Prospective COVID-19 related changes in physical activity and sedentary time and associations with symptoms of depression and anxiety

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ABSTRACT

Problem: The COVID-19 pandemic is associated with psychological distress. Decreased moderate-vigorous physical activity (MVPA) and increased sedentary time may be exacerbating pandemic-related symptoms of anxiety and depression, but existing studies exploring these associations are almost entirely cross-sectional.
Methods: Reported data from 2018 and Summer 2020 were used to create change categories based on compliance with MVPA guidelines and relative sedentary time. Participants completed the Patient Health Questionnaire-4 (PHQ-4) in Summer 2020. Associations among changes in MVPA and sedentary time (separately and jointly) with psychological distress (total PHQ-4 score) were examined with ordinal logistic regression and associations with depressive or anxiety symptoms were examined with logistic regression.
Results: Among 2,240 participants (65% women, mean age 57.5 years), 67% increased sedentary time and 21% became inactive between the two time points. After multivariate adjustment, participants who became (OR = 1.71, 95% CI: 1.05–2.78) or remained inactive (OR = 2.07, 1.34–3.22) were more likely to experience depressive symptoms compared to those who remained active. Participants who increased sedentary time were also more likely to experience depressive symptoms compared to those who maintained sedentary time (OR = 1.78, 1.13–2.81). Jointly, those who increased sedentary time while remaining (OR = 3.67, 1.83–7.38) or becoming inactive (OR = 3.02, 1.44–6.34) were much more likely to have depressive symptoms compared to the joint referent (remained active/maintained sedentary time). Associations with anxiety symptoms were not statistically significant.
Conclusions: These findings support the value of promoting MVPA and limiting sedentary time during stressful events associated with psychological distress, like the COVID-19 pandemic.

1. Introduction

On March 11th, 2020, the World Health Organization declared the novel coronavirus disease (COVID-19) a global pandemic. Subsequently, a range of mitigation efforts were implemented to slow the spread of COVID-19, such as prohibiting large gatherings, limiting indoor activities with people who live outside one's home, physical distancing, quarantining upon suspected exposure to the virus, and closing or drastically shifting operations at schools, daycares, restaurants, gyms/fitness centers, and other businesses. These rapid and unforeseen changes in daily life have been associated with increases in psychological distress, including symptoms of anxiety and depression (Brooks et al., 2020; Giusti et al., 2020; Serafini et al., 2020). Thus, identifying strategies for improving mental health during the pandemic remains a public health priority.

Physical activity is a well-established non-pharmacologic strategy for easing symptoms of anxiety and depression (Ashdown-Franks et al., 2020; McDowell, Dishman, Gordon, & Herring, 2019; Zhai, Zhang, & Zhang, 2015). Unfortunately, just as COVID-19 mitigation efforts are associated with a decline in overall mental health, these shifts appear to have led to a substantial reduction in physical activity and an increase in overall sedentary time (Alomari, Khabour, & Alzoubi, 2020; Arora & Grey, 2020; Janssen et al., 2020; Knell, Robertson, Dooley, Burford, & Mendez, 2020; Smith et al., 2020). It is possible that this decrease in physical activity and increase in sedentary time may be further contributing to the recognized psychological effects of the pandemic. This is not yet entirely clear, however, largely because many existing studies on the associations between physical activity or sedentary time

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and mental health during the pandemic are cross-sectional and assess physical activity during the pandemic (limiting conclusions given the inherent concerns of reverse causation) or assess pre-pandemic physical activity retrospectively (risking recall bias) (Brailovskaia et al., 2021; Carriedo, Cecchini, Fernandez-Rio, & Méndez-Giménez, 2020; Cross et al., 2021; Duncan, Avery, Seto, & Tsang, 2020; Faulkner et al., 2020; Jacob et al., 2020; López-Bueno et al., 2020; Maugeri et al., 2020; Meyer et al., 2020; Qin et al., 2020; Schuch et al., 2020; Stanton et al., 2020). Among the few studies conducted in the United States (U.S.), results broadly suggest that there is an inverse association between total physical activity during the pandemic and symptoms of depression in older adults (Callow et al., 2020) and college students (Coughenour, Gakh, Pharr, Bungum, & Jalene, 2020). Although there are far fewer studies on the relationship between sedentary time and mental health, existing studies suggest that a reported increase in screen-based sedentary time may be associated with more symptoms of depression (Meyer et al., 2020) and less positive affect (Maher, Hevel, Reifsteck, & Drollette, 2021), but not anxiety (Meyer et al., 2020). There are two longitudinal studies on the topic, though generalizability remains limited as both studies were relatively small; one study (Okely et al., 2020) examined associations between physical activity and mental wellbeing among Scottish older adults (n = 137; average age 84 years), and the other examined associations among both physical activity and sedentary time with mental wellbeing among U.K. university students (n = 214; average age 20 years) (Savage et al., 2020).

