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The impacts of lockdown restrictions on children's and adolescents' physical activity levels and sedentary behaviour including gender differences: A systematic review and meta-analysis

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Abstract

Background: The 2019 COVID-19 pandemic outbreak has caused a global public health emergency. In addition to preventing the spread of the disease, restrictions such as school closures may reduce children and adolescents' opportunities for physical activity and increase the prevalence of sedentary behaviour. However, the current evidence regarding the effects of COVID-19 on physical activity and sedentary behaviour in children and adolescents is insufficiently clear.

Objectives: This systemic review and meta-analysis aimed to examine the changes of children's and adolescents' total physical activity, moderate to vigorous physical activity, sedentary behaviour, and screen time before and during COVID-19-related restrictions. Subgroup analysis was aimed to compare the changes between boys and

girls, objective measures and subjective measures, cross-sectional studies and longitudinal studies.
Methods: A total of five databases were searched. In addition, grey literature, reference list and registries were also checked. A total of 26 studies were included in the systematic review. Total physical activity, moderate to vigorous physical activity, sedentary and ST were analysed separately using random effects models. Additionally, this study also used meta-analysis to investigate the differences between boys and girls, objective measures and subjective measures, cross-sectional studies and longitudinal studies.
Results: The results of the meta-analysis showed that children and adolescents had a significant decrease in total physical activity (SMD= -0.76, 95% CI= -1.46 to -0.06, I^2= 99.5%), moderate to vigorous physical activity (SMD= -0.36, 95% CI= -0.6 to -0.11, I^2= 94.7%), sedentary behaviour (SMD= 1.44, 95% CI= 0.31 to 2.56, I^2= 98.6%), and a significant increase in screen time (SMD= 0.75, 95% CI= 0.49 to 1.02, I^2= 97.3%). Meta-analysis results showed a significant decline in moderate to vigorous physical activity in boys, but no change was found in girls. However, results from the systematic review suggested that girls are more likely to develop more screen time than boys
Conclusion: Children and adolescents' physical activity and sedentary behaviour are negatively impacted by restrictions associated with Covid-19. In addition, girls' screen time is more likely to increase than boys'.

Keywords :Physical activity, Youths, Lockdown

1.0. Introduction:

1.1. The impact of COVID-19

In December 2019, a new coronavirus (COVID-19) was found to be the cause of a local outbreak of pneumonia in China, which resulted in the collapse of healthcare systems and millions of deaths all over the world (Tan et al., 2020; Torres-Signes et al., 2021). On January 30, 2020 (WHO, 2020), the World Health Organization (WHO) declared it a global public health emergency. COVID-19 is primarily transmitted between humans via aerosols (WHOa, 2020). Therefore, social distancing has been shown to be an important component of measures designed to reduce the spread and impact of COVID-19 (Berry et al., 2022). Children and adolescents are a population group that has been hit particularly hard by the restrictions despite the fact that they are less likely to develop severe symptoms and are mainly spared the direct health effects of COVID-19 (Kang et al., 2020; Bialek et al., 2020). The indirect effects of COVID-19-related restrictions are highly likely to have negative impacts on children's and adolescents' lifestyles, health, and wellbeing (Richardson et al., 2021).
Restrictions such as lockdowns, school closures, and social isolation have been implemented globally to contain the COVID-19 contagion. Indeed, more than half of the world's population was subject to some form of government-imposed restrictions in April 2020 (WHOb, 2020). According to the United Nations Educational, Scientific, and Cultural Organization (UNESCO), 195 countries closed their schools in April 2020, and the school closures lasted an average of 3.5 months of an academic year (UNESCO, 2021). In addition, an estimated 1.5 billion children and adolescents have

become distant learners as a result of school closures (UNESCO, 2021). Schools are universally regarded as an important venue for health promotion, and their physical education classes, gymnasia, and activity facilities provide many opportunities for children and adolescents to engage in physical activity (van Sluijs et al., 2021). As a result of COVID-19-related restrictions, children and adolescents may spend more time sitting and have fewer opportunities to engage in physical activity.

1.2. Physical activity (PA) and sedentary behaviour (SB) among children and adolescents

PA and SB are two of the many health-related behaviours among children and adolescents that affect their health and well-being (Chaput et al., 2020). Numerous health concerns, including obesity, coronary heart disease, and musculoskeletal health, have been shown to be positively influenced by the promotion of PA among children and adolescents (Brown et al., 2009; Janssen et al., 2010; Wu et al., 2017). The positive effects of reducing SB include a decreased risk of obesity, cardiovascular disease, and all-cause mortality, as well as a variety of mental health problems (Prentice-Dunn et al., 2012; Wu et al., 2017). Additionally, children and adolescents with more PA and less SB may benefit from an improvement in cognitive development and academic performance (Tremblay et al., 2011). It is necessary to note that physical inactivity (PI) and SB are two independent health risk factors (Ekelund et al., 2016). If long periods of daily sitting are unavoidable (such as during a COVID-19 lockdown period), it is essential to remain physically active (Ekelund et al., 2016).

Global PI is already an existing non-infectious public health problem. As the fourth leading cause of death worldwide, PI was characterised as a global pandemic by the Lancet series on PA and health (Kohl et al., 2012). The WHO guidelines suggest that children and adolescents between 5 and 17 years should meet the recommendation of at least 60 minutes of moderate-to-vigorous physical activity (MVPA) per day and limit the amount of time spent being sedentary, particularly the amount of recreational screen time (ST) (WHOc, 2020). However, three-quarters of children and adolescents worldwide do not currently meet the physical activity guidelines (Guthold et al., 2020). In addition, gender differences exist in the PA and SB of children and adolescents. Kalman et al. (2015) reported that girls have a lower PA level than boys. More specifically, 85% of girls and 78% of boys did not meet the WHO PA guidelines globally (Guthold et al., 2020). The Canadian SB guidelines reflect gender differences among children and adolescents and suggest that boys and girls may engage in different SB (Liwander et al., 2013). For example, girls are likely to spend a lot of time on communication-based SB such as phone calls, texting, and instant messaging, while boys are more likely to watch TV and videos or play computer games (Liwander et al., 2013). Consequently, there may be gender differences in the effects of COVID-19-related restrictions on children and adolescents. Considering gender issues in research and policy may permit a more accurate examination of changes in child and adolescent health behaviours and help improve the health of this group during the COIVID-19 pandemic.

1.3. Current evidence on the impacts of COVID-19-related restrictions on PA and SB

In 2020, some preliminary cross-sectional studies demonstrated that social restrictions reduced PA and increased SB among children and adolescents (Guerrero et al., 2020; Moore et al., 2020; Mitra et al., 2020). However, these are all cross-sectional studies that collected data by asking participants to recall previous COVID-

19 behaviours and compare them with current behaviours. Due to recall bias, the reported results may not accurately reflect the actual situation (Rudolf et al., 2015; Laeremans et al., 2017). One year later (2021), a scoping review found that four studies identified an increase in PA, while six studies found no significant differences in PA during the pandemic among children and adolescents (Rossi et al., 2021). However, Rossi et al. (2021) only examined PA and did not report on SB-related results. Paterson et al. (2021) also undertook a scoping review and found that PA declined and SB increased, especially with regard to ST (Paterson et al., 2021). Nonetheless, 67.9% of the 150 referenced studies utilised a cross-sectional design and did not assess the quality of data from individual studies (Paterson et al., 2021).

Currently, there are two systematic reviews and one meta-analysis in relation to this topic. One of the systematic reviews by Viner et al. (2021) included 36 studies. However, this study included too few PA and SB studies because it also examined changes in sleep, mental health, and diet, among others (Viner et al., 2021). Only two of six studies demonstrated a significant reduction in PA and a significant increase in ST (Viner et al., 2021). Kharel et al. (2022) also conducted a systematic review demonstrating that 32 studies (78.1%) reported a decrease in PA, and eight (19.5%) studies reported no significant change in PA. However, 11 studies have included children or adolescents with specific diseases, such as physical disabilities, ASD (autism spectrum disorder), or diabetes (Kharel et al., 2022). Some of the studies also included children or infants under 4 years old (2022). Meta-analytical results by Wunsch et al. (2022) reported a slightly negative effect on the PA of children and adolescents, but not significantly (Fisher's z = 0.08, 95% CI = -0.27 to 0.12). The current review of studies combined subjective and objective measurement methods, and some bias arising from the subjectivity of the former method may influence the results. This is due to the fact that subjective methods of measuring PA and SB tend to overestimate or underestimate results (Rudolf et al., 2015).

The current systematic review and meta-analysis of studies did not separate the analysis of cross-sectional and longitudinal data, or subjective and objective methods. Another research gap is that no studies have applied a meta-analytical approach to the differences between PA and SB. Additionally, the current systematic reviews included literature from before October 2021. However, new studies published in 2022 may provide a larger selection of studies for inclusion in a systematic review of this field. For example, Burkart et al. (2022) compared PA and SB before and during the pandemic with objectively collected data. Therefore, a current systematic review can incorporate some longitudinal studies and also apply a device-based measurement method.

