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Sedentary Behavior and Public Health: Integrating the Evidence and Identifying Potential Solutions

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Keywords

sedentary behavior, physical activity, accelerometer, workplace sitting, school sitting, research translation

Abstract

In developed and developing countries, social, economic, and environmental transitions have led to physical inactivity and large amounts of time spent sitting. Research is now unraveling the adverse public health consequences of too much sitting. We describe improvements in device-based measurement that are providing new insights into sedentary behavior and health. We consider the implications of research linking evidence from epidemiology and behavioral science with mechanistic insights into the underlying biology of sitting time. Such evidence has led to new sedentary behavior guidelines and initiatives. We highlight ways that this emerging knowledge base can inform public health strategy: First, we consider epidemiologic and experimental evidence on the health consequences of sedentary behavior; second, we describe solutions-focused research from initiatives in workplaces and schools. To inform a broad public health strategy, researchers need to pursue evidence-informed collaborations with occupational health, education, and other sectors.

1. INTRODUCTION

Insufficient physical activity is a global public health concern, affecting millions of people in developed and developing countries (58). Physical inactivity is associated with an increased risk of common noncommunicable diseases: type 2 diabetes, cardiovascular disease, major cancers, musculoskeletal disability, and a broad range of other adverse health outcomes (105). As research on physical activity and health has evolved, new ways of thinking about how to understand and influence the adverse health consequences of inactivity (91) have emerged. This work now includes public health research concerns about understanding and influencing sedentary behavior: social, economic, and environmental changes that can promote prolonged periods of time spent sitting (115).

Sedentary behavior is distinct from physical inactivity (91). Whereas the latter refers to performing insufficient amounts of moderate-to-vigorous physical activity (i.e., not meeting specified physical activity guidelines), sedentary behavior is defined by the Sedentary Behavior Research Network as “any waking behavior characterized by an energy expenditure ≤ 1.5 metabolic equivalents (METs), while in a sitting, reclining or lying posture” (122). Any time a person is sitting or lying down with low levels of energy expenditure, they are engaged in sedentary behavior; thus, common sedentary behaviors include TV viewing, video game playing, computer use (collectively termed screen time), sitting in automobiles, and reading. It is possible to meet or exceed the public health guidelines for physical activity and also to spend most waking hours sitting (64).

This new focus on sedentary behavior in one sense brings the physical activity and health field back to its roots (15). The seminal findings from Morris and colleagues (87) in the 1950s identified differences in cardiovascular health outcomes for bus drivers (who sat at work) compared with bus conductors who were physically active at work.

The emergence of explicit concerns about sedentary behavior and health can be traced back to studies pioneered by Leonard Epstein (47), who examined experimentally how overweight and obese children’s choices to take part in physically active or sedentary behaviors could be influenced. Taking these insights into a public health research and translational framework (38), the time that adults spend sitting may be understood to be a class of behaviors that can coexist with, and potentially compete with, physical activity, with distinct health consequences and environmental and social determinants (98, 100).

Physical inactivity:

“insufficient amounts of MVPA (i.e., not meeting specified physical activity guidelines)”

Sedentary behavior:

“[a]ny waking behavior characterized by an energy expenditure ≤ 1.5 METs while in a sitting or reclining posture.” This is distinct from how physical inactivity is understood

Environmental determinants:

construct emphasizing circumstances in which behavior is influenced predominantly by the attributes of the settings in which it takes place

Early empirical findings supported such a focus. An Australian study reported in 2000 found TV time to be associated cross-sectionally with higher average body mass measures, including in those identified as being highly physically active (114). A large-scale epidemiologic observational study conducted in the United States, published in 2001, showed prospective relationships between TV time and type 2 diabetes incidence in men (73). Since that time, a foundation in public health research on sedentary behavior and health has rapidly developed (94). Those findings are now influencing recommendations for chronic disease management and informing broader preventive health guidelines and policies (95). This influence is highlighted in the evidence synthesized by the 2018 Physical Activity Guidelines Advisory Committee (PAGAC; see below) for the second edition of the *Physical Activity Guidelines for Americans* (105). Also, the American Diabetes Association has incorporated recommendations on reducing and breaking up sitting time (29). Several countries now provide national guidelines on physical activity and sedentary behavior (14, 118).

Here, we present relevant elements of the evidence base and examples of interventions that can inform public health strategies, being mindful that the evidence and its limitations, strengths, and potential implications need to be evaluated both critically and constructively (124). Our perspective is rooted in a public health approach informed by the behavioral epidemiology framework (110, 112) and an ecological model of sedentary behavior (100, 111). We emphasize the interplay of evidence from observational and experimental studies as well as the development and testing of scalable interventions to reduce sitting in workplaces and schools.

2. EVIDENCE ON SEDENTARY BEHAVIOR AND HEALTH

2.1. Assessment of Sedentary Behavior: Advances and Emerging Implications

From the early 2000s, the evidence consolidated rapidly on the detrimental relationships between sedentary behavior and cardiometabolic risk markers and health outcomes. This initial evidence was developed primarily from studies with self-report exposure measures, typically with single-item questions on TV time or on total sitting time (97). The inclusion of such questions in large population-based surveys has provided informative insights into the prevalence of sedentary behavior across different populations and subpopulations. For example, cross-country comparisons (5, 6, 82) have reported wide variations in sitting time; countries such as Portugal, Brazil, and Colombia report 2.5–3 h per day in contrast to reports of 7 h per day of sitting in Saudi Arabia and Japan. Within countries, sitting time varies by indices of socioeconomic status and by other markers of social disadvantage. These can differ for different domains of sitting (6). For example, those of higher socioeconomic status will typically have higher volumes of workplace sitting, whereas those who are less advantaged will typically have higher levels of television viewing time. Such variations in a passive (TV viewing) and more mentally active (workplace or transport-related sitting) sedentary time may have implications for health (60). Addressing the social and cultural inequities in the health effects of sedentary behavior has been highlighted as a particular need in research (4). Although historical trend data are limited, available evidence suggests that there have been recent increases in time spent sitting (44, 91).

