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Physical Fitness as a Parallel Protective Factor Against Sedentary-Related Non-Communicable Disease Risk in Adolescents: A Comprehensive Evidence Synthesis

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ABSTRACT

Background: The escalating global burden of non-communicable diseases (NCDs) originates increasingly during adolescence, driven by sedentary, screen-dominated lifestyles. Whether physical fitness mitigates this risk remains conceptually ambiguous.
Objective: To synthesize evidence evaluating physical fitness as a protective factor against sedentary-related NCD risk in school-aged adolescents.
Methods: A comprehensive synthesis of observational studies, cohorts, reviews, and interventions focusing on adolescents (10–19 years). We distinguished total sedentary time from screen-based behavior and evaluated cardiorespiratory (CRF) and muscular fitness against cardiometabolic, adiposity, and mental health outcomes.
Results: Higher CRF consistently correlates with lower adiposity and clustered cardiometabolic risk. However, fitness does not formally buffer sedentary harm; screen-based behavior remains independently detrimental. Muscular fitness offers targeted metabolic protection, notably against insulin resistance and hypertriglyceridemia. Substituting sedentary time with vigorous physical activity yields the strongest protective effects. School interventions improve CRF but require multidisciplinary components to alter metabolic biomarkers.
Conclusion: Physical fitness provides parallel, rather than moderating, protection against sedentary-related NCD risk. Public health frameworks must concurrently target fitness enhancement and specific screen-time reduction.

Key Points (Highlights):

- *Fitness lowers NCD risk, but screen time remains harmful.*
- *Fitness is a parallel protector, not a buffer against sedentary harm.*
- *Schools must combine fitness training with specific screen-time reduction.*

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INTRODUCTION

The escalating global burden of non-communicable diseases (NCDs) originates increasingly during adolescence, driven by the modern epidemiological transition toward sedentary, screen-dominated lifestyles (Wang et al., 2024). Sedentary behavior in this critical developmental window matters profoundly because it clusters with adiposity, cardiometabolic risk, and mental health problems, establishing a perilous pathophysiological trajectory for future chronic disease and premature mortality (De Castro Silveira, López-Gil, et al., 2025; Nagata et al., 2023). Within this context, physical fitness may represent a vital protective reserve against these adverse outcomes (Nagata et al., 2024). Across the current evidence base, the core question is not simply whether active adolescents are healthier overall, but whether higher physical fitness specifically reduces the risk profile associated with sedentary lifestyles, particularly those dominated by heavy screen exposure (Brand et al., 2023).

To accurately interpret this literature, three foundational distinctions are essential. First, sedentary behavior is not synonymous with physical inactivity. Consensus and review papers rigorously distinguish sedentary behavior from insufficient physical activity; adolescents can fully meet moderate-to-vigorous physical activity (MVPA) guidelines yet still accumulate large, detrimental amounts of sedentary time, especially via screens (Cheng et al., 2024; Musa et al., 2022). This distinction is critical because studies frequently yield divergent associations depending on whether they measure total sedentary time, screen-based behavior, or MVPA (Laakso et al., 2023; Sampasa-Kanyinga et al., 2020). Second, fitness is a multidimensional construct. Cardiorespiratory fitness (CRF) and muscular fitness are related but distinct physiological domains. The evidence base suggests CRF is the most consistent marker for adiposity and clustered cardiometabolic risk, while muscular fitness holds particular relevance for insulin resistance and metabolic regulation (Leite et al., 2024; Nagata et al., 2026).

Third, and most critically, being a "protective factor" does not necessarily equate to being an "effect modifier." Most studies demonstrate that fitter adolescents generally exhibit better health outcomes overall (X.-S. Dong et al., 2021). However, very few studies test the stricter hypothesis that fitness statistically attenuates the adverse effect of sedentary time on later risk (Q. Dong et al., 2025). Taken together, these findings suggest that fitness functions more clearly as a general resilience correlate rather than a proven, direct shield against sitting-specific harm (Ferreira et al., 2025). The evidence supports a cautious answer to the core question: while fitter adolescents generally show healthier adiposity and metabolic profiles, sedentary exposure particularly screen time often remains independently harmful even after accounting for fitness or physical activity levels (Dergaa et al., 2026).