1.4. *Aims and potential value*

To the best of our knowledge, this is the first systematic review and meta-analysis focusing on examining the impacts of COVID-19-related restrictions on children's and adolescents' (5–17 years old) PA and SB. This study aims to review findings from primary studies and apply a meta-analytical procedure to quantitatively estimate changes in PA and SB before and during COVID-19-related restrictions, accompanied by a subgroup analysis of gender difference, study designs (cross-sectional and longitudinal), and measurement methods (subjective and objective) among 5–17-year-old youth. This study may be able to assist policymakers in developing PA and SB interventions for this age group during the COVID-19 pandemic. Investigating the difference between boys and girls could help develop different intervention plans for boys and girls, making the intervention more effective. Furthermore, it is critical to

understand the precise impact of such restrictions on PA and SB in order to better prepare for future waves of COVID-19 or other future pandemics.

2.0. Methodology

This review was performed according to Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines and the Cochrane Handbook for systematic reviews of interventions (Moher et al., 2009; Higgins & Thomas, 2019).

2.1. Eligibility criteria

This review and meta-analysis included English studies and peer-reviewed articles that addressed changes in children's and adolescents' PA before and during the COVID-19 pandemic. As our focus was on non-interventionist studies, studies were selected for eligibility based on the PECO (participants, exposure, comparison, outcome) rather than the PICO (participants, intervention, comparison, outcome) (Mintzker et al., 2022). Table 1 shows the inclusion and exclusion criteria.

Table 1. *The inclusion and exclusion criteria*

	Inclusion	**exclusion**
Population	Healthy children and adolescents aged 5-17 years old.	Children or adolescents with disabilities or specific health conditions such as physical disability, diabetes, and autism; Children or adolescents who are no longer students; Children or adolescents who are athletes.
Exposure	Changes of PA or SB under COVID-19-related restrictions.	Exposure unrelated to COVID-19 restrictions, such as participation in some kinds of PA or SB intervention plans during COVID.
Comparison	Studies compared the changes in PA/SB data before and during COVID-19 restrictions.	Studies did not compare the changes in PA/SB data before and during COVID-19 restrictions.
Outcome	Studies reported PA data including but not limited to total PA, moderate to vigorous PA (MVPA), vigorous PA, walking, and cycling. Studies reported any form of SB include but not limited to total sitting time, ST, and TV hours.	Studies investigating other health-related behaviours rather than PA/SB; for the meta-analysis, studies that did not report M(SD) data before and during COVID-19 restrictions.

M (SD): Mean (Standard deviation)

2.2. Information sources

An online search was conducted on July 10th, 2022 across the following databases: Medline, Embase, SPORTDiscus, Scopus, and Web of Science. Grey literature searching was done through the Policy Commons website, which provides almost 2.5 million full-text think-tank publications, including policy reports, administrative documents, books, projects and campaign documents (Olson, 2021). The search date

limit was set for after December 2019 (the start of COVID-19), which was to ensure that only articles concerning COVID-19 were included.

2.2. The searching procedure

Across these databases, key terms are followed by other key terms and linked by Boolean operators OR and AND: "Child", "Children", "adolescent" "youth", "teenager", "sedentary time", "sedentary behaviour/behavior", "ST", "sitting time", "Physical activity", "Movement behaviour/behavior", "COVID-19", "SARS-CoV". Comprehensive search history records are shown in appendix 1. Furthermore, the reference lists of all primary studies, studies included in the existing review studies, and registered and pre-registered studies on PROSPERO were also examined for additional pertinent studies.

The title and abstract screening and full text screening were performed by Covidence software. Two reviewers (TW L, BY) were involved in the screening process. The primary reviewer TW L completed the title and abstract screening independently. During the full-text screening process, the two reviewers worked independently. All disagreements were resolved through discussion.

2.3. Data collection process and data items

Analysis of the extracted data was informed by three existing systematic reviews in the field and the Cochrane handbook (Higgins & Thomas, 2019; Viner et al., 2021; Kharel et al., 2022; Wunsch et al., 2022). Data extracted included the following: general information (i.e. authors and years, country), participant characteristics (sample size, age, gender), information on methods (aim, sampling time, measurement tools), study design (cross-sectional or longitudinal), outcomes (PA/SB before and during COVD restriction, the changes of PA/SB, statistical results). For PA and SB data extraction, only total MVPA (moderate to vigorous physical activity), SB, sitting time, ST, and TV hours were extracted. Collection methods for the primary data are reported in the data extraction sheets which outline whether the data are from accelerators, self or proxy questionnaires (specific type of questionnaire), or other types of descriptive results (interview results).

Data from the eligible studies were extracted by one author independently (TW L) through Covidence software and exported into a Microsoft EXCEL sheet. The identification of the study type (cross-sectional or longitudinal) and the identification of the measurement methods (objective or subjective) were all done independently by one author (TW L). Points of uncertainty regarding the selection of articles for inclusion in the meta-analysis were discussed with the second reviewer BY, and another collaborator (ZY) served as a mediator until consensus was reached. After completion, the extracted data was double-checked and verified by TW L. To obtain data or additional details not reported in the six studies, one author (TW L) tried to contact the original study authors (Bingham et al., 2021, Chambonniere et al., 2021; Dubuc et al., 2021; Gilbert et al., 2021; Guo et al., 2021; Schmidt et al., 2020). However, no response was received from any of the authors. Due to time constraints, the decision was made to proceed and not wait for the authors' replies.

2.4. Risk of bias and quality assessment

Begg's funnel plots for the evaluation of publication bias across studies were implemented using Stata 14.0 software. The sensitivity analysis of the results uses the trim and fill method.

To assess the quality within studies, one author (TW L) independently used the Newcastle-Ottawa Scale (NOS) for cohort studies (Wells GA et al., 2000) and the modified NOS for cross-sectional studies (Modesti et al., 2016). The NOS was compared using a quality assessment tool for observational cohort and cross-sectional studies created by the National Heart, Lung, and Blood Institute (NHLBI). The advantage of NOS is that it has a visual scoring system that rates studies based on three dimensions: selection (maximum 5 stars), comparability (maximum 2 stars) and outcome (maximum 3 stars). The NOS evaluated the appropriateness of the research design, recruitment strategy, response rate, sample representativeness, objectivity/reliability of outcome determination, provided power calculation, and statistical analyses (Modesti et al., 2016). During the quality assessment process, the primary author (TW L) conferred with a collaborator (ZY) and then made the final decision. Table 2 shows the NOS scoring criteria.

Table 2. *The scoring of the NOS for cohort and cross-sectional studies*

	Scoring NOS for cohort studies	**Scoring NOS for cross-sectional**
Method:	Thresholds for converting the Newcastle-Ottawa scale to the Agency for Health Research and Quality (AHRQ) standards: good, fair, and poor (Likis Fe et al., 2012, Vienna, 2015).	The NOS for a cross-sectional study will eventually classify the quality of the study into 4 levels (Modesti et al., 2016).
	Good quality: 3 or 4 stars in selection domain AND 1 or 2 stars in comparability domain AND 2 or 3 stars in outcome/exposure domain.	**Very good Studies:** 9-10 points
	Fair quality: 2 stars in selection domain AND 1 or 2 stars in comparability domain AND 2 or 3 stars in outcome/exposure domain.	**Good studies:** 7-8 points
	Poor quality: 0 or 1 stars in selection domain OR 0 stars in comparability domain OR 0 or 1 stars in outcome/exposure domain.	**Satisfactory studies:** 5-6 points **Unsatisfactory studies:** 0 to 4 points

2.5. Effect measures

Inconsistencies in study results arose from the diversity of measurement methods, which included accelerometer, YAP (Youth Activity Profile), and PAQ-C/A (Physical Activity Questionnaire for Older Children/ Adolescents). Consequently, standardised mean differences (SMD) were utilised in the meta-analysis.

2.6. *Synthesis methods and results*

Systematic review

General characteristics were tabulated including author and year, sample size, gender information; measurement tool(s), sampling time, study type, statistical significance (P value) or effect size of total PA, MVPA, ST, SB. For studies providing data during

and before COVID, the changes in PA, MVPA, SB, and ST were calculated manually (during minus before).