While findings based on self-report measures have provided compelling initial evidence of the potential public health importance of addressing sedentary behavior, the limitations of these exposure measures have been recognized. TV-watching time has acceptable recall properties (23), but it cannot be used as a proxy for overall sedentary time (22). Responses to questions about overall sitting time considerably underestimate the true time involved, relative to sitting time assessed using small, wearable monitoring devices (27). For example, a recent review of studies assessing population levels of sedentary behavior in adults reported a median of 5.5 h per day from

Type 2 diabetes:

highly prevalent form of advanced chronic disease risk, for which sedentary behavior is now understood to have a key role in prevention and management

Behavioral epidemiology:

framework informing public health strategy through interdisciplinary research combining concepts and methods from behavioral science, epidemiology, and relevant content disciplines

Ecological model of sedentary behavior:

conceptual model to guide research through identifying the multiple levels of influence on sitting in particular settings

Cardiometabolic risk markers:

blood glucose, insulin, lipids, and related biological attributes providing proximal indices of health risk and identifying benefits of sedentary behavior change

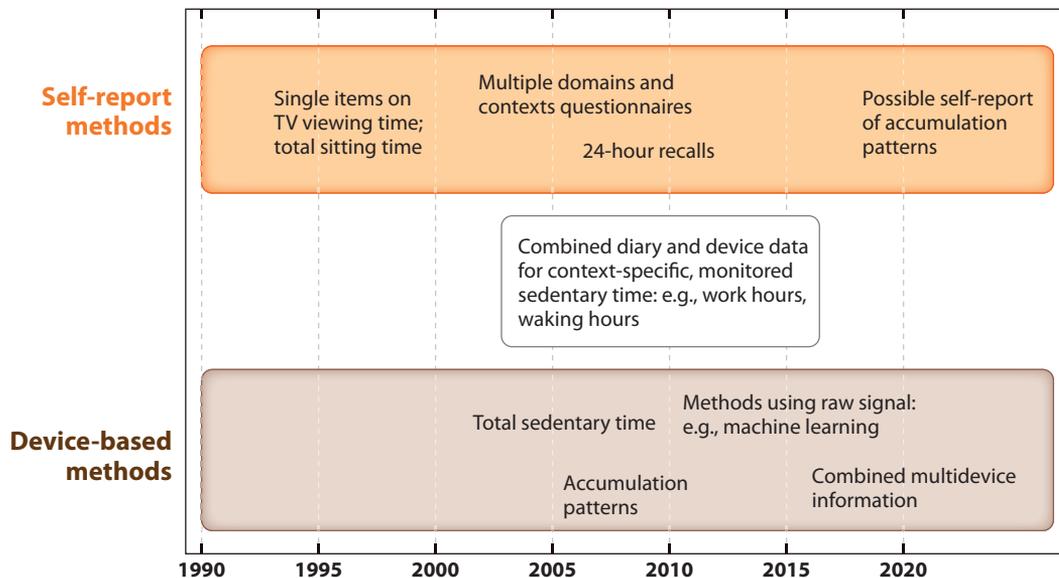


Figure 1

Evolution of measurement methods to characterize sedentary behavior in public health research.

self-report measures, relative to a median of 8.2 h per day from device-based measures of assessment. **Figure 1** illustrates the timeline and key elements of measurement development, which we discuss below.

Since the early 2000s, device-based measures have been increasingly employed in observational studies with adults, children, and adolescents. Device-based measures—initially tested in laboratory and clinical environments—are now being employed in well-known larger scale observational studies such as the National Health and Nutrition Examination Survey (NHANES; 68), the UK Biobank, and other studies. Initial insights from accelerometer studies using cut-points (50, 93) to designate total sedentary time, subsequently complemented by the availability of data from a combined acceleration and postural-detection device (the activPAL), have enabled more accurate identification of total sitting time in free-living settings (70). The rapid development of objective monitoring devices has permitted a greater in-depth investigation not only into how much sitting time is undertaken each day, but also into how and when it is accumulated (69, 93).

Identifying such patterns can include focusing on the distribution across all waking hours of sitting bouts of different durations, the frequency of prespecified attributes of changes in sitting time (for example, durations or the content of interruptions), and other health-relevant characteristics (see following section). The application of more sophisticated analytic methods such as sequence maps and clusters (21), multivariate pattern analyses (1), machine learning (75), and methods for analyzing features of raw acceleration (2) is now available.

Context-specific measurements are needed to determine the outcomes of setting-specific interventions (such as those we describe below for workplaces and schools) and to identify the domain-specific determinants of particular sedentary behaviors, consistent with the ecological model (100, 111). Further to the identification of domain-specific sedentary behaviors, recent evidence suggests a distinction to be made between passive (e.g., TV viewing) versus mentally active (e.g., reading, computer use) sedentary behaviors, at least initially in the context of mental-health outcomes (60, 61). This distinction is particularly relevant given that studies have generally found

Setting-specific intervention:

behavior change approach emphasizing changing environmental and social influences, as distinct from emphasizing individual-level agency

socioeconomic differences in the proportion of time spent in particular sedentary behaviors; TV-viewing levels are higher among those in lower socioeconomic positions, whereas occupational sitting time tends to be higher among those with higher educational attainment or income (92). Operationalizing such distinctions in measurement and benchmarking them against risk biomarkers has the potential to provide insights into some of the health-related differences that are now being seen, for example, between sitting in cars (120) and sitting to watch TV (34).