The aims of this study build on the existing cross-sectional studies to investigate the longitudinal association of pandemic-related changes in physical activity and sedentary time (separately and jointly, as prior studies suggest these two behaviors may have more complicated, co-dependent relationships with mental health outcomes (Barwais, Cuddihy, & Tomson, 2013; Blough & Loprinzi, 2018)) with symptoms of anxiety and depression in a subset of a large U.S.-based cohort. Given the sex differences in the onset and severity of anxiety and depression (Breslau et al., 2017) and the potential role of pre-pandemic psychologic distress, a secondary aim is to explore potential differences in the association between physical activity and sedentary time with symptoms of anxiety and depression by sex and pre-pandemic history of anxiety and depression.

2. Methods

2.1. Study population and design

Data were provided by a subsample of participants from the Cancer Prevention Study-3 (CPS-3), an ongoing prospective study of cancer incidence and mortality initiated by the American Cancer Society in 2006 (Patel et al., 2017). Over 303,000 participants aged 30–65 years with no history of cancer (except for basal or squamous cell skin cancer) were enrolled across the U.S. and Puerto Rico at various community locations from 2006 to 2013. CPS-3 participants completed a survey on lifestyle and health history at enrollment and additional surveys to update exposure information every three years beginning in 2015. All participants included in the current study completed the 2018 triennial survey between April 2018 and January 2020, which provided data for pre-pandemic behaviors. All aspects of CPS-3 were approved by the institutional review boards of Emory University.

In June 2020, 13,052 active CPS-3 participants (i.e., those who completed the 2018 CPS-3 survey) were invited to join a new, online study participant portal and the first 3,000 participants to respond were granted access to register for the portal. Among the 2,979 participants who registered for the online portal, 2,429 (81.5%) completed a pandemic-focused questionnaire that sought to determine how the COVID-19 pandemic affected participants' health behaviors, physical and mental health, employment status, and financial security (referred to herein as the 'COVID-19 survey'). Participants were excluded from the current analysis for missing (n = 47), incomplete (n = 10), or implausible (described in more detail below; n = 108) physical activity or sedentary behavior data on the 2018 or COVID-19 surveys, or missing depression or anxiety data on the COVID-19 survey (n = 24). This left a final analytic sample of 2,240 participants.

2.2. Measures

Physical activity and sedentary time: On both the 2018 and COVID-19 surveys, participants completed a validated measure (Supplemental Fig. 1) assessing 24-h activities, including physical activities, sedentary activities, and sleep (Rees-Punia et al, 2019a, 2019b; Subbiah, Rees-Punia, & Patel, 2020). The 2018 and COVID-19 24-h activity surveys had tailored recall periods: on the 2018 survey, participants were asked, "*During the past year, estimate the hours per day you spent on typical weekdays and weekends in each of the following activities. Please average your seasonal physical activities over the entire year. Account for all 24 h per day*", and on the COVID-19 survey, the recall period was, "*Since the COVID-19 pandemic started*". The survey items "sitting or lying down while watching TV" and "other sitting (at work, at computer, while driving, eating, etc.)" were used to capture total sedentary time. The items "walking 3 or more mph or faster than 20 min per mile", "moderate activities" and "strenuous activities" were used to capture total moderate-to-vigorous intensity aerobic physical activity (MVPA). Response options were "0, <1, 1–2, 3–4, 5–6, 7–8, 9–10, 11+ hours per day" and the mean number of hours within each response category (i.e. 0, 0.5, 1.5, 3.5, 5.5, 7.5, 9.5, 11 h per day) were summed and weighted for weekdays (5) and weekend days (2) to obtain daily average MVPA and sedentary time before (2018) and during the pandemic (COVID-19 survey). Twenty-four-hour activity surveys with less than three complete items on weekends and weekdays were considered incomplete, and surveys accounting for less than 14 h/day or more than 34 h/day (i.e., accounted for ±10 or more hours/day) were considered implausible and were not included in analyses.