Meta-analysis

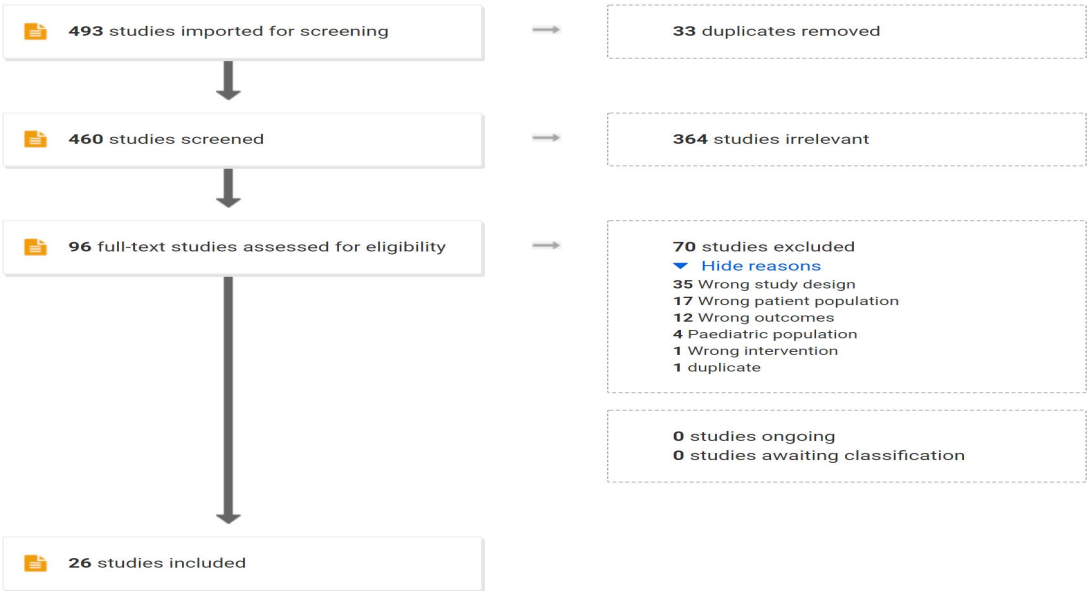
The meta-analysis was conducted using Stata 14.0 software. Due to the considerable heterogeneity of the included studies (I > 75%), a random effect model will be used (Higgins et al., 2019). Then, PA, MVPA, SB, and ST will be analysed as outcome indicators. Subgroup analysis included gender (boys' total PA vs girls' total PA, boys' MVPA vs girls' MVPA, boys' SB vs girls' SB, boys' ST vs girl's ST), study design (Cross-sectional vs Longitudinal), and measurement method (Subjective vs Objective). Other outcomes (PA, SB, and ST) could not be analysed due to the limited number of device-based studies included. Therefore, MVPA was the only one included in the subjective and objective subgroup analysis.

3.0. Results

3.1. Study selection:

Figure 1 depicts a PRISMA flowchart of the study selection procedure. The search history and results for each database are shown in appendix 2. Studies were excluded for a variety of reasons: 50% (35) of the exclusions were due to incorrect study design, mostly from studies that included during-COVID data but not pre-COVID data or used after-COVID restrictions data (e.g., Salway et al., 2020); 24% (17) of the exclusions were due to adult studies (e.g., Ning et al., 2021); 17% (12) of excluded results reported changes in behaviour patterns but not PA/SB (e.g., Morrison et al., 2021); and 5% of the exclusions were due to the study population being 0–4-year-olds (e.g., Okely, 2021). The details of studies that were excluded can be seen in appendix 3.

Figure 1. *PRISMA flow diagram. In this diagram, 493 studies came from Embase & Medline: 206, Web of science: 276, SPORTDiscus: 6, Scopus: 5, Policy commons: 0)*



3.2. *Study characteristics*

Our meta-analysis included studies from Tunisia, Saudi Arabia, Qatar, UK (N = 2), USA (N = 3), France (N = 2), Italy (N = 2), Canada, Austria, China (N = 3), Croatia, Germany (N = 2), Spain (N = 2), Australia (N = 2), New Zealand, and the Czech Republic. The total sample is 42,418 (15,502 boys, 20,425 girls). One study did not

provide gender information (Genin et al., 2021) and one study only included boys (Peddie et al., 2021). Only three studies used accelerometers to report results of PA and SB (Burkart et al., 2022, Dallolio et al., 2022, García-Alonso et al., 2022). One study used ecological momentary assessment (EMA) (Munasinghe et al., 2020) and one study was conducted through interviews (Gilbert et al., 2021). The rest of the study results are all from self-report or proxy report (N = 20). Eleven of the included studies utilised a longitudinal design to compare data collected during the pandemic to data collected before the pandemic (Munasinghe et al., 2020; Schmidt et al., 2020; Dubuc et al., 2021; James et al., 2021; Medrano et al., 2021; Nathan et al., 2021, Peddie et al., 2021; Stverakova, 2021; Burkart et al., 2022; Dallolio et al., 2022; Garca-Alonso et al., 2022). Other studies employed a cross-sectional design, used a retrospective baseline and obtaining pre-pandemic data through memory recall (N = 15). Table 3 provides an outline of the individual studies, and their complete results are available in Appendix 4.

3.3. *Risk of bias within studies*

With the NOS of the risk of bias within longitudinal studies, four studies were of good quality, seven were of fair quality, and one was of poor quality. For the modified NOS quantification in cross-sectional studies, nine studies were satisfactory, and five studies were good studies. Details of the specific ratings are shown in Figure 2. The primary limitation of longitudinal studies was sample selection. The majority of longitudinal studies have a small sample size, which may result in some bias in the findings (e.g., Dallolio et al., 2022 (N = 77), Burkart et al., 2022 (N = 74), Garca-Alonso et al., 2022 (N = 110), Peddie et al., 2021 (N = 109), Stverakova 2021 (N = 98). In cross-sectional studies, the fact that results are reported through self-reporting methods is the most significant limitation. All accelerometer-based studies are longitudinal.

Figure 2. *The risk of bias in individual studies. Selection (maximum 5 stars), comparability (maximum 2 stars) and outcome (maximum 3 stars).*

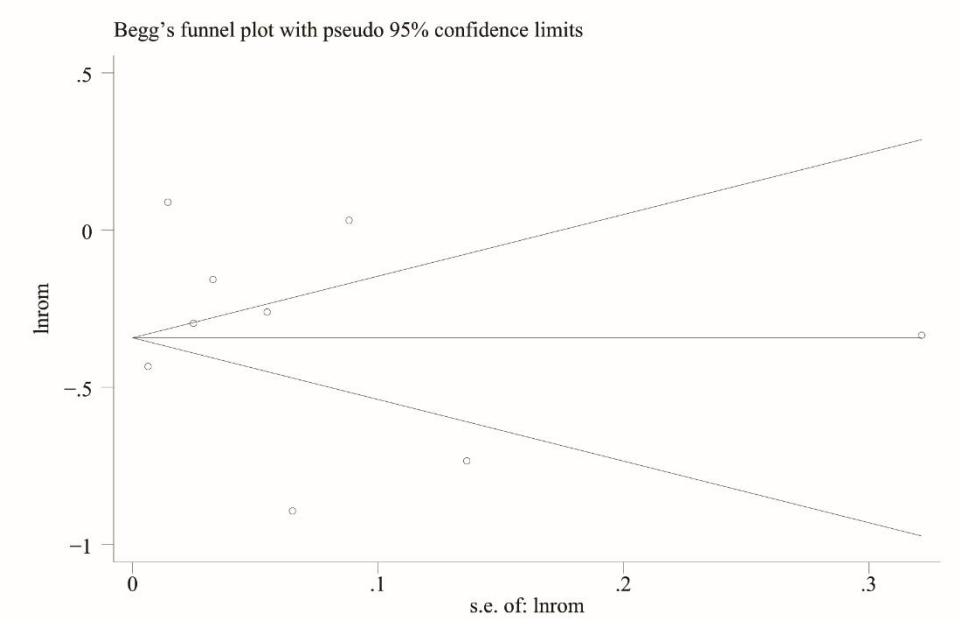
Characteristics of included studies	Quality assessment (NOS/ Adapted NOS for cross-sectional studies)			Study type	Scores for cross-sectional studies or longitudinal studies
Author (s) Year/ Country	Selection	Comparability	Outcome		Scores
Abid et al., 2021	★★	★	★★	Cross-sectional	Satisfactory studies: 5-6 points
Alanazi et al., 2022	★★★	★	★★	Cross-sectional	Satisfactory studies: 5-6 points
Al-Mulla et al., 2022	★★	★	★★	Cross-sectional	Satisfactory studies: 5-6 points
Bingham et al., 2021	★★★	★	★★	Longitudinal	Good quality
Burkart et al., 2022	★★	★★	★★★	Longitudinal	Fair quality
Chambonniere et al., 2021	★★★	★	★★	Cross-sectional	Satisfactory studies: 5-6 points
Dallolio et al., 2022	★★	★★	★★★	Longitudinal study	Fair quality

Dunton et al., 2020	★★	★	★★	Cross-sectional	Satisfactory studies: 5-6 points
Dubuc et al., 2021	★★★	★	★★	Longitudinal study	Good quality
Farello et al., 2022	★★★★	★	★★	Cross-sectional	Good studies: 7-8 points
Garc á-Alonso et al., 2022	★★	★★	★★	Longitudinal study	Fair quality
Genin et al., 2021	★★★★	★	★★	Cross-sectional	Good studies: 7-8 points
Gilbert et al., 2021	★★★	★	★★★	Cross-sectional	Good studies: 7-8 points
Greier et al., 2021	★★	★	★★	Cross-sectional	Satisfactory studies: 5-6 points
Guo et al., 2021	★★★	★★	★	Cross-sectional	Satisfactory studies: 5-6 points
James et al., 2021	★★★	★★	★★	Longitudinal study	Good quality
Jia et al., 2021	★★★	★★	★★	Cross-sectional	Good studies: 7-8 points
Jovanovic et al., 2021	★★	★★	★★	Cross-sectional	Satisfactory studies: 5-6 points
Marckhoff er al., 2022	★★★★	★	★★	Cross-sectional	Good studies: 7-8 points
Medrano et al., 2021	★★	★★	★★	Longitudinal	Fair quality
Munasinghe et al., 2020	★★	★	★★	Longitudinal	Fair quality
Nathan et al., 2021	★★	★	★★	Longitudinal	Fair quality
Peddie et al., 2021	★	★★	★★	Longitudinal	Poor quality
Schmidt et al., 2020	★★★★	★	★★	Longitudinal	Good quality
Stverakova 2021	★★	★	★★	Longitudinal	Fair quality
Yang et al., 2020	★★★	★	★★	Cross-sectional	Satisfactory studies: 5-6 points