As shown in **Figure 1**, self-report instruments have also emerged to identify the time spent sitting in multiple contexts and different settings, which may improve the precision of measurement and allow potential influences on other sitting-related outcomes to be examined (24–26). However, total sitting time measures (the sum of reported times spent sitting in different contexts: work, leisure, commuting, etc.) have been used to provide estimates of daily or weekly time sitting at a group level (24). As with the majority of other sedentary behavior self-report instruments, total sitting time measures have only moderate correlations with device-based measures (25, 27). More robust measures may be obtained by asking specifically about the past day of sitting rather than about the past week or a typical day (26) or about the proportion of time spent sitting (20).

A further development in self-report measures is the use of 24-h recalls, which have at least moderate validity compared with device-based measures; they do have the advantage of giving further contextual information such as the time of day spent doing certain behaviors (54). Some self-report instruments can provide useful estimates of sitting time at a group level, can rank groups as high or low sitters, and can detect change; however, they are not accurate at an individual level (64).

Using questionnaires for identifying accumulation patterns of sitting time has shown only limited success, especially in light of what we describe below in the context of epidemiologic observational studies using device-based measurement. There is considerable potential to build on the advantages of self-report because it allows for context and activity type to be determined, potentially in combination with already-ubiquitous consumer global positioning system capacities or, for example, through a combination of using apps and text messaging to prompt the user to note what activity they are doing at a specific time.

2.2. Epidemiologic Observational-Study Evidence: Current Perspective

Several systematic reviews and meta-analyses of the epidemiologic associations of sedentary behavior with a number of outcomes have been published in recent years (12, 83, 102, 103, 121, 128). The 2018 Physical Activity Guidelines Advisory Committee (PAGAC) for the second edition of the *Physical Activity Guidelines for Americans* convened a subcommittee to review and summarize, in a follow-up report, the current scientific evidence regarding the relationships between sedentary behavior and health outcomes in adults (74, 105). The key findings of this comprehensive review process were based on studies that had employed predominantly the basic self-report exposure measures of sedentary time, which we describe above. Notably, the group concluded that there is strong evidence that exposure to high volumes of sitting time can significantly increase one's risk for all-cause and cardiovascular mortality, as well as for incident cardiovascular disease and type 2 diabetes. In addition, strong evidence exists for the dose–response associations between sedentary behavior and all-cause mortality (with an increasing slope at higher amounts of sedentary behavior), cardiovascular mortality, and cardiovascular disease incidence.

The PAGAC review also acknowledged that the association between sedentary behavior and all-cause mortality can vary by the amount of moderate-to-vigorous physical activity (MVPA); the hazards of sedentary behavior appear to be much more pronounced in physically inactive people. To illustrate this concept, investigators developed a heat map (see **Figure 2**) for the PAGAC to highlight the all-cause mortality risks associated with the range of combinations of sitting time

Device-based measurement: employing small wearable devices to assess posture, movement and acceleration, and other behavioral and biological variables

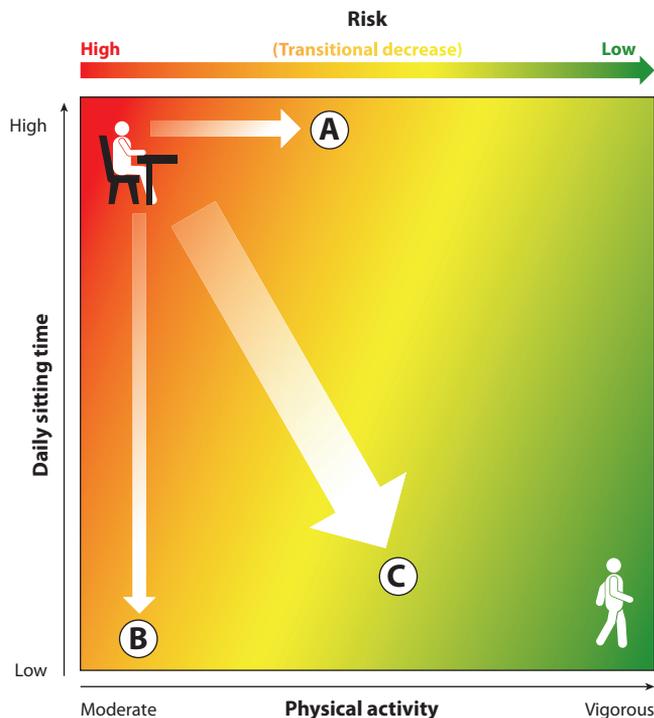


Figure 2

Heat map produced for the *2018 Physical Activity Guidelines Advisory Committee Scientific Report* (74, 105) based on data presented by Ekelund and colleagues (46) to visually describe the risk of all-cause mortality associated with various combinations of sitting and MVPA using regression techniques to interpolate the hazard ratios between the four levels of sitting time categories (*y*-axis, *bottom to top*: <4 h/day, 4–6 h/day, 6–8 h/day, >8 h/day) and the four levels of MVPA categories (*x*-axis, *left to right*: ~5 min/day, 25–35 min/day, 50–65 min/day, 60–75 min/day) (*red*, higher risk; *green*, lower risk; *orange* and *yellow*, transitional decreases in risk of all-cause mortality). Overlaid are three possible opportunities to lower risk for physically inactive adults. Choice *A*, MVPA to recommended levels (>150 min/week), without changes in sitting time. Choice *B*, sitting time from >8 h/day to <4 h/day without changes in MVPA. Choice *C*, MVPA to recommended levels and sitting time from >8 h/day. Size of the arrow denotes similar risk reduction for Choices *A* and *B* with greater risk reduction for Choice *C*. Abbreviation: MVPA, moderate-to-vigorous physical activity. Adapted with permission from Peter Katzmarzyk (74).