Change in physical activity and sedentary time: Continuous time in MVPA at both time points was collapsed into the categories 'active' or 'inactive' (Tremblay et al., 2017), using the Aerobic Physical Activity Guidelines for Americans ($\geq$150 min of MVPA per week) as the cut point (DHHS, 2018). Based on these categories, change in MVPA from 2018 to the pandemic was categorized as: *remained active* (met guidelines in 2018 and during the pandemic; referent), *became active* (did not meet guidelines in 2018 but met guidelines during the pandemic), *became inactive* (met guidelines in 2018 but not during the pandemic), and *remained inactive* (did not meet guidelines in 2018 or during the pandemic).

As there is no clear cut-point for "excess" sedentary time, categories were based on relative changes in sedentary time between 2018 and June 2020: *increased* (increase of >1 h/day), *decreased* (decrease of >1 h/day), or *maintained* (within ±1 h/day) sedentary time during the pandemic compared to 2018. A 1-h cut point is appropriate as prior studies have shown significant differences in mental health status with the replacement of 1 h of sedentary time with physical activity (Curtis et al., 2020; A. A.; Kandola et al., 2021).

A joint exposure variable based on changes in MVPA and sedentary time was also created. We first collapsed the '*remained*' and '*became*' active, as well as the '*decreased*' and '*maintained*' sedentary time because of small sample sizes within these categories. Therefore, the joint exposure variable comprised six categories (see Supplemental Table 1): (i) *remained or became active/decreased or maintained sedentary time* (referent), (ii) *remained or became active/increased sedentary time*, (iii) *became inactive/decreased or maintained sedentary time*, (iv) *became inactive/increased sedentary time*, (v) *remained inactive/decreased or maintained sedentary time*, and (vi) *remained inactive/increased sedentary time*.

Depression and anxiety: The Patient Health Questionnaire-4 (PHQ-4) is a 4-item tool for assessing overall psychological distress (Cronbach's alpha = 0.85), with sub-scores for depression (2-items; Cronbach's

alpha = 0.81) and/or anxiety (2-items; Cronbach's alpha = 0.82) symptoms (Kroenke, Spitzer, Williams, & Löwe, 2009). To align with the timing of the pandemic, the PHQ-4 leading question was modified to assess how often participants experienced symptoms "*since the start of the COVID-19 pandemic*". All four items used a Likert scale from 0 to 3 (ranging from "not at all" to "nearly every day"). Scores were summed, and total PHQ-4 score (representing total psychological distress) was categorized as: *normal* (0–2), *mild* (3–5), *moderate* (6–8), and *severe* (9-12). PHQ-4 depression and anxiety sub-scores were used to indicate high (≥3) or low (<3) depressive or anxiety symptoms.

Covariates: Demographic information, including age and sex, were assessed at baseline (2006–2013). Other covariates, including sleep quality (assessed with a modified version of the Pittsburgh Sleep Quality Index), and twelve items assessing pandemic-related life stressors, were obtained from the COVID-19 survey. Principal components analyses were used to create three variables from the twelve pandemic-related stress items based on the life stressor literature, including a recent COVID-19 publication (Ettman et al., 2020). These were: *work/life balance stress* (scored 0–2), *financial stress* (scored 0, 1), and *employment stress* (scored 0,1), with higher scores indicating greater stress (Cronbach's α = 0.58, 0.77, 0.53, respectively).