3.4. *Risk of bias across studies*

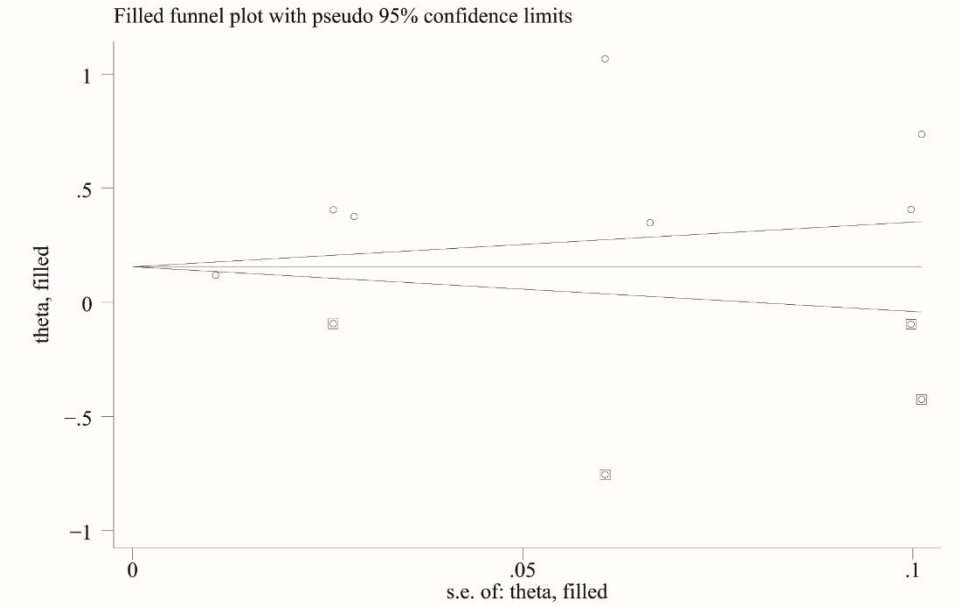
Publication bias across studies was assessed using funnel plots for the four outcomes (PA, MVPA, SB, ST). The symmetry of the funnel plot was judged subjectively by visual inspection. It was discovered that the funnel plot for ST exhibited asymmetrical scattering, but the funnel plot for PA had equal distribution on both sides. Therefore, there was probably publication bias in ST. No publication bias analysis was conducted due to the insufficient number (< 10 studies) of MVPA (N = 4) and SB (N = 4) studies. However, it is important to note that the funnel plot contains fewer than ten studies (PA = 9, ST = 7). Therefore, the funnel plot may not be a valid measure of publication bias and caution is needed in the interpretation of the results. The funnel plots can be seen in Figures 3 and 4.

Figure 3. *Total PA's funnel plot*



X-axis: standard error, Y-axis: standardised mean difference

Figure 4. *ST's funnel plot after filled (trim and filling analysis)*



X-axis: standard error, Y-axis: standardised mean difference: original studies: ○ *filled studies.* ◙

3.5. *Results of individual studies*

In primary studies where total PA, MVPA, SB, or ST were not reported, the PAQ scores, MET-min/week, and days of activity were reported as total PA. Regardless of whether PA guidelines (MVPA over 60 min per day) were met, was recorded as MVPA. Total sitting time was recorded as SB. The study includes a variety of effect measurement methods including median (25%, 75%), mean and standard deviation, percentage of PA/SB/ST guidelines met, and a comparison of percentage of SB/PA hours performed (e.g., SB<4hours/day: N (%) before COVID vs N (%) during COVID, PA>60mins: N(%) vs N(%) during COVID). P-values were used for most

outcome measures, with a few studies using odds ratios (OR) and 95% confidence intervals (CI) (N = 1) and descriptive outcomes (N = 1).

3.6. *Results of systematic review*

Overall, 12 of 17 studies reported a significant decrease in total PA during the COVID-19-related restriction period compared to the pre-COVID-19 period. Ten of 13 studies reported a significant increase in SB, and 12 of 14 studies reported a significant increase in ST. Six of nine studies reported a significant difference in MVPA reduction, and one study reported a statistically significant difference in MVPA reduction. Aside from this, all 22 studies reported that SB or ST increased during the pandemic, with 15 of these studies indicating a significant increase. The two studies that assessed television hours also revealed a significant increase.

However, three studies reported an increase in total PA (Schmidt et al., 2020, Nathan et al., 2021, James et al., 202) and one reported an increased MVPA in boys (Peddie et al., 2021). Notably, all studies demonstrating an increase in PA are longitudinal studies. Furthermore, the increase in PA in these four studies did not vary statistically from pre-pandemic levels, and only one study found a significant increase (James et al., 2021).

There were conflicting results regarding how gender differences affected changes in PA and SB. Eight of the included studies provided data on boys and girls during and before the epidemic, however, only four of the eight studies found a significant difference between boys and girls. Abid et al. (2021) reported a greater increase in ST among girls than boys. Jovanovic et al. (2021) reported that boys participated in significantly more physical activity per week than girls. On the other hand, Dallolio et al. (2022) found that during the epidemic, boys were more restricted and participated in more SB and less total PA and MVPA than girls (Dallolio et al., 2022). Moreover, Marckhoff et al. (2022) found that boys' total PA decreased more than girls', and also reported an overall increase in ST.

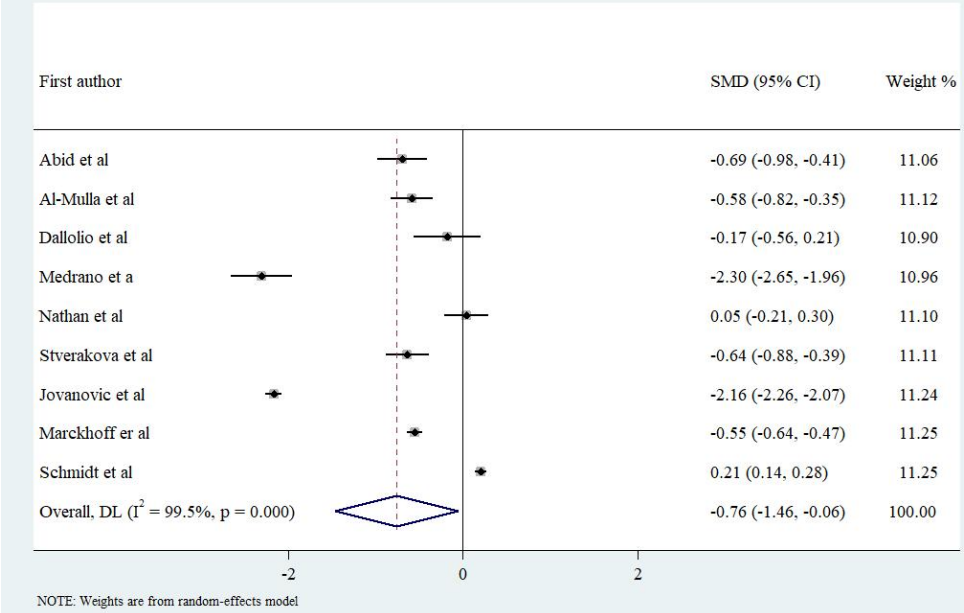
3.7. *Results of the meta-analysis*

Each meta-analysis outcome of total PA, MVPA, SB, and ST is presented in Table 4. The meta-analysis outcome regarding gender difference is presented in Table 5. Table 6 presents the results of the meta-analysis based on the results of the device measurements versus the subjective measurements. The results of the meta-analysis based on cross-sectional and longitudinal investigations are presented in Table 7.

Table 4. *Meta-analysis results of total PA, MVPA, SB, and ST*

Outcome on total PA: Nine studies assessed total PA in the meta-analysis. The results show that during the COVID-19 pandemic, total PA decreased significantly (SMD = -0.76, 95% CI = -1.46 to -0.06, $I^2 = 99.5\%$).

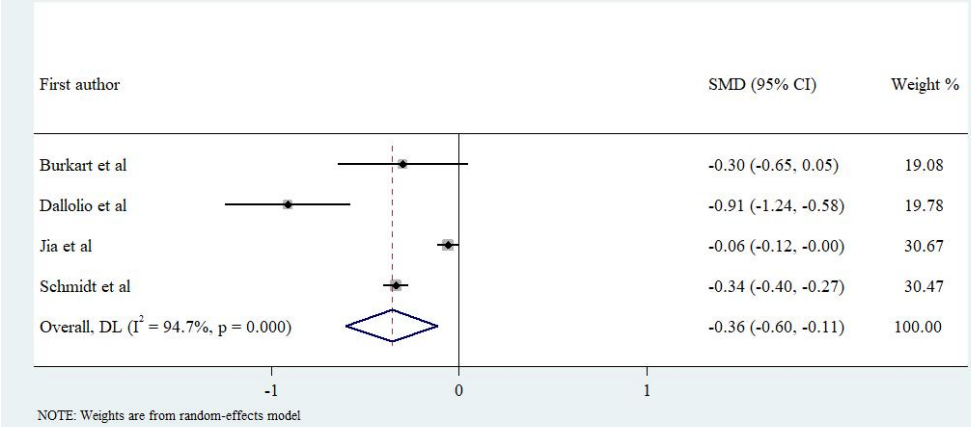
Figure 5. *Total PA standardised mean difference (SMD)*



Outcome on MVPA:

Four studies assessed MVPA in the meta-analysis, and the result indicated a significant drop in MVPA during the COVID-19 pandemic. (SMD = -0.36, 95% CI = -0.6 to -0.11, $I^2 = 94.7\%$).

