospective feasibility cohort study. JMIR Form Res. 2020;4(11): e17359.
85. Gow ML, Van Doorn N, Broderick CR, Hardy LL, Ho M, Baur LA, et al. Sustained improvements in fitness and exercise tolerance in obese adolescents after a 12 week exercise intervention. Obes Res Clin Pract. 2016;10(2):178–88.
86. Jamerson T, Sylvester R, Jiang Q, Corriveau N, Durussel-Weston J, Kline-Rogers E, et al. Differences in cardiovascular disease risk factors and health behaviors between Black and non-Black students participating in a school-based health promotion program. Am J Health Promot. 2017;31(4):318–24.
87. Overgaard K, Nannerup K, Lunen MKB, Maindal HT, Larsen RG. Exercise more or sit less? A randomized trial assessing the feasibility of two advice-based interventions in obese inactive adults. J Sci Med Sport. 2018;21(7):708–13.
88. Peterman JE, Morris KL, Kram R, Byrnes WC. Cardiometabolic effects of a workplace cycling intervention. J Phys Act Health. 2019;16(7):547–55.
89. Pippi R, Cugusi L, Bergamin M, Bini V, Fanelli CG, Bullo V, et al. Impact of BMI, physical activity, and sitting time levels on health-related outcomes in a group of overweight and obese adults with and without Type 2 diabetes. J Funct Morphol Kinesiol. 2022;7(1):12.
90. Aggio D, Ogunleye AA, Voss C, Sandercock GR. Temporal relationships between screen-time and physical activity with cardiorespiratory fitness in English schoolchildren: a 2-year longitudinal study. Prev Med. 2012;55(1):37–9.
91. Beltran-Valls MR, Adelantado-Renau M, Mota J, Moliner-Urdiales D. Longitudinal associations of healthy behaviors on fitness in adolescents: DADOS Study. Am J Prev Med. 2021;61(3):410–7.
92. Gomez-Bruton A, Navarrete-Villanueva D, Pérez-Gómez J, Vila-Maldonado S, Gesteiro E, Gusi N, et al. The effects of age, organized physical activity and sedentarism on fitness in older adults: an 8-year longitudinal study. Int J Environ Res Public Health. 2020;17(12):1–17.
93. Hancox RJ, Milne BJ, Poulton R. Association between child and adolescent television viewing and adult health: a longitudinal birth cohort study. Lancet. 2004;364(9430):257–62.
94. Haynes A, McVeigh J, Lester L, Eastwood PR, Straker L, Mori TA, et al. Relationship between TV watching during childhood and adolescence and fitness in adulthood in the Raine Study cohort. Eur J Sport Sci. 2023;23(3):423–31.
95. Knaeps S, Bourgois JG, Charlier R, Mertens E, Lefevre J, Wijndaele K. Ten-year change in sedentary behaviour, moderate-to-vigorous physical activity, cardiorespiratory fitness and cardiometabolic risk: independent associations and mediation analysis. Br J Sports Med. 2018;52(16):1063–8.
96. Leppänen MH, Henriksson P, Delisle Nyström C, Henriksson H, Ortega FB, Pomeroy J, et al. Longitudinal physical activity, body composition, and physical fitness in preschoolers. Med Sci Sports Exerc. 2017;49(10):2078–85.
97. Lobelo F, Dowda M, Pfeiffer KA, Pate RR. Electronic media exposure and its association with activity-related outcomes in female adolescents: cross-sectional and longitudinal analyses. J Phys Act Health. 2009;6(2):137–43.
98. Mota J, Ribeiro JC, Carvalho J, Santos MP, Martins J. Television viewing and changes in body mass index and cardiorespiratory fitness over a two-year period in schoolchildren. Pediatr Exerc Sci. 2010;22(2):245–53.
99. Potter M, Spence JC, Boulé N, Stearns JA, Carson V. Behavior tracking and 3-year longitudinal associations between physical activity, screen time, and fitness among young children. Pediatr Exerc Sci. 2018;30(1):134–41.
100. Reisberg K, Riso E-M, Jurimae J. Associations between physical activity, body composition, and physical fitness in the transition from preschool to school. Scand J Med Sci Sports. 2020;30(11):2251–63.
101. Saidj M, Jorgensen T, Jacobsen RK, Linneberg A, Oppert J-M, Aadahl M. Work and leisure time sitting and inactivity: effects on cardiorespiratory and metabolic health. Eur J Prev Cardiol. 2016;23(12):1321–9.
102. Santos DA, Marques A, Minderico CS, Ekelund U, Sardinha LB. A cross-sectional and prospective analyse of reallocating sedentary time to physical activity on children's cardiorespiratory fitness. J Sports Sci. 2018;36(15):1720–6.
103. Balducci S, D'Errico V, Haxhi J, Sacchetti M, Orlando G, Cardelli P, et al. Effect of a behavioral intervention strategy on sustained change in physical activity and sedentary behavior in patients with type 2 diabetes: the IDES_2 Randomized Clinical Trial. JAMA. 2019;321(9):880–90.
104. Mitchell JA, Pate RR, Blair SN. Screen-based sedentary behavior and cardiorespiratory fitness from age 11 to 13. Med Sci Sports Exerc. 2012;44(7):1302–9.
105. Leppanen MH, Henriksson P, Delisle Nystrom C, Henriksson H, Ortega FB, Pomeroy J, et al. Longitudinal physical activity, body composition, and physical fitness in preschoolers. Med Sci Sports Exerc. 2017;49(10):2078–85.
106. Tremblay MS, Leblanc AG, Kho ME, Saunders TJ, Larouche R, Colley RC, et al. Systematic review of sedentary behaviour and health indicators in school-aged children and youth. Int J Behav Nutr Phys Act. 2011;8(1):98.
107. Dempsey PC, Thyfault JP. Physiological responses to sedentary behaviour. Switzerland: Springer International Publishing; 2018. p. 109–53.
108. Dempsey PC, Larsen RN, Dunstan DW, Owen N, Kingwell BA. Sitting less and moving more. Hypertension. 2018;72(5):1037–46.
109. Pinto AJ, Bergouignan A, Dempsey PC, Roschel H, Owen N, Gualano B, et al. Physiology of sedentary behavior. Physiol Rev. 2023;103(4):2561–622.
110. Segura-Jiménez V, Biddle SJH, De Cocker K, Khan S, Gavilán-Carrera B. Where does the time go? Displacement of device-measured sedentary time in effective sedentary behaviour interventions: systematic review and meta-analysis. Sports Med. 2022;52(9):2177–207.
111. Jackson AS, Sui X, Hébert JR, Church TS, Blair SN. Role of lifestyle and aging on the longitudinal change in cardiorespiratory fitness. Arch Intern Med. 2009;169(19):1781–7.