and MVPA from the harmonized meta-analysis by Ekelund and colleagues (46). Those who sit the most and do the least MVPA have the highest risk. In contrast, the lowest mortality risk is evident in those who sit the least and do the most MVPA. The heat map indicates conceptually that many combinations of less sitting time and more MVPA will be associated with a reduced risk of all-cause mortality.

In recognition that the hazards of sedentary behavior are most exaggerated in physically inactive adults, an additional perspective on this interplay between sitting time and MVPA that has been put forward is that there are at least three opportunities to lower risk for insufficiently active adults (84). In **Figure 2**, hypothetically, Choice *A* could be to increase physical activity to recommended levels (>150 min per week) without changes in sitting time (i.e., remain at 8+ h per day). Choice *B* could be to reduce sitting time substantially (reduce from 8+ h to <4 h per day) without increasing MVPA (remain at 0 min per week). Intriguingly, the amount of risk reduction for both of these choices is similar, although some residual risk due to too much sitting or too

little MVPA may remain for Choices A and B, respectively. Choice C would be to both increase MVPA to recommended levels and reduce sitting from >8 h per day. This combination would be expected to yield more benefit than A or B alone, with further reduction in risk likely with greater reductions in sitting time.

The PAGAC review found that evidence that greater time spent in sedentary behavior is related to other health outcomes (including cancer mortality and weight status) is limited and that interactions with physical activity are not well understood (105). However, the report acknowledged “somewhat stronger” evidence for screen-based behaviors in relation to cardiometabolic health and weight status or adiposity and that replacing sitting time with physical activity would be beneficial.

The focus of sedentary behavior research with children and youth has emphasized limiting recreational screen time on the basis of a more diverse range of outcomes than has been examined for adults (16, 123). However, the potential for employing prospective data on sedentary behavior and health in children and adolescents has inherent limitations, owing primarily to the challenges of characterizing prolonged exposures to sedentary behavior over multiple years, in a context where growth and development can confound the interpretation of findings that may indicate potentially important biological outcomes.

2.3. Recent Contributions to Epidemiologic Insights from Device-Derived Measures of Variations in Sitting Patterns

The PAGAC review described above concluded that there is insufficient evidence (not assignable, owing to the small number of studies to date) available to determine the importance of sedentary behavior bouts (a period of uninterrupted sitting time) or breaks (a bout of activity of any intensity between two sedentary bouts) in the relationship between sedentary behavior and all-cause and cardiovascular mortality. Recent studies that have used device-based measurement (via accelerometers) have subsequently identified population groups for whom sedentary behavior bouts and breaks may be particularly important as determinants of health outcomes.

In a geographically diverse, biracial sample of middle-aged and older US adults using accelerometer measures, Diaz and colleagues (41, 42) were the first to report that both total sedentary time and prolonged uninterrupted sedentary bouts were associated with increased risk for all-cause mortality, after controlling for the role of physical activity. A subsequent analysis by the same group using isothermal substitution modeling showed that replacing sedentary time and prolonged, uninterrupted sedentary bouts with either light-intensity physical activity or MVPA was associated with a substantial reduction in all-cause mortality risk in less active adults but not in the more active adults who were doing around 3.5 h per day of physical activity.

Another study with a subcohort of racially and ethnically diverse older women (aged 63–97) who participated in the Women’s Health Initiative reported that both high sedentary time and longer mean sedentary bout durations were associated in a dose–response manner with increased cardiovascular disease risk, after controlling for health status, physical function, and cardiovascular disease risk factors, including MVPA (8). Similar relationships were observed with the prevalence of diabetes in this cohort (9). Notably, in both of these studies, when joint associations were evaluated, high total sedentary time and high sedentary bout duration were associated with the highest risk of all-cause mortality and cardiovascular disease respectively, supporting the importance of encouraging less time spent sedentary and shorter sedentary bouts for health benefits.

Among children and youth, how patterns of accumulation of sedentary time are defined across the literature can vary substantially, and associations with health outcomes are not consistent (125). Continued application of more sophisticated analytical techniques of sedentary time accumulation patterns in prospective studies will help to identify options for future public health messaging.

Isothermal substitution modeling: estimates effects of substituting time in one activity (e.g., 1 sedentary h) with time in another activity (light activity), with no other changes to time use

Behavior settings:

key concept from environmental psychology, identifying physical and social attributes of contexts, which can constrain some behaviors and encourage others

2.4. Experimental Evidence and Biological Mechanisms

Experimental evidence from controlled laboratory trials and free-living intervention studies is critical to providing a better understanding of biological plausibility, the causal structure of relationships, and potential mechanistic pathways linking sedentary behavior with adverse health outcomes. The past decade has seen the development of experimental models and study designs focused specifically on sedentary behavior (40, 62, 63) as well as findings from acute human experimental trials (10, 19, 116). These have provided unique insights on the impacts of prolonged sitting bouts relative to sitting interrupted by various countermeasures (for example, sit-to-stand transitions, standing, light- to moderate-intensity walking, upper and lower body cycling/pedaling, and body-weight resistance activities).