Responses to previous CPS-3 surveys were also used to develop a covariate representing the potential for severe outcomes if infected with COVID-19. Participants were categorized as being at "high risk" for severe complications if they reported any condition considered by the

Centers for Disease Control to increase the risk of severe outcomes, including: history of cancer, kidney disease, chronic obstructive pulmonary disease, type 2 diabetes, heart attack, stroke, cardiac bypass surgery, obesity, or being a current smoker (CDC, 2021). Participants were similarly classified as "*may be at increased risk*" for severe COVID-19 complications if they reported: asthma, HIV, type 1 diabetes, hypertension, liver disease, and overweight. Participants with no self-reported history of any of the above conditions were considered "*low risk*". Model covariates were selected a priori.

2.3. Statistical analysis

Sample characteristics by physical activity change category were tested with chi-squared tests. Associations of changes in physical activity and sedentary time (separately and jointly) with overall psychological distress (*normal, mild, moderate, severe*) were examined in multivariate ordinal logistic regression models. Associations with depression and anxiety symptoms (low, high) were examined in multivariate logistic regression models. Models were adjusted for: 1) age and sex and 2) age, sex, sleep quality, risk of serious complications from COVID-19, employment stress score, financial stress score, and work-life balance score. To account for baseline differences in sedentary time (since change categories are relative and not based on a specific cut-point), a model further adjusted for 2018 sedentary time (continuous minutes per day) is presented.

Table 1
Participant characteristics.

	Total	Remained active	Became inactive	Became active	Remained inactive	p-value[a]
	N=2,240	N=660	N=480	N=196	N=904	
	N (%)					
Sex						
Women	1,456 (65)	352 (53.3)	324 (67.5)	117 (59.7)	663 (73.3)	p < 0.001
Men	784 (35)	308 (46.7)	156 (32.5)	79 (40.3)	241 (26.7)	
Age group						
<50	518 (23.1)	133 (20.2)	116 (24.2)	35 (17.9)	234 (25.9)	p = 0.056
50-<60	668 (29.8)	207 (31.4)	151 (31.5)	50 (25.5)	260 (28.8)	
60-<70	835 (37.3)	257 (38.9)	166 (34.6)	89 (45.4)	323 (35.7)	
70+	219 (9.8)	63 (9.5)	47 (9.8)	22 (11.2)	87 (9.6)	
Race/Ethnicity						P = 0.46
White/Non-Latinx	1,720 (76.8)	519 (78.6)	374 (77.9)	154 (78.6)	673 (74.4)	
Black/Non-Latinx	74 (3.3)	16 (2.4)	12 (2.5)	7 (3.6)	39 (4.3)	
Latinx (all races)	278 (12.4)	77 (11.7)	60 (12.5)	24 (12.2)	117 (12.9)	
Other	168 (7.5)	48 (7.3)	34 (7.1)	11 (5.6)	75 (8.3)	
Sleep quality						
Very bad	64 (2.9)	11 (1.7)	17 (3.5)	4 (2)	32 (3.5)	p = 0.039
Fairly bad	503 (22.5)	125 (18.9)	111 (23.1)	40 (20.4)	227 (25.1)	
Fairly good	1,322 (59)	407 (61.7)	278 (57.9)	120 (61.2)	517 (57.2)	
Good	351 (15.7)	117 (17.7)	74 (15.4)	32 (16.3)	128 (14.2)	
Risk of COVID complications						
Low risk	607 (27.1)	257 (38.9)	122 (25.4)	66 (33.7)	162 (17.9)	p < 0.001
Might be at increased risk	806 (36)	251 (38)	184 (38.3)	69 (35.2)	302 (33.4)	
Increased risk	827 (36.9)	152 (23)	174 (36.3)	61 (31.1)	440 (48.7)	
Employment stress score						
0	1,649 (73.6)	485 (73.5)	360 (75)	147 (75)	657 (72.7)	p = 0.78
1	591 (26.4)	175 (26.5)	120 (25)	49 (25)	247 (27.3)	
Financial stress score						
0	1,857 (82.9)	576 (87.3)	394 (82.1)	174 (88.8)	713 (78.9)	p < 0.001
1	383 (17.1)	84 (12.7)	86 (17.9)	22 (11.2)	191 (21.1)	
Work-life balance score						
0	1,124 (50.2)	368 (55.8)	227 (47.3)	105 (53.6)	424 (46.9)	p = 0.0012
1	570 (25.4)	149 (22.6)	123 (25.6)	59 (30.1)	239 (26.4)	
2	546 (24.4)	143 (21.7)	130 (27.1)	32 (16.3)	241 (26.7)	

[a] p-values for differences in characteristics by physical activity change groups.