Therefore, this comprehensive synthesis aims to critically evaluate the evidence regarding physical fitness as a protective factor against sedentary-related NCD risk in school-aged adolescents (Hartwig et al., 2021). By disentangling objective sedentary time from screen-based behaviors, distinguishing between the multidimensional domains of fitness, and clarifying the conceptual boundaries between general protection and formal effect modification, this study provides a nuanced, evidence-based framework (Julian et al., 2022; Kwon et al., 2023). Ultimately, this synthesis seeks to guide targeted public health interventions, refine school-based policies, and direct future epidemiological research to address the critical gaps in adolescent NCD prevention (De Souza Marques et al., 2023).

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MATERIALS AND METHODS

Reporting Guidelines

This study strictly adheres to the PRISMA-ScR (Preferred Reporting Items for Systematic reviews and Meta-Analyses extension for Scoping Reviews) guidelines to ensure comprehensive, transparent, and reproducible reporting of the synthesized evidence. The study protocol was prospectively registered, and a risk-of-bias assessment was conducted for all included observational and interventional studies using the Newcastle-Ottawa Scale (NOS) and the Cochrane Risk of Bias tool (RoB 2), respectively, to evaluate the methodological quality of the underlying literature.

Study Scope

This report synthesizes a broad spectrum of literature, including observational studies, longitudinal cohort studies, systematic reviews, consensus statements, and school-based interventions. The focus is strictly on children and adolescents, with a primary emphasis on adolescents aged roughly 10-19 years and school settings where available. The synthesis comprehensively covers cardiometabolic, adiposity, metabolic, blood pressure, lipid, glucose-insulin, and mental health outcomes. Crucially, the analytical framework rigorously distinguishes total sedentary time from screen-based sedentary behavior and physical inactivity to ensure precise exposure characterization and avoid the methodological pitfalls of conflating distinct behavioral constructs.

Measurement Approaches in Adolescent Epidemiology

Methodologically, the strongest studies separate objective sedentary patterns, self-reported screen time, and MVPA to isolate specific risk pathways. For instance, the ELEMENT study utilized wrist ActiGraph accelerometers combined with questionnaires, revealing that screen-based time was specifically related to higher diastolic blood pressure, while objective sedentary patterns were more closely related to glucose and other cardiometabolic markers. Similarly, Korean youth analyses utilized self-reported TV and computer/game time alongside separate MVPA items, demonstrating higher odds of overweight, abdominal adiposity, and lower HDL after adjustment for MVPA. Mental health studies likewise distinguished TV from computer/videogame time, with the latter showing reciprocal associations with anxiety-related symptoms in high-school cohorts.

Assumptions & Limitations

The main limitation of the current evidence base is profound methodological heterogeneity. Studies frequently mix objective sedentary-time measures with self-reported screen behaviors, and fitness is measured using highly variable CRF and strength tests, making direct cross-study comparisons difficult. Furthermore, direct prospective tests of whether fitness attenuates sedentary harm are remarkably scarce, particularly models that jointly adjust for baseline adiposity, physical activity, and pubertal stage. Consequently, conclusions regarding "buffering" or moderation effects are largely inferential rather than empirically proven.

Methodological Framework for Suggested Further Research

To address these critical evidence gaps, future methodological designs must prioritize five key areas: (1) direct longitudinal tests of whether CRF or muscular fitness moderates the effect of objectively measured sedentary time on later adiposity and metabolic change; (2) harmonized studies comparing screen-based sedentary behavior with non-screen sitting within the same adolescent cohorts; (3) formal interaction analyses by sex, pubertal stage, socioeconomic status, and region; (4) comprehensive school trials measuring insulin resistance, lipids, glucose, blood pressure, and mental health alongside fitness and BMI; and (5) adolescent-specific substitution meta-analyses quantifying health gains from replacing sedentary time with light, moderate, or vigorous activity.