Such sitting interruptions, usually involving brief periods of postural change and/or physical activity, are distinct from the sedentary breaks that have been described in population-based studies using accelerometer measurement, which will reflect the frequency of transitions from a sedentary to a nonsedentary state according to accelerometer cut-points. Much of the research to date has focused on vascular, autonomic, and metabolic factors; for more discussion of hypothesized mechanisms, see recent review papers (37, 38, 62). It is notable that experimental evidence to date has identified predominantly benefits of interrupting prolonged sitting on traditional cardiometabolic risk markers such as postprandial glucose, insulin, and blood pressure control in healthy and overweight adults and in those with, or at a high risk of developing, type 2 diabetes (10, 116).

A smaller number of studies are now providing further insights into the benefits of interrupting prolonged sitting in younger people (7, 49, 117), showing peripheral (28, 32, 86, 108) and cerebrovascular hemodynamics (18, 127) and perturbations in sympathetic regulation (31, 39). Furthermore, the collection of both muscle and adipose tissue samples in recent experimental trials provides initial insights into potential molecular pathways. These indicate that loss of muscular contractile stimulation induced through prolonged sitting impairs skeletal muscle metabolism of lipids and glucose and that the molecular, genetic, and lipidomic processes through which these responses occur may be both similar to and separate from the pathways activated by engaging in regular exercise (11, 56, 57, 80).

For public health, it is imperative that epidemiologic observational evidence is used, in combination with insights into underlying biology derived from experimental studies in the laboratory, to collectively inform public health initiatives and also to establish a rational, mechanistic case for how changing sedentary behavior can make important biological differences that are relevant for better health outcomes (88). The findings of experimental studies have so far identified only acute effects of controlled, experimentally contrived behavioral changes. There remains the need to better understand such effects in free-living environments.

It also seems likely that there will be differences in relationships with biomarkers, underlying mechanisms, and health outcomes, as functions of context and other activities involved with sedentary behavior (34), for instance, the distinction between mentally active versus passive sedentary behaviors (60, 61). There is a plethora of future opportunities for innovative observational studies and experimental investigations in this space, all of which will have considerable potential to fine-tune and inform public health initiatives.

3. SEDENTARY BEHAVIOR AND PUBLIC HEALTH: IDENTIFYING POTENTIAL SOLUTIONS

We now address two of the key environmental contexts of daily life and the “behavior settings” (111) in which adults and children accumulate high volumes of sitting time: workplaces and

schools. Studies have begun to produce controlled-trial evidence of key importance for public health strategy, that is, the feasibility and benefits of changing sedentary behaviors (90, 110, 112).

3.1. Addressing Workplace Sitting: Stand Up Australia and BeUpstanding

The Stand Up Australia program has involved the development of, through a series of studies, a comprehensive approach to workplace sitting reduction. Designed typically to be delivered over three months, the studies use an environmental component (sit-stand workstations) and the organizational and individual factors thought likely to influence sedentary behavior (45). The key intervention message was to “stand up, sit less, move more.” With this message, the intention was to reduce sitting time, particularly prolonged, uninterrupted sitting time of 30 minutes or more, by replacing it with a mix of standing and moving and to do so both in and out of the work setting (45).

The comprehensive intervention (see **Table 1**) developed through the Stand Up Australia program of studies was evaluated in a cluster-randomized controlled trial: the Stand Up Victoria study (45). It resulted in substantial reductions in sitting time that were sustained across the 12-month evaluation period (65). Nearly all the change in sitting time was driven by increases in standing time, with the changes occurring predominantly within work hours (65, 129). These findings suggest that the sit-stand workstation was the primary driver of the behavior changes observed. However, in line with an ecological perspective, both the qualitative findings (59) and the pilot research (89) emphasized that environmental change alone is unlikely to be sufficient for large, sustained change. Rather, such changes need to be underpinned by organizational and workplace-culture supports. The second key observation was that the behavior changes did not transfer to the nonwork setting, either beneficially or detrimentally (65, 129). Thus, for interventions like Stand Up Australia to have a large population-level impact, either there needs to be a higher exposure to the intervention (for example, predominantly full-time workers that undertake their work in the workplace) and/or the intervention needs to more comprehensively target and address behaviors outside of the work setting.

The changes in sitting time observed in the Stand Up Victoria intervention group were associated with beneficial, albeit small, changes in some cardiometabolic biomarkers (weight, body fat, waist circumference, diastolic blood pressure, fasting triglycerides, total and high-density lipoprotein cholesterol, and insulin), though the effects were observed predominantly at 12 months and were stronger when replacing sitting with stepping rather than standing (129). These findings were consistent with both the epidemiologic (70, 72, 130) and mechanistic studies (35, 38, 78, 106), further supporting a rationale for guideline messaging around both sitting less and moving more (3). That is, it is important not just to reduce sitting time, but also to consider what the sitting time is replaced with. Given that strategies that increase ambulation in the workplace are likely to be either short in duration (e.g., walking to see a colleague) or not feasible to undertake multiple times a day (e.g., go for a walk during a lunch break), the acceptability and effectiveness of using short body-weight resistance activities (e.g., calf raises, squats) that can be undertaken while remaining static at the desk are a pertinent option for exploration. Such activities have shown to be approximately equivalent in benefit to ambulation, at least in the short term (33, 36, 39, 79).