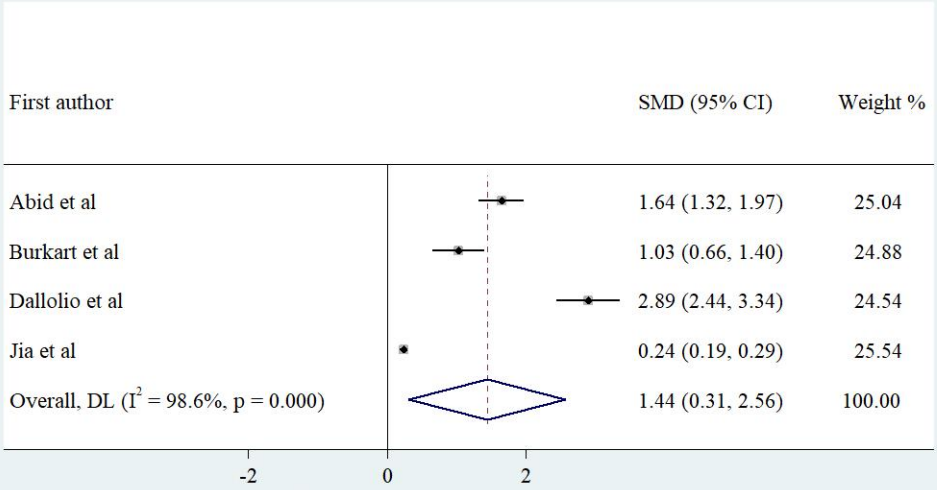
Figure 6. *MVPA standardised mean difference (SMD)*



Outcome on SB:

The results of the meta-analysis showed that SB significantly increased during the COVID-19 pandemic (SMD = 1.44, 95% CI = 0.31 to 2.56, $I^2 = 98.6\%$).

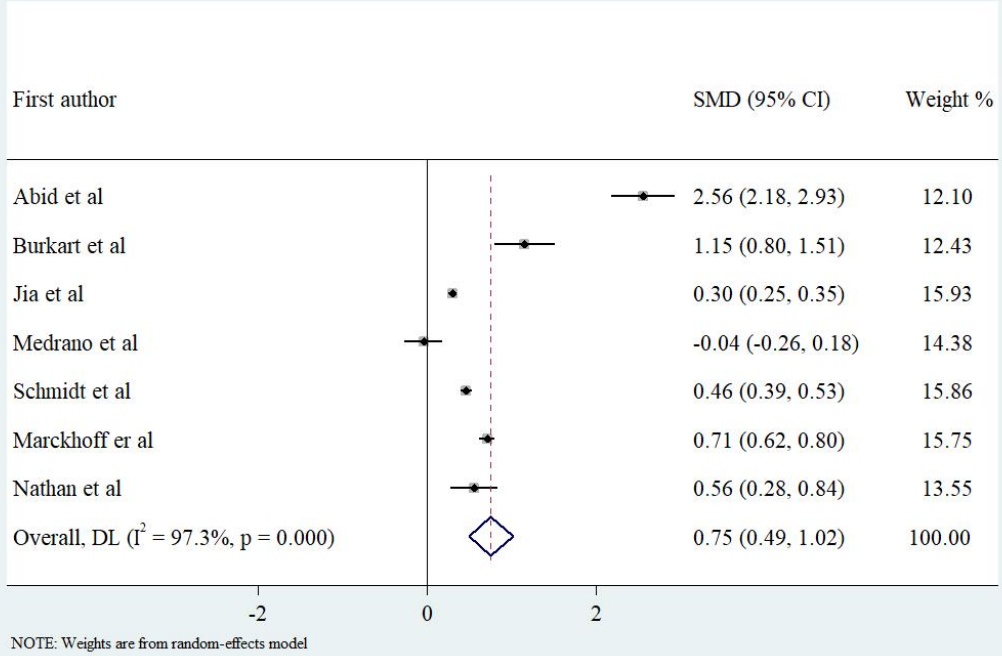
Figure 7. SB standardised mean difference (SMD)



Outcome on ST

Seven studies assessed ST in the meta-analysis. According to the meta-analysis, ST increased significantly (SMD = 0.75, 95% CI = 0.49 to 1.02, I^2 = 97.3%) during the COVID-19 pandemic.

Figure 8. *ST standardised mean difference (SMD)*



These four outcomes (total PA, MVPA, SB, and ST) demonstrated excessive heterogeneity (I^2 >75%) (Higgins & Thomas, 2019). Hence, it was necessary to perform a subgroup analysis to explore the possible causes of heterogeneity.

Table 5. *Meta-analysis results of gender difference among total PA, MVPA, SB, and ST*

Outcome on boys' total PA compared with total PA:

Figures 9 and 10 show the meta-analysis of boys' total PA and girls' total PA. The results showed that total PA decreased significantly during the pandemic for both boys (SMD = -1.10, 95%CI = -1.89 to -0.31, I^2 = 98.3%) and girls (SMD = -0.94, 95%CI = -1.77 to-0.11, I^2 = 98.8%).

Figure 9. *Boys' total PA standardised mean difference (SMD)*

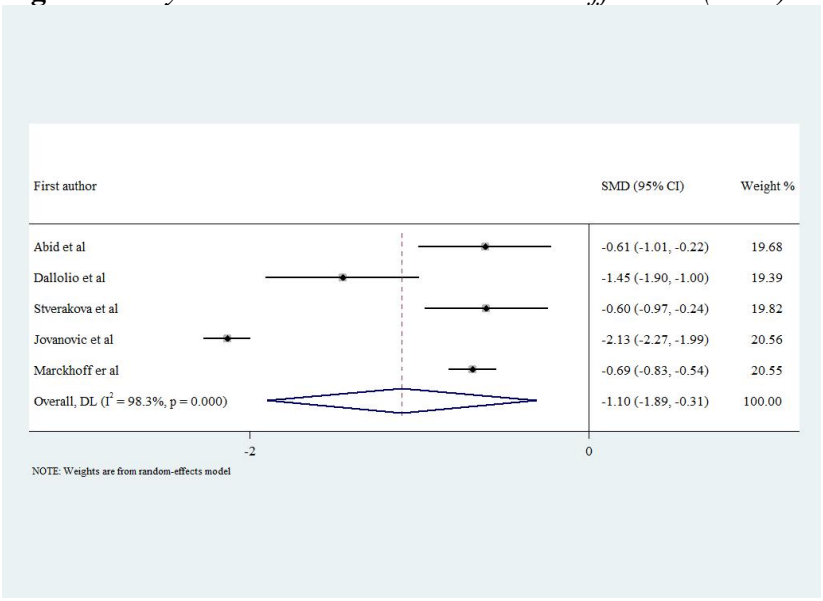
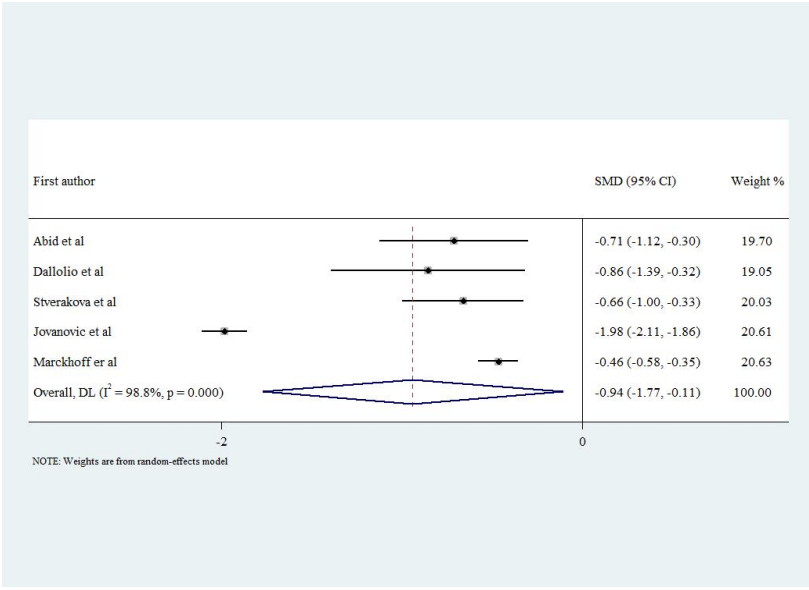


Figure 10. *Girls' total PA standardised mean difference (SMD)*



Outcome on boys' MVPA compare with girls' MVPA:

Figures 11 and 12 show the meta-analysis of boys' MVPA and girls' MVPA. The results indicate a significant decrease in MVPA during COVID-19 in boys (SMD = -0.26, 95%CI = -0.44 to -0.08, I^2 = 84.5%), but not in girls (SMD = -0.16, 95%CI = -0.47 to 0.16, I^2 = 96.8%).