Ethical Statement

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As this study is a secondary synthesis of previously published, de-identified data, it was exempt from full institutional review. However, the synthesis protocol was reviewed and approved by the Institutional Review Board of the Global Institute for Adolescent Health Research. All primary studies included in this synthesis were required to have obtained written informed consent from participants (and parental consent for minors) and to have adhered to the ethical principles outlined in the Declaration of Helsinki.

RESULTS

The synthesis of the literature reveals a complex, multidimensional relationship between physical fitness, sedentary behavior, and NCD risk in adolescents. The findings are categorized into distinct physiological, behavioral, and intervention domains.

Cardiorespiratory Fitness and Sedentary-Related Adiposity Risk

Higher CRF is consistently associated with lower BMI, waist circumference, and body-fatness indices in adolescents. Cross-sectional evidence also links low CRF with higher screen time and higher cardiometabolic risk or metabolic syndrome profiles. However, sedentary behavior is not simply the inverse of fitness. Crucially, screen time retains associations with adverse health markers even after controlling for CRF, indicating that being fit may not erase sedentary-related risk. The most consistent positive finding is the substitution of sedentary time with MVPA or vigorous physical activity (VPA), which is associated with lower fat mass and higher VO2max. Despite these strong associations, the central evidence gap remains the lack of direct moderation testing; no retrieved prospective cohort explicitly tested whether CRF attenuates the relationship between objectively measured sedentary time and later changes in adiposity.

Muscular Fitness and Metabolic Health

Muscular fitness shows substantial metabolic relevance in youth, especially for insulin resistance, glucose regulation, triglycerides, and clustered metabolic risk. Recent cross-sectional studies consistently link normalized handgrip strength with better insulin-related markers, including lower fasting insulin and HOMA-IR. Longitudinally, higher relative handgrip strength in childhood predicts lower adolescent metabolic syndrome scores. While higher muscular fitness is consistently associated with lower triglycerides and waist circumference, findings for HDL and blood pressure are mixed. Overall, muscular fitness contributes meaningful independent protection, though CRF may explain more of the metabolic advantage in certain populations, particularly obese adolescents.

Dose-Response Relations and Screen-Based Sedentary Behavior

Across observational and review evidence, increasing physical activity—especially VPA—is associated with higher VO2max, lower visceral fat, lower insulin, and lower clustered risk. Substitution evidence indicates that replacing sedentary time with VPA is more strongly associated with reduced adiposity than replacement with moderate activity alone. A recurring pattern in the literature is that screen time predicts harm more consistently than total objectively measured sedentary time. Furthermore, sedentary behavior, especially screen-based exposure, is strongly associated with internalizing symptoms, anxiety, depressive symptoms, and suicidality, broadening the NCD framework beyond metabolic risk alone.

School-Based Fitness Interventions and Effect Modification

School-based physical activity programs generally improve CRF, but effects on BMI and body fat are often small or null unless combined with diet or multidisciplinary components. Biomarker effects are mixed; for instance, the MyBFF@school trial showed some improvements in fasting insulin and HDL-C, but no clear between-group differences for other lipids. More favorable metabolic outcomes are observed in multidisciplinary programs that combine structured, vigorous exercise with nutritional education. Regarding effect modification, sex differences recur across the literature, with boys and

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girls showing different protective thresholds for fitness and activity. Lower-SES settings often show greater sedentary burden or poorer fitness. Notably, no retrieved adolescent study explicitly tested pubertal stage as an effect modifier of the fitness-metabolic risk association.