In addition to reducing sitting time (65), the Stand Up Victoria intervention was shown to be cost-effective (51), led to improved clustered metabolic risk scores and improved fasting blood glucose (71), was acceptable to both employers and employees (59), and provided benefits for some aspects of work productivity (104). These effects are key to informing the business case for organizations to invest in such approaches. Although the collective evidence suggests that the benefits (on productivity, health, and well-being) of workplace-delivered interventions addressing

Table 1 Key elements of the sedentary behavior intervention trials in workplaces (Stand Up Victoria) and schools (Transform-Us) described above

Study	Intervention setting	Study design	Setting characteristics	Participant characteristics	Intervention strategies	Intervention duration	Outcomes
Stand Up Victoria	Workplace	Randomized controlled trial	1 organization, 14 clusters, 5–39 participants per worksite	$N = 231$, 68% women, mean \pm SD = 45.6 \pm 9 years	<ul style="list-style-type: none"> ■ Organizational (management training; workshops; tailored emails) ■ Environmental (sit-stand workstations) ■ Individual (health coaching) ■ Other intervention strategies determined by the team via a participatory approach 	3 months	Significant reductions in workplace and overall daily sitting time in both the short (3 months) and the long term (12 months)
Transform-Us!	Schools	Hybrid implementation-effectiveness trial	Effectiveness trial: 20 intervention schools (state of Victoria), 20 control schools (state of New South Wales) Implementation trial: 1,786 primary schools	<ul style="list-style-type: none"> ■ Effectiveness trial: $n = 1,200$ primary-school-aged children (recruitment in progress) ■ Implementation trial: All primary-school children in Victoria 	<ul style="list-style-type: none"> ■ Active lessons ■ Active breaks ■ Active homework ■ Supportive active environments in the classroom and school grounds (e.g., playground line markings, physical activity equipment in the classroom) ■ Parent newsletters 	4 years	<p>Target outcomes:</p> <ul style="list-style-type: none"> ■ Reduce sedentary time ■ Increase light-, moderate-, and vigorous-intensity physical activity ■ Reduce increases in overweight/obesity ■ Reduce blood pressure ■ Improve quality of life ■ Improve academic achievement

Abbreviation: SD, standard deviation.

prolonged sitting time are expected to be small, the population health impact may be considerable when they are implemented and sustained at scale. This potential is illustrated by the rapid and widespread uptake of workplace sitting initiatives resulting from the BeUpstanding program (<https://beupstanding.com.au/>) in Australia.

The BeUpstanding program is the translational arm of the Stand Up Australia program (67). It uses a train-the-champion approach and an online toolkit to support and guide workplace champions to deliver and evaluate the program within their team. The intervention is designed to raise awareness of the benefits of sitting less and to build a supportive culture where sitting less and moving more is the norm. The participative approach—central to Stand Up Australia—remains, with teams collectively deciding how they want to stand up, sit less, and move more. Pilot findings are promising: The program is feasible to implement and effective at reducing sitting time across a broad range of desk-based workplaces (55, 66). BeUpstanding is being evaluated in the context of a national implementation trial in desk-based workplaces from across Australia. There has been strong buy-in and support for the program from key policy and practice partners in Australia. Such support is critical not only for the promotion of the program, but also for its sustainability.

3.2. Addressing Classroom Sitting: Transform-Us!

Children spend more than 60% of class time sitting (109). The school environment and pedagogical practice represent significant opportunities to reduce and break up children's sitting. Such broad attributes of classroom environments have changed little since the early 1900s, with typical school classrooms providing seated desks and chairs in a row by row format from the front to the back of the classroom. New evidence on the consequences of prolonged periods of sitting for children is now questioning whether such arrangements are ideal from a health perspective. A growing number of studies have examined the impact of height-adjustable desks on children's and adolescents' sitting time, classroom behavior, learning and cognitive outcomes, adiposity, and musculoskeletal health (85). While studies were relatively consistent in reducing children's sitting time, obtaining evidence of associations with health remains a challenge. A lack of research with adolescents was also identified.

A recent intervention with Australian adolescents compared the impact of height-adjustable desks on energy expenditure, adiposity and musculoskeletal health among adolescents attending classes with or without the desks (30). Those who had exposure to the adjustable desks expended a further 38 kcal per 60-min lesson after 17 weeks compared with those without the desks. Waist circumference was 2.6 cm less among intervention-group participants than among those who used traditional classroom furniture, and no intervention effects were found for musculoskeletal health.

Pedagogical approaches, such as active breaks (i.e., interrupting a seated academic lesson to take a short physical activity break) and active lessons (i.e., integrating movement into a class lesson for a learning outcome), have been effective for reducing and breaking up children's sitting in the classroom. Watson and colleagues (126) reviewed 13 studies that implemented active lessons and 19 studies that delivered active breaks in the classroom. Overall increases in children's physical activity were reported, as well as improvements in classroom behavior, on- and off-task behavior, selective attention, and academic achievement.

The Transform-Us! program (see **Table 1**) is one of the few interventions to test the effectiveness of changes to classroom and school environments as well as active pedagogical approaches among Australian primary school children (17, 113, 131). The 2.5-year randomized controlled trial was effective in reducing children's daily sedentary time and also had beneficial outcomes on children's body mass index and waist circumference. Transform-Us! is currently being disseminated across the Australian state of Victoria as a real-world program embedded into

a statewide education-sector approach. Implementation involves online teacher professional development to deliver active lessons and active breaks throughout the school day, as well as active homework. Changes to the school environment include standing easels/desks, timers, access to novel sport/circus equipment in the classroom, and playground line markings.