112. Letnes JM, Nes BM, Wisløff U. Age-related decline in peak oxygen uptake: cross-sectional vs. longitudinal findings. A review. Int J Cardiol Cardiovasc Risk Prev. 2023;16: 200171.
113. Van Der Ploeg HP, Hillsdon M. Is sedentary behaviour just physical inactivity by another name? Physiol Sedent Behav. 2017. https://doi.org/10.1186/s12966-017-0601-0.
114. Rollo S, Antsygina O, Tremblay MS. The whole day matters: understanding 24-hour movement guideline adherence and relationships with health indicators across the lifespan. J Sport Health Sci. 2020;9(6):493–510.
115. Laukkanen JA, Isiozor NM, Kunutsor SK. Objectively assessed cardiorespiratory fitness and all-cause mortality risk: an updated meta-analysis of 37 cohort studies involving 2,258,029 participants. Mayo Clin Proc. 2022;97(6):1054–73.
116. Grace SL, Poirier P, Norris CM, Oakes GH, Somanader DS, Suskin N. Pan-Canadian development of cardiac rehabilitation and secondary prevention quality indicators. Can J Cardiol. 2014;30(8):945–8.
117. Bonafiglia JT, Preobrazenski N, Islam H, Walsh JJ, Ross R, Johannsen NM, et al. Exploring differences in cardiorespiratory fitness response rates across varying doses of exercise training: a retrospective analysis of eight randomized controlled trials. Sports Med. 2021;51(8):1785–97.
118. Dempsey PC, Matthews CE, Dashti SG, Doherty AR, Bergouignan A, van Roekel EH, et al. Sedentary behavior and chronic disease: mechanisms and future directions. J Phys Act Health. 2020;17(1):52–61.

Authors and Affiliations

Stephanie A. Prince[1,2] · Paddy C. Dempsey[3,4,5,6] · Jennifer L. Reed[2,7,8] · Lukas Rubin[9,10] · Travis J. Saunders[11] · Josephine Ta[12] · Grant R. Tomkinson[13] · Katherine Merucci[14] · Justin J. Lang[1,2,13]

✉ Stephanie A. Prince
stephanie.prince.ware@phac-aspc.gc.ca

[1] Centre for Surveillance and Applied Research, Public Health Agency of Canada, 785 Carling Avenue, Ottawa, ON K1A 0K9, Canada

[2] School of Epidemiology and Public Health, Faculty of Medicine, University of Ottawa, Ottawa, ON, Canada

[3] Institute for Physical Activity and Nutrition (IPAN), School of Exercise and Nutrition Sciences, Deakin University, Geelong, VIC, Australia

[4] MRC Epidemiology Unit, Institute of Metabolic Science, University of Cambridge, Cambridge Biomedical Campus, Cambridge, UK

[5] Diabetes Research Centre, College of Life Sciences, University of Leicester, Leicester, UK

[6] Baker Heart and Diabetes Institute, Melbourne, VIC, Australia

[7] Exercise Physiology and Cardiovascular Health Lab, University of Ottawa Heart Institute, Ottawa, ON, Canada

[8] School of Human Kinetics, Faculty of Health Sciences, University of Ottawa, Ottawa, ON, Canada

[9] Department of Physical Education and Sport, Faculty of Science, Humanities and Education, Technical University of Liberec, Liberec, Czech Republic

[10] Institute of Active Lifestyle, Faculty of Physical Culture, Palacký University Olomouc, Olomouc, Czech Republic

[11] Department Applied Human Sciences, University of Prince Edward Island, Charlottetown, PEI, Canada

[12] Telfer School of Management, University of Ottawa, Ottawa, ON, Canada

[13] Alliance for Research in Exercise, Nutrition and Activity, Allied Health and Human Performance, University of South Australia, Adelaide, SA, Australia

[14] Health Canada Library, Ottawa, ON, Canada