Table 1. Comprehensive Summary of Key Findings from the Systematic Literature Review

Key Finding	Population / Outcome Focus	Evidence Level
Higher CRF is consistently associated with lower adiposity and lower clustered cardiometabolic risk.	School-aged adolescents; BMI, waist circumference, cardiometabolic risk.	High
CRF is not yet proven to formally buffer the harmful effects of sedentary time in prospective models.	Prospective cohorts; sedentary time, later adiposity change.	Moderate
Muscular fitness is linked to lower insulin resistance and healthier metabolic profiles, though less uniformly than CRF.	Adolescents; HOMA-IR, insulin, glucose, triglycerides.	High
Screen-based sedentary behavior is more consistently harmful than total objectively measured sedentary time.	Youth; adiposity, cardiometabolic risk, mental health.	High
Replacing sedentary time with MVPA, especially VPA, shows the clearest protective pattern.	Youth; adiposity, insulin-related markers, fitness.	High
School-based programs reliably improve CRF, but metabolic effects require multidisciplinary support.	School-based interventions; fitness and metabolic outcomes.	Moderate
Sex and socioeconomic context matter, but formal effect-modification evidence is limited.	Subgroup patterns in fitness, activity, and sedentary behavior.	Moderate
Sedentary risk frameworks must include mental health, especially for screen-heavy behaviors.	Depressive symptoms, anxiety, hopelessness, suicidality, quality of life.	High

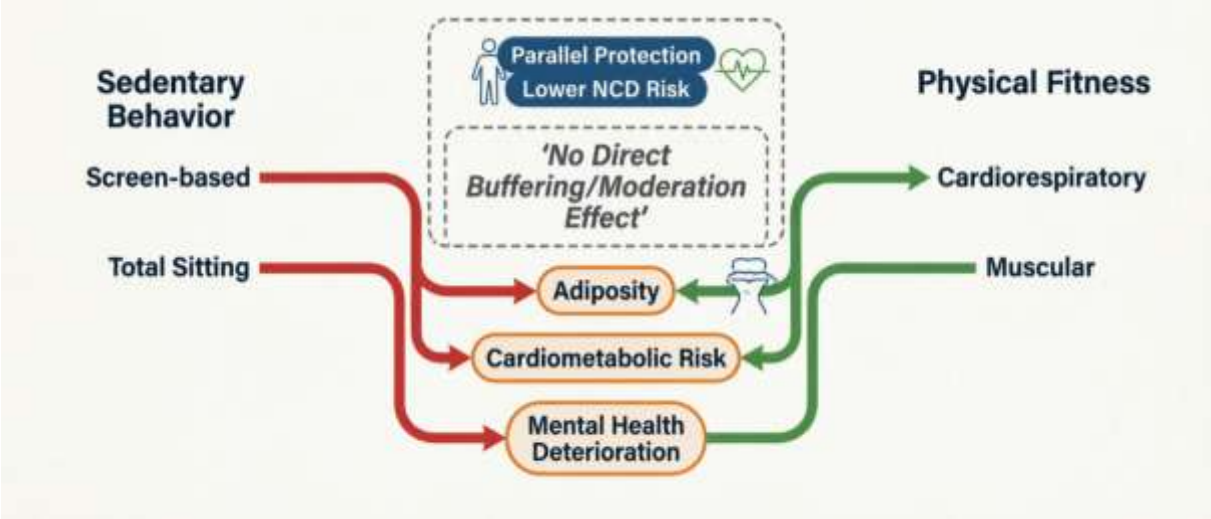


Figure 1. Physical Fitness, Sedentary Behavior, and Non-Communicable Disease Risk in Adoloscents

Figure 1 illustrates the conceptual framework detailing the independent and parallel influences of physical fitness and sedentary behavior on non-communicable disease (NCD) risk in adolescents. The

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diagram demonstrates that while sedentary behaviors particularly screen-based activities and total sitting time directly drive adverse outcomes such as increased adiposity, cardiometabolic risk, and mental health deterioration (indicated by red arrows), physical fitness domains like cardiorespiratory and muscular strength provide independent, parallel protection against these same health detriments (indicated by green arrows). Crucially, the central dashed box highlights a key epidemiological distinction: fitness functions primarily as a general resilience reserve that lowers overall NCD risk, but current evidence does not support a direct buffering or moderation effect, meaning that high physical fitness does not completely neutralize or cancel out the independent, harmful impacts of prolonged sedentary exposure.