Planning for the scale-up of Transform-Us! has involved two pilot dissemination trials (from 2015 to 2017) to assess the feasibility of online dissemination and the teacher training approach. Stakeholder consultation has been ongoing since 2017. Outcomes have informed the intervention dissemination strategy and the content of the online training to promote increased engagement from teachers. In partnership with 15 key stakeholders, Transform-Us! commenced at scale in 2018 and will continue to 2022. All 1,794 primary (elementary) schools in the state of Victoria will have access to the program.

3.3. Translating from Intervention Trial Evidence into Policy and Practice

The examples above illustrate approaches for integrating evidence-based sedentary behavior interventions into practice settings. However, within sedentary behavior intervention research, and public health more broadly, there is a substantial lack of evidence for the sustainable implementation and long-term health benefit of such innovations when they are implemented more broadly (96, 99). In physical activity research, for example, interventions implemented in workplaces, schools, and community settings have proliferated, and yet only a minority have been effectively integrated into practice at a scale sufficient to achieve health benefits (107). Major challenges to effective research–practice translation include the design and development of interventions in isolation of factors relevant to future real-world implementation; social-ecological differences between the testing of interventions under optimal, controlled research conditions versus the inevitable variability and rapidly evolving nature of real-world settings (see the sidebar titled *Sedentary Behavior: Public Health Implications and Opportunities*); and the influence of implementer characteristics, the delivery setting, the wider community, and factors at the systems level on the adoption, dissemination, and sustainability of such interventions in practice. Ongoing political commitment, community and organizational buy-in, and interventions that are readily able to be accepted and integrated into existing organizational practices are likely precursors to successful real-world implementation (77).

Stemming from early work on the roles of efficacy and effectiveness trials in health promotion research (48), real-world translation has tended to be perceived as a separate process in the research–practice cycle (13), resulting in interventions typically designed and tested under controlled conditions prior to subsequent real-world dissemination and implementation. Successful

SEDENTARY BEHAVIOR: PUBLIC HEALTH IMPLICATIONS AND OPPORTUNITIES

For public health, the rapid emergence of new evidence on adverse health consequences of high amounts of sitting has generated new opportunities, particularly so in building partnerships between public health, occupational health and safety, education, and other sectors. There is a range of opportunities to be pursued as collaborative partnerships. These include building new evidence-based strategies for reducing sitting-related health risks in the workplace/schools and taking into account not only the health burdens of physically inactive commuting but also those associated with prolonged periods of time spent sitting in motor vehicles and in front of the TV/screens. This focus is particularly relevant, given the pace of change not only in communication technology and the conditions of work but also more broadly in people's conditions of life in developed and developing countries.

scale-up is established when an intervention achieves system-level embeddedness and ultimately sustainable health benefits population wide (107).

The PRACTIS guide (77) provides a systematic framework for mapping features of the implementation context, determining ways of partnering with systems to apply research findings in practice, and identifying ways to anticipate and address potential threats to effective dissemination, implementation, and scale-up of public health interventions in health care and community settings. A core premise is that planning for real-world implementation needs to occur during the intervention's conceptualization and development phases.

4. SEDENTARY BEHAVIOR AND PUBLIC HEALTH: CHALLENGES AND FUTURE OPPORTUNITIES

The field of sedentary behavior and public health faces established and emerging challenges. In the context of the health system and health care, pursuing preventive approaches can be a daunting and highly complex task. The vast majority of resources are consumed by curative infrastructure provision, expenditure on pharmaceuticals, and treating preventable chronic diseases. In this context, the sedentary behavior and public health field faces challenges posed by operating in that broader curative versus preventive health context. There is also a perception that the growing focus on sedentary behavior and public health may detract from the more well-established approaches to promoting MVPA (119). However, a “move more, sit less” message should actually reinforce and add helpful synergy to physical activity and public health endeavors (95).

Researchers, policy makers, and practitioners in this new field can find themselves negotiating a fraught and contested mass-media and social-media context. The rapid development of the sedentary behavior and public health research field has taken place in, and to some extent has been shaped by, at times, an uncomfortable mix of overblown claims about sitting being the new smoking (124). With the increasing volume of evidence from measurement, biological, and etiologic studies in the sedentary behavior and health field, there is a particular need for intervention trial evidence on the feasibility and benefits of sedentary behavior change.

Reporting on and debate about the evidence for the effects of sitting on health has proliferated in print, broadcast, online, and social media. In this context, the evidence-informed approaches that we have described will be crucial for the health field to move forward with discipline, rigor, and relevance. Evidence is now pointing to new public health research and advocacy opportunities, especially in partnership with other government and nongovernment instrumentalities and also with business and industry sectors. One case in point is the rapidly developing nexus of sedentary behavior and public health with occupational health and safety in research, in policy, and in practice. This interdisciplinary nexus has been illustrated above by our account of the Stand Up Australia program of research and by rapid and widespread uptake of initiatives through the Be-Upstanding workplace dissemination project. In schools, the initial evidence on sitting-reduction initiatives and more physically active learning environments for children in collaboration with the education sector through the Transform-Us! project is also promising.

Below we highlight some of the factors likely to drive the future sedentary behavior and public health research and translational agenda:

- The current generation of sedentary behavior research studies has been significantly enriched by the opportunities provided through small wearable devices and related technologies; these can not only identify volumes of time spent in sedentary behaviors, but also provide opportunities to interrogate the detail of sitting patterns.
- The availability of large volumes of data covering the whole of the day has supported the development and application of innovative analytic methods, including the use of isothermal

Compositional data analysis: framework to analyze data in which a series of non-negative components sum to a total (e.g., daily time in sedentary behavior + light activity + moderate activity + vigorous activity + sleep + other time = 24 h)

substitution and compositional data analysis techniques to identify the interrelationships of sedentary behavior, physical activity, and sleep with health risk biomarkers and health outcomes.