Figure 11. *Boys' MVPA standardised mean difference (SMD)*

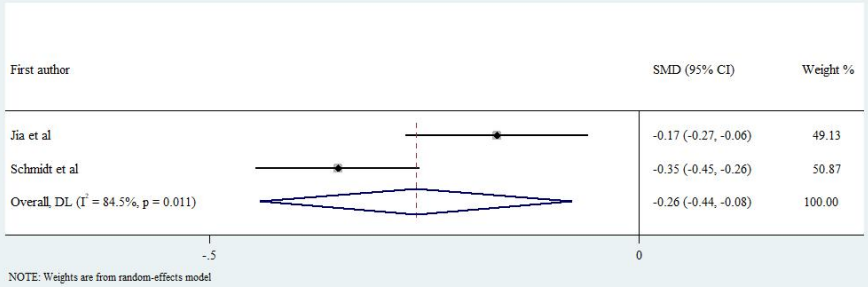
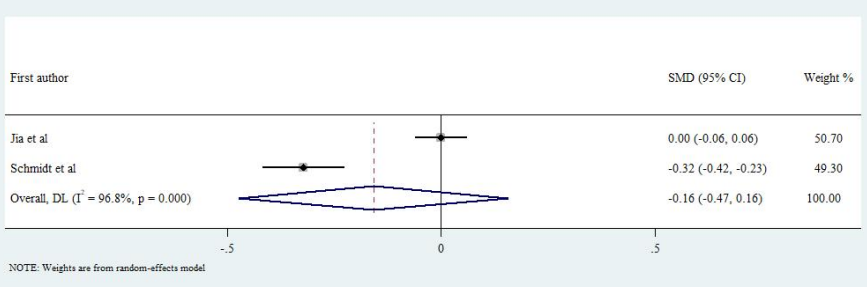


Figure 12. *Girls' MVPA standardised mean difference (SMD)*



Outcome on boys' SB compare with girls' SB:

The meta-analysis outcome of SB for boys and girls can be seen in Figure 13 and Figure 14. The results indicate a significant drop in SB for both boys (SMD = 1.73, 95%CI = 0.10 to 3.35, I^2 = 98.2%) and girls (SMD = 1.43, 95%CI = 0.07 to 2.78, I^2 = 97.2%) during COVID-19.

Figure 13. *Boys' SB standardised mean difference (SMD)*

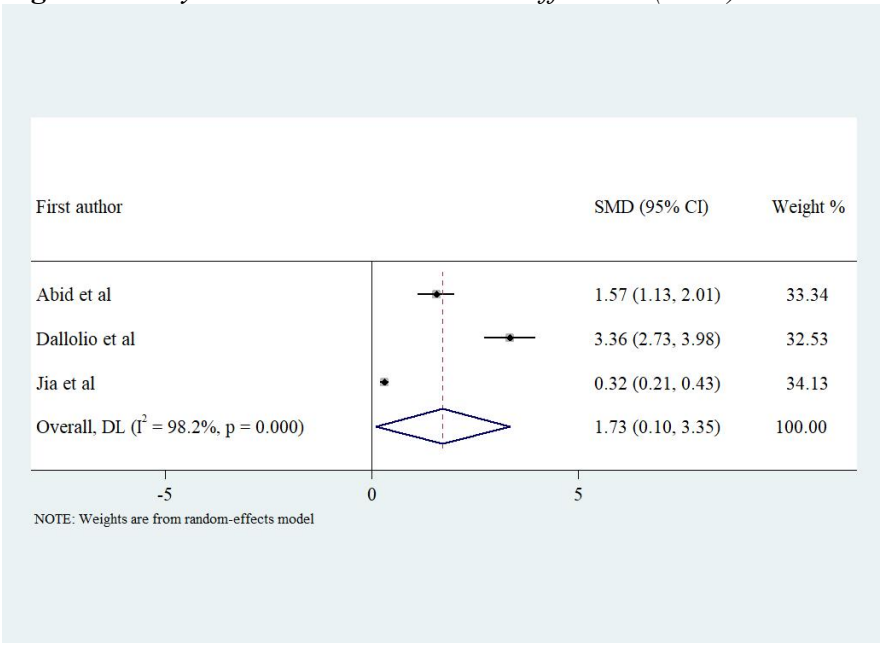
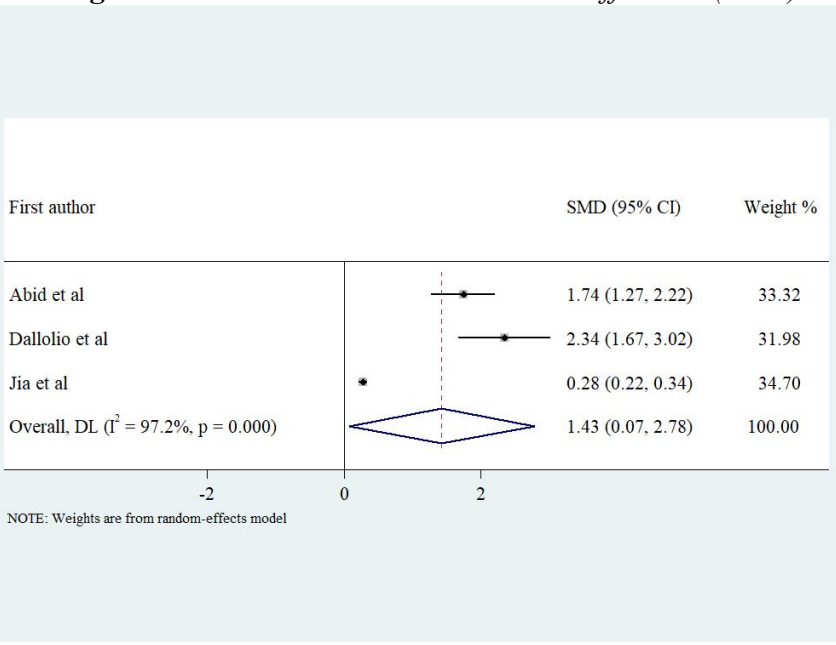


Figure 14. Girl*s' SB standardised mean difference (SMD)*



Outcome on boys' ST compare with girls' ST:

The results of the ST meta-analysis for boys and girls are depicted in Figures 15 and 16. During the COVID-19, ST decreased significantly for both boys (SMD = 0.77, 95%CI = 0.36 to 1.18, I^2 = 97.1%) and girls (SMD = 0.93, 95%CI = 0.58 to 1.28, I^2 = 97.4%).