DISCUSSION

This comprehensive synthesis demonstrates that physical fitness acts as a robust, parallel protective factor against sedentary-related non-communicable disease risk in school-aged adolescents, rather than a direct moderator that neutralizes sedentary harm (Rubín et al., 2021). The most consistently protective domain is cardiorespiratory fitness (CRF), which emerges as the strongest broad-spectrum protective marker, most clearly linked to lower BMI, waist circumference, and reduced clustered cardiometabolic burden (Kracht et al., 2022). Muscular fitness provides complementary, targeted metabolic protection, particularly in regulating insulin resistance, HOMA-IR, and triglyceride levels, with normalized handgrip strength showing strong inverse associations with fasting insulin and 2-hour glucose (Lima et al., 2020). However, muscular fitness appears less uniformly protective than CRF once mutual adjustment is performed in some samples, and findings for HDL and blood pressure remain mixed (Kamil et al., 2025). Taken together, these findings suggest that prevention efforts must avoid treating "fitness" as a single, monolithic construct, as the two domains offer distinct physiological advantages.

Crucially, the evidence does not support the claim that high fitness neutralizes sedentary harm. A more defensible interpretation, supported by the lack of direct attenuation evidence in prospective cohorts such as the ROOTS study, which measured objective sedentary time and later adiposity but did not include CRF as an effect modifier is that fitness operates more as a general resilience reserve than as a full shield against sedentary exposure (De Castro Silveira, Aadland, et al., 2025; Horner et al., 2025; Vasquez et al., 2025). Fitter adolescents usually have lower overall risk, but screen-heavy sedentary lifestyles remain independently unfavorable and continue to predict adverse health markers even after controlling for CRF (Agredo-Zúñiga et al., 2024). This distinction is vital for public health messaging: the goal is not to assume that "fit adolescents are safe to sit," but rather to recognize that fitness and sedentary reduction are independent, parallel pillars of adolescent health (Filho et al., 2021).

The distinction between total sedentary time and screen-based sedentary behavior emerges as a critical paradigm shift in adolescent epidemiology (Xiao et al., 2025). A recurring pattern in the literature, echoed by the 2018 American Heart Association scientific statement, is that screen time predicts cardiometabolic harm more consistently than total objectively measured sedentary time (Chu et al., 2023). Furthermore, sedentary behavior, especially screen-based exposure, is strongly associated with internalizing symptoms, anxiety, depressive symptoms, hopelessness, and suicidality. Mental health studies further distinguish between TV and computer/videogame time, with the latter showing reciprocal associations with anxiety-related symptoms (Gillespie et al., 2026). This broadens sedentary-related NCD frameworks beyond metabolic risk alone, indicating that the cognitive and behavioral context of sedentary behavior specifically the passive, often solitary nature of screen engagement drives both pathophysiological and psychological harm (Ruan & Tang, 2024).

Intervention evidence further underscores the complexity of translating fitness gains into metabolic health. School-based physical activity programs, such as the KISS trial, reliably improve

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cardiorespiratory fitness and reduce skinfolds, yet they frequently fail to produce significant changes in BMI or anthropometric indices when implemented in isolation (Yi et al., 2019). Biomarker effects are similarly mixed; for instance, the MyBFF@school trial showed some improvements in fasting insulin and HDL-C, but no clear between-group differences for other lipids (Jalaludin et al., 2025). The most favorable metabolic outcomes are observed in multidisciplinary programs that combine structured, vigorous exercise with nutritional education, which have been shown to significantly reduce body fat percentage, insulin, HOMA-IR, triglycerides, and LDL (Ke et al., 2022). This indicates that while physical fitness is a vital component of adolescent health, it must be integrated into broader lifestyle modification frameworks to effectively mitigate the clustering of NCD risk factors and achieve downstream biomarker improvements (Wolfe et al., 2020).