- Rapid advances in the capacities of widely marketed consumer wearable devices provide many new opportunities for surveillance, ecological momentary assessment, and just-in-time interventions.
- Rapid advances in other consumer technologies, particularly screen-based devices with the potential to promote even greater volumes of time spent sedentary, suggest several areas of research are needed in understanding the impacts on health, children's cognitive development, and adults' mental health.
- Studies are needed to build on new evidence showing relationships among passive (e.g., TV viewing, screen-based entertainment) versus mentally active (e.g., reading, driving, computer work) sedentary behaviors with cognitive function and mental health outcomes.
- Further studies are needed to identify the impacts of prolonged periods of sitting time on functional status, metabolic health, and cognitive decline in older adults.
- A greater emphasis needs to be placed on systems approaches to enhancing the translation of evidence-based research into practice for population-wide effect, with the view to achieve system embeddedness (successful scale-up) as opposed to short-term implementation and impact.

Further to the workplace and school-setting initiatives that we have described above, and the research opportunities highlighted, there are broader areas of research opportunity in sedentary behavior and public health. These include a focus on domestic environments (52) and, more broadly, on examining how the built- and natural-environment attributes of rapidly developing cities (53, 76, 101) and rural localities can promote indoor living and the proliferation of sedentary, screen-focused time use. Related concerns for both urban and rural areas include sitting in transport. Large numbers of working adults spend increasing proportions of their waking hours commuting to and from work in private motor vehicles. Initial evidence suggests that time spent sitting in cars may be metabolically toxic (43, 120). Understanding the further health consequences of automobile commuting and identifying synergies of sedentary behavior research with active living research focused on physically active transport will be a source of new research opportunities in the future.

SUMMARY POINTS

1. A body of epidemiologic observational evidence now shows distinct impacts of sedentary behavior on morbidity and mortality, which, if they are to be offset by MVPA, may require levels of participation well beyond the current minimum public health recommendations.
2. Measurement of sedentary behavior has advanced significantly, particularly through the refinement of self-report measures that can be particularly valuable in identifying context and also through the rapid development of device-based measurement and related analytic capacities.
3. For developing and refining public health strategy, and providing a rational basis for public health recommendations, experimental evidence elucidating underlying mechanisms

through which sedentary behavior impacts on adverse health outcomes is emerging. This is particularly so in the context of type 2 diabetes and cardiovascular disease, which are major public health burdens.

4. Evidence from intervention trials in workplace and school settings has demonstrated the feasibility and benefits of changing sedentary behavior.
5. A public health perspective on sedentary behavior should emphasize the complementarity of evidence relating to measurement, mechanisms, and interventions in order to better inform public-health guidelines and policy.
6. The rapidly emerging body of evidence on sedentary behavior and health can underpin new opportunities for intersectoral public health strategy, bringing together the interests of public health with those of occupational health and safety, education, and other constituencies.
7. We need to identify innovative ways for establishing sustainability at scale and system-wide integration of effective interventions.

FUTURE ISSUES

1. Researchers must further inform public health strategy by gathering new evidence from epidemiologic observational studies using device-derived measures to further examine prospective relationships between patterns of sedentary time and chronic disease risk biomarkers, and with all-cause and disease-specific mortality.
2. Further observational and experimental studies should examine relationships among total sedentary time and patterns of sedentary time with other health-related outcomes, particularly in musculoskeletal and mental health.
3. Investigators should conduct studies with children and youth, focused on behavioral precursors and early-stage biomarkers of chronic disease risk.
4. Future work should examine the relationships of total sedentary time and prolonged sitting with health outcomes and risk markers, functional capacities, and quality of life in older adults with multiple clinical conditions, particularly osteoarthritis, type 2 diabetes, cardiovascular disease, and dementia.
5. Research should identify the relationships of environmental attributes in settings associated with high volumes of sedentary time and prolonged patterns of sedentary time, such as neighborhoods, workplaces, and commuting settings.
6. Researchers need to develop and test theoretically informed behavior change interventions to reduce sitting time in different contexts (particularly worksites, schools, and domestic environments).
7. We need to build stronger partnerships with employer and employee representatives across the government, business, and industry sectors to gather new evidence on opportunities to promote healthier, productive workplace and school environments through changing sedentary behavior.

DISCLOSURE STATEMENT

J.S. is on the board of a not-for-profit organization that aims to promote the health and well-being of children and youth with Down syndrome. Her spouse owns a height-adjustable desk business benefiting students. All other authors are not aware of any affiliations, memberships, funding, or financial holdings that might be perceived as affecting the objectivity of this review.

AUTHOR CONTRIBUTIONS

All authors contributed material relating to their areas of particular expertise and have critically read the manuscript as a whole.

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68. Provides key evidence that interruptions to prolonged periods of sitting can benefit cardiometabolic health.

70. Illustrates innovative methods for estimating the potential benefits of different modalities of reducing sedentary time.

71. Describes the effectiveness of sit-to-stand desks as part of a multilevel approach to reducing workplace sitting.

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97. Explains the underlying logic and major components of a public health research strategy.

100. Explains how the behavior settings construct and an ecological model can inform public health intervention.

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115. Uses a behavioral economics model to analyze and identify opportunities for public health strategy.

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