Figure 15. *Boys' ST standardised mean difference (SMD)*

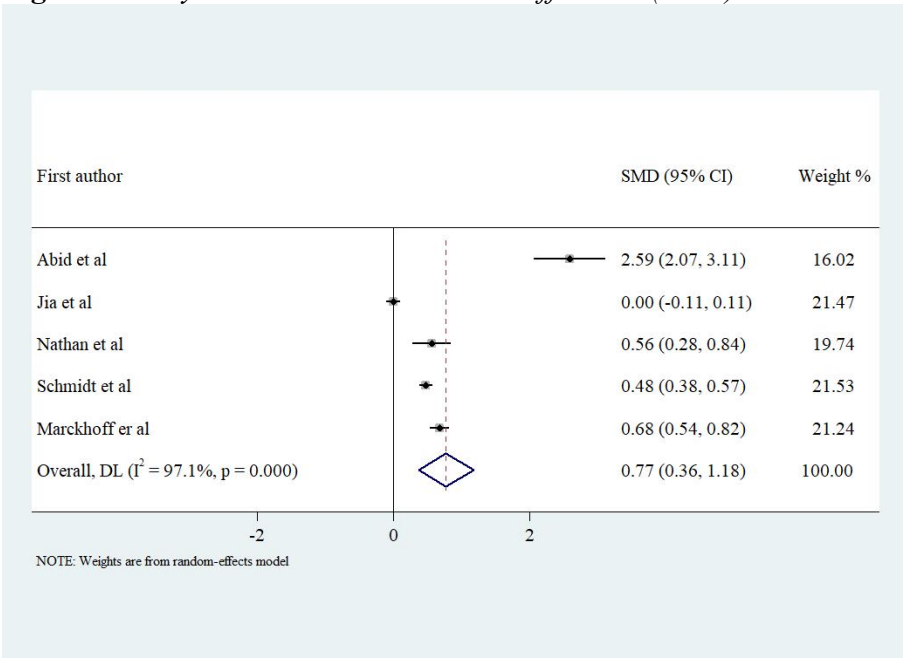


Figure 16. Girl*s' ST standardised mean difference (SMD)*

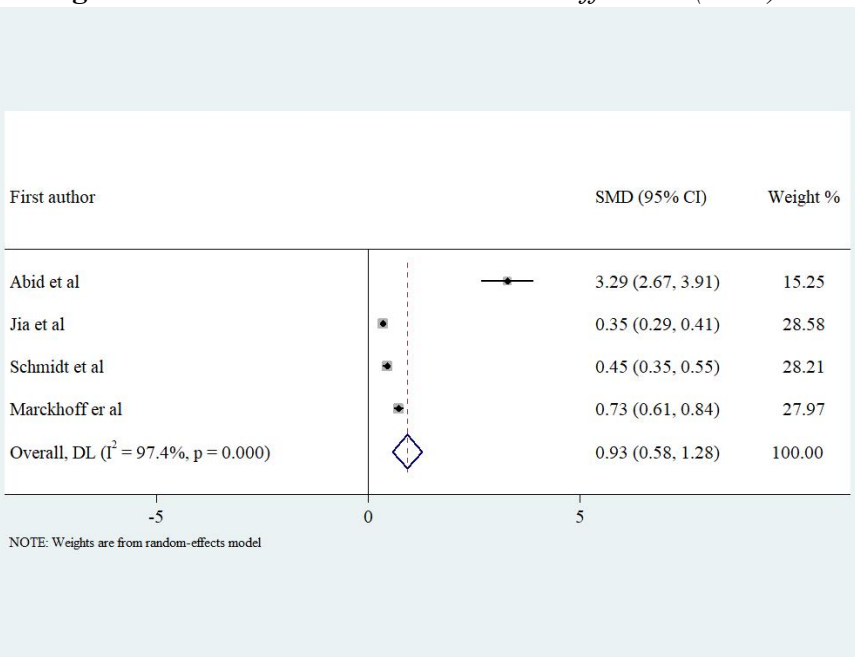


Table 6. *Meta-analysis results on objective versus subjective measures of MVPA*

Both objective (SMD = -0.61, 95%CI = -1.21 to -0.01, I^2 = 83.9%) and subjective (SMD = -0.61, 95%CI = -1.01 to -0.20, I^2 = 98.5%) measures showed a significant decrease in MVPA. The results of the included objective measures were based on accelerometers and the results of the subjective studies were derived from self or others' report questionnaires. As there were only two studies with subjective or objective measures for Total PA, SB, and ST, no comparative analysis was conducted.

Figure 17. *MVPA: objective methods (SMD)*

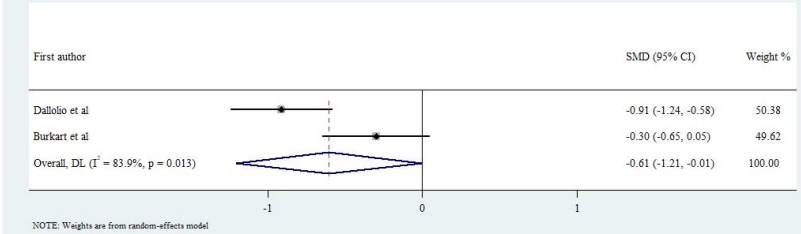


Figure 18. *MVPA: subjective methods (SMD)*

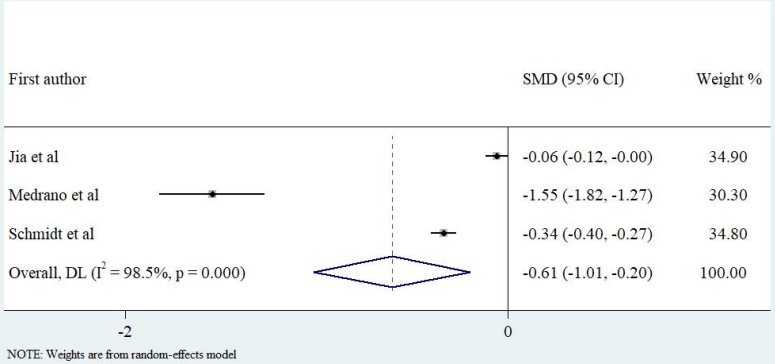


Table 7. *Meta-analysis results on cross-sectional studies versus longitudinal studies in total PA, SB and ST. (Only two cross-sectional studies of the MVPA were available, which did not allow for meta-analysis)*

Outcomes on cross-sectional and longitudinal studies of total PA:

Total PA decreased in the cross-sectional study (SMD = -1.00, 95% CI = -2 to -0.00, I^2 = 99.5%), but not in the longitudinal study (SMD = -0.56, 95% CI = -1.31 to 0.18, I^2 = 98.3%). Figure 19 shows the meta-analysis of cross-sectional studies, and Figure 20 shows the longitudinal studies.

Figure 19. *Cross-sectional studies of total PA (SMD)*

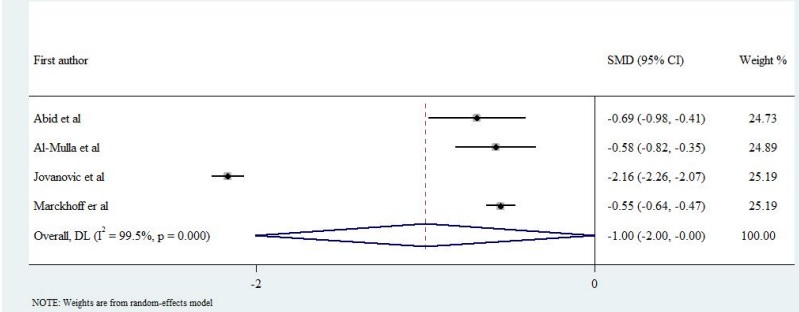
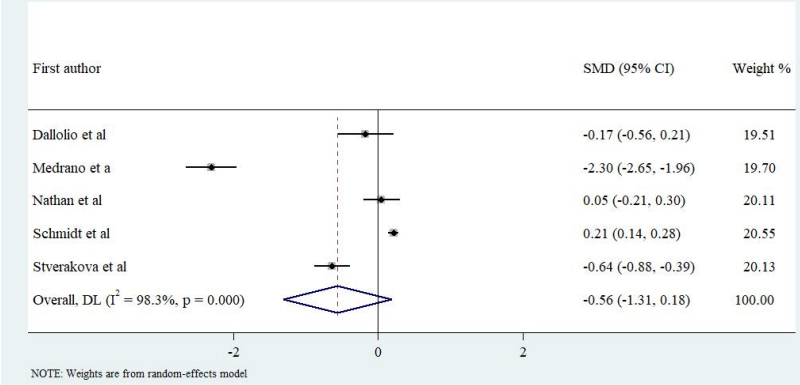


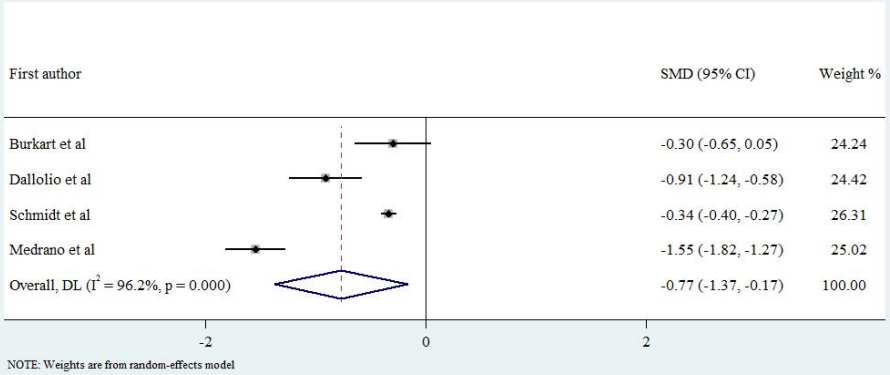
Figure 20. *Longitudinal studies of total PA (SMD)*



Outcomes on longitudinal studies of MVPA:

Results from the longitudinal study showed a significant decrease in MVPA during COVID-19 (SMD = -0.77, 95%CI = -1.37 to -0.17, I^2 = 96.2%). As only one cross-sectional study reported on the MVPA, a meta-analysis of cross-sectional study of MVPA could not be conducted. Figure 20 shows the meta-analysis of longitudinal studies in MVPA.

Figure 21. *Longitudinal studies of MVPA (SMD)*



Outcomes on cross-sectional and longitudinal studies of SB:

The cross-sectional studies found no increase in SB (SMD = -1.03, 95% CI = -0.44 to 2.31, $I^2 = 98.6\%$), but the longitudinal study found an increase of SB (SMD = 1.48, 95% CI = 0.21 to 2.75, $I^2 = 97.3\%$).

Figure 22. *Cross-sectional studies of SB (SMD)*

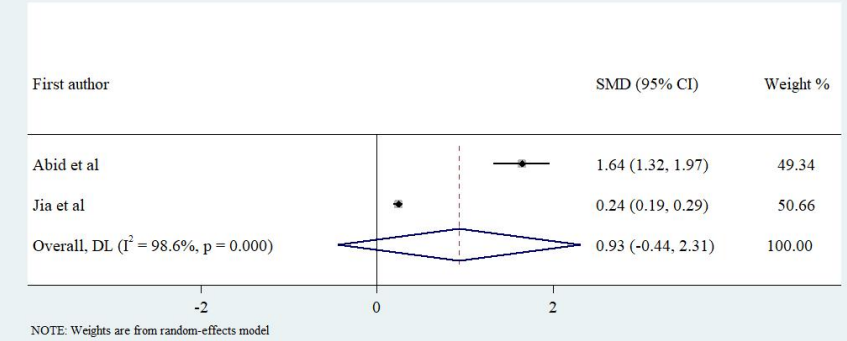
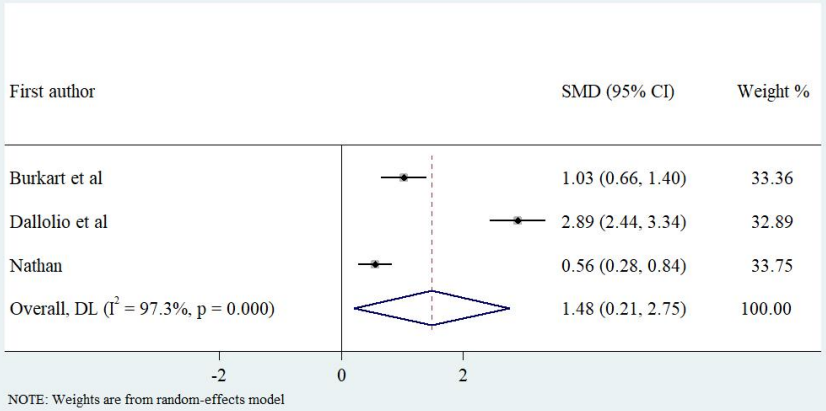


Figure 23. *Longitudinal studies of SB (SMD)*



Outcomes on cross-sectional and longitudinal studies of ST:

The results of the meta-analysis were consistent in both cross-sectional (SMD = 0.84, 95%CI = 0.40 to 1.29, I^2 = 98.3%) and longitudinal (SMD = 0.76, 95%CI = 0.37 to1.15, I^2 = 88.5%) results for ST, both showing a significant increase during COVID-19. Figure 22 displays the cross-sectional meta-analysis results. Figure 23 displays the results of meta-analysis of longitudinal studies.