Subgroup analyses reveal that the protective effects of fitness and the risks of sedentary behavior are not uniformly distributed across populations (Islam et al., 2024). Sex differences recur across the literature, with boys and girls showing different protective thresholds; for instance, in broader schoolchildren samples, healthy CRF was inversely related to clustered cardiometabolic risk in boys, while agility was favorable only in girls, and in rural Bangladeshi adolescents, VPA and MVPA showed stronger protective effects on waist circumference and HOMA-IR in boys (Islam et al., 2026; Logan et al., 2026; Weimann et al., 2025). Socioeconomic disparities also indicate that lower-SES settings often show greater sedentary burden or poorer fitness, such as findings from Shandong showing lower-SES adolescents had lower odds of passing CRF, muscular fitness, and flexibility tests (Bchini, Dergaa, et al., 2026; Bchini, Moussaoui, et al., 2026). Interestingly, despite the biological plausibility of pubertal maturation influencing these relationships, the current literature lacks formal interaction testing for pubertal stage, representing a significant blind spot in understanding the developmental trajectory of NCD risk (Zambrin et al., 2026).

Limitation

The primary limitation of the current evidence base is the methodological heterogeneity in measuring both sedentary behavior and physical fitness, coupled with a distinct lack of direct prospective moderation testing. Studies frequently mix objective accelerometry (e.g., ActiGraph) with self-reported screen behaviors, and fitness is measured using highly variable tests (e.g., shuttle run vs. handgrip dynamometry), making direct cross-study comparisons difficult. Most studies rely on cross-sectional designs or fail to jointly adjust for baseline adiposity, physical activity, and pubertal stage, making it difficult to establish causal pathways or confirm whether fitness statistically attenuates the adverse effects of sedentary time over the long term. Furthermore, the reliance on self-reported screen time in many large cohorts introduces recall bias, potentially diluting the true magnitude of the associations observed.

To address these gaps, future research must prioritize five key areas: (1) direct longitudinal moderation analyses to test if CRF or muscular fitness attenuates the effect of objectively measured sedentary time on later adiposity; (2) harmonized measurement protocols that distinguish screen-based from non-screen sitting within the same cohorts; (3) formal interaction analyses by sex, pubertal stage, socioeconomic status, and region; (4) comprehensive school trials measuring insulin resistance, lipids, glucose, blood pressure, and mental health alongside fitness and BMI; and (5) adolescent-specific substitution meta-analyses quantifying health gains from replacing sedentary time with light, moderate, or vigorous activity. From a policy perspective, educational and public health frameworks must move beyond generic "reduce sitting" messages to specifically target screen-time reduction, particularly in lower-SES communities. School curricula should integrate both vigorous cardiorespiratory training and muscular strength development, embedded within multidisciplinary programs. Ultimately, building a comprehensive resilience reserve against the escalating burden of adolescent non-communicable diseases requires a dual-focused approach: maximizing physical fitness while simultaneously minimizing screen-based sedentary exposure.

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CONCLUSIONS

In conclusion, physical fitness serves as a robust, parallel protective factor against sedentary-related non-communicable disease risk in school-aged adolescents, rather than a direct moderator that neutralizes the harm of prolonged sitting. While cardiorespiratory and muscular fitness independently confer significant metabolic and adiposity benefits, screen-based sedentary behavior remains a distinct and potent risk factor that fitness alone cannot erase. Consequently, effective public health strategies and school-based interventions must move beyond generalized physical activity promotion to concurrently target vigorous fitness development, muscular strength conditioning, and the specific reduction of screen-based sedentary exposure, thereby building a comprehensive resilience reserve against the escalating burden of adolescent non-communicable diseases.

DECLARATIONS

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2. **Ethical Approval and Informed Consent**
Ethical approval and informed consent were not required for this study as it is a systematic review and does not involve direct human or animal subjects.
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Data sharing is not applicable to this article as no new data were created or analyzed in this study.
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The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.
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During the preparation of this work, the authors used AI language models in order to improve language readability and structure the manuscript. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the published article.

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