3.8. *Heterogeneity and sensitivity analysis*

It is noteworthy that after the subgroup analyses by gender, measurement method, and study design, there was still high heterogeneity with I-square > 75% (Higgins & Thomas, 2019). However, in the subgroup analysis based on accelerometer measurements, I-square was reduced to 83.9%. In addition, in the subgroup of boys' MVPA, I-square was reduced to 84.5%, and reduced to 88.5% in the longitudinal studies of ST. Although the reduction in heterogeneity in the subgroup analysis was not statistically significant, it appears that heterogeneity may be related to gender, study design, and data measurement methods. In addition to this, the use of a validated assessment tool, seasonal climate differences at different sampling times, failure to subdivide age groups, and ethnic and racial differences may also cause differences between studies (Ridgers et al., 2015; Lewis et al., 2016; Cross et al., 2020; Saffer et al., 2013). Besides, to further analyse the publication bias of ST in the funnel plot (Figure 4), a sensitivity analysis of the ST results revealed P<0.05, indicating that publication bias exists in ST (Figure 24).

Figure 24. *Sensitivity analysis on ST results*

Egger's test

Std_Eff	Coef.	Std. Err.	t	P>|t|	[95% Conf.	Interval]
slope	.0528217	.0748421	0.71	0.512	-.1395662	.2452095
bias	9.0093	3.13267	2.88	0.035	.9565137	17.06209

4.0. Discussion

In the results of the meta-analysis, both total PA and MVPA decreased significantly, and both SB and ST increased significantly. The results of the systematic review associated with SB and ST were consistent with those of the meta-analysis. However, some different results of PA emerged from the few studies. There were four studies that revealed an increase in PA or MVPA (Schmidt et al., 2020, Nathan et al., 2021, Peddie et al., 2021, James et al., 2021). In addition, James et al. (2021) and Schmidt et al. (2020) found a significant increase in total PA. Schmidt et al. (2020) also confirmed an increase in habitual PA (playing outside, walking and cycling, gardening, housework), and an increase in adherence to WHO guidelines. The Schmidt et al. (2020) study was conducted during the heaviest lockdown in Germany (2020.04), but the weather in Germany was warmer during that time. In April 2020, Germany recorded a mean temperature of 10.4 °C (9.6 °C in 2019) and an average of 292.4 sunshine hours (227.9 in 2019). In warm settings, higher temperatures are related to greater PA and less ST (Lewis et al., 2016). James et al. (2021) observed an increase in PA among students with a higher socioeconomic status who had easier access to physical activity sites near their residences. Therefore, the studies that found an increase in physical activity were conducted with limited sample sizes and may not be typical of the general population.

In terms of gender differences, the results of the meta-analysis indicated a decline in total PA and MVPA, and an increase in SB and ST for both boys and girls. However, a systematic review revealed contradictory findings regarding gender differences. This study cannot conclusively determine whether there are gender differences affecting changes in PA between boys and girls. However, it appears that girls may have more ST than boys.

For both subjective and objective measures, the results were consistent in terms of changes in MVPA based on accelerometer measurements and questionnaire reports.

Due to the small number of studies included in the analysis and the lack of analysis of total PA, SB, and ST, the results of this study are not sufficient to draw conclusions about the differences between objective and subjective measures. However, in general, self-reported or other reporting methods may underestimate or overestimate true results due to the risk of recall bias (Laeremans et al., 2017, Lee et al., 2011). Therefore, in PA-related fields, there is a preference for relying on the results of objective devices. Under COVID-19-related restrictions, conducting guest observations may be subject to ethical and moral restrictions. Therefore, most of the current research on this topic comes from subjective or objective reporting methods (Paterson et al. 2021). In terms of study design, longitudinal and cross-sectional study differences were found to be inconsistent regarding SB and total PA. This may indicate that differences in study designs can impact the results.

4.1. *Comparison with previous literature*

Compared to previous systematic reviews, this study reveals more alarming effects of COVID-19-related restrictions on PA and SB in children and adolescents. In the prior systematic review, Viner et al. (2021) demonstrated a substantial reduction in PA and an increase in ST. However, only two out of six studies reported significant changes in PA and ST (Lopez Bueno et al., 2020; Pietrobelli et al., 2020). The systematic review by Kharel et al. (2022) indicated a significant decline in PA among children and adolescents, whereas eight studies did not find a significant change and one observed an increase in PA. Interestingly, the study in which Kharel et al. (2022) found an increase in PA is also the same study that showed an increase in PA in our study (Schmidt et al., 2020). In addition, Kharel et al. (2022) reported an increase in ST during the pandemic, which is consistent with the findings of our study. However, Kharel et al. (2022) categorised the varying degrees of COIVD-19-related restrictions into 4 different levels, which was not done in our study.

The meta-analysis result by Wunsch et al. (2022) showed a non-significant decrease in PA under the COVID restriction (Fisher's z = -0.08, 95% CI = -0.27 to 0.12). The results of our meta-analysis showed significant decreases in total PA and MVPA. In addition, our study also performed a meta-analysis of the changes in SB and ST during the pandemic in children and adolescents, which has never been conducted in previous studies.

4.4. Strengths and limitations of evidence

Overall, our study has several key strengths. First, to the authors' knowledge, this is the first study to use a meta-analytic approach to quantify changes in both PA and SB during COVID in healthy children and adolescents. Previous meta-analysis studies only analysed changes in PA (Wunsch et al., 2022, Neville et al., 2022). Previous studies have included different PA domains together in meta-analyses (e.g., light PA, MVPA, outside PA, walking, gardening, TV hours, video game hours) (Wunsch et al., 2022, Neville et al., 2022). As PA and SB are a complex and multidimensional behaviour, this may produce bias in the results (Thompson et al., 2015, Pettee et al., 2012). Separate analyses of total PA and MVPA, SB and ST were also a strength of this study. In addition, this study analysed subjective methods versus objective device-based methods for measuring PA and SB changes for boys and girls, as well as the differences in cross-sectional versus longitudinal outcomes.

However, there are limitations to this study that must be taken into account. Firstly, 53% (14/26) of the articles analysed were cross-sectional design studies. Cross-sectional studies measuring PA and SB data in a single pass and depending on

comparisons of data prior to recall of COVID may cause bias (Rudolf et al., 2015; Laeremans et al., 2017). Although our study analyses longitudinal and cross-sectional studies separately in the meta-analysis, the data's reliability is still unclear due to the limited number of studies included. Secondly, the results of meta-analysis were highly heterogeneous, resulting in less credible conclusions. One of the possible reasons for high heterogeneity may be the large age span of the sample (5-18). However, children (5-10) and adolescents (11-17) were not analysed separately in our study. Therefore, the findings of our meta-analysis must be interpreted with caution. In addition to this, exposure information (e.g., restriction levels) from the initial study was not investigated in this analysis. Our study also did not investigate when COVID-19-related restrictions started in each study, which could be significant as people may change their behaviour under the lockdown period. For example, Dubuc et al. (2021) reported that PA and SB change over the duration of restrictions.

5.0. Conclusion and suggestions for future research

This systematic review and meta-analysis revealed that under COVID-19-related restrictions, healthy children and adolescents had a significant decrease in total PA and MVPA, and a significant rise in SB and ST. These behavioural changes may be different between boys and girls. To prevent future adverse physical and mental impacts on children and adolescents, it is necessary for governments and schools to intervene in the PA and SB of children and adolescents during and after COVID-19, and to consider boys' and girls' gender differences when implementing interventions for PA and SB.

Consistent with previous systematic review recommendations, future study should largely concentrate on gathering data on the same forms of PA or SB using the same assessment tool (Paterson et al., 2021). This will strengthen the comparability between studies' outcomes. In addition, objective device-based measurements in this field remain rare and it is recommended that objective measurements like accelerometer readings can be used more often when permitted by ethical and moral standards. On the other hand, with the increase in vaccination rates and the gradual reduction or even elimination of COVID-19-related restrictions globally (WHO Coronavirus Dashboard, 2022), it is possible that future studies could focus more on PA and SB changes after COVID-19.

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