Table 2
Pre-pandemic (2018) to pandemic (June 2020) changes in physical activity and associations with symptoms of depression and anxiety.

	Remained active (Ref)	Became active	Became inactive	Remained inactive
	OR (95% CI)			
Psychological Distress (total PHQ-4)[a]				
Model 1 [b]	1.0	0.96 (0.68–1.35)	**1.47 (1.16–1.87)**	**1.55 (1.26–1.91)**
Model 2 [c]	1.0	0.89 (0.62–1.28)	**1.32 (1.02–1.70)**	**1.30 (1.04–1.63)**
Anxiety sub-score [d]				
Model 1	1.0	0.84 (0.47–1.48)	**1.53 (1.07–2.19)**	**1.54 (1.12–2.11)**
Model 2	1.0	0.79 (0.43–1.44)	1.32 (0.89–1.94)	1.21 (0.85–1.72)
Depression sub-score [d]				
Model 1	1.0	1.41 (0.72–2.76)	**2.06 (1.30–3.28)**	**2.73 (1.81–4.10)**
Model 2	1.0	1.34 (0.67–2.68)	**1.71 (1.05–2.78)**	**2.07 (1.34–3.22)**

[a] Associations with psychological distress (total PHQ-4 score categories: normal, mild, moderate, severe) were examined with ordinal logistic regression models [b] Adjusted for age and sex.
[c] Additionally adjusted for sleep quality, risk of poor COVID outcome, employment stress score, financial stress score, and work-life balance score.
[d] Associations with anxiety and depression symptoms (low/high) were examined with logistic regression.

Table 3
Pre-pandemic (2018) to pandemic (June 2020) changes in sedentary time and associations with symptoms of depression and anxiety.

	Maintained sedentary time (Ref)	Decreased sedentary time	Increased sedentary time
	OR (95% CI)		
Mental health (total PHQ-4)[a]			
Model 1 [b]	1.0	0.96 (0.70–1.31)	**1.47 (1.18–1.82)**
Model 2 [c]	1.0	0.75 (0.54–1.04)	1.23 (0.98–1.55)
Model 3 [d]	1.0	0.73 (0.52–1.02)	**1.26 (1.00–1.59)**
Anxiety sub-score[e]			
Model 1	1.0	0.75 (0.46–1.24)	**1.49 (1.08–2.05)**
Model 2	1.0	**0.58 (0.34–0.99)**	1.15 (0.81–1.62)
Model 3	1.0	0.59 (0.35–1.02)	1.13 (0.79–1.60)
Depression sub-score[e]			
Model 1	1.0	1.16 (0.63–2.14)	**2.17 (1.42–3.31)**
Model 2	1.0	0.94 (0.50–1.79)	**1.77 (1.13–2.77)**
Model 3	1.0	0.94 (0.49–1.80)	**1.78 (1.13–2.81)**

[a] Associations with psychological distress (total PHQ-4 score categories: normal, mild, moderate, severe) were examined with ordinal logistic regression models [b] Adjusted for age and sex.
[c] Additionally adjusted for sleep quality, risk of poor COVID outcome, life stress variables.
[d] Additionally adjusted for 2018 sedentary time (continuous).
[e] Associations with anxiety and depression symptoms (low/high) were examined with logistic regression.

As a secondary aim, potential modification of the association between physical activity and sedentary time with overall psychological distress by sex and pre-pandemic levels of depression and anxiety (captured with the 2018 survey item "how often have you been bothered by emotional problems such as anxiety, feeling depressed, or irritable?" dichotomized as never/rarely/sometimes vs. often/always) was explored. All analyses were performed with SAS version 9.4 with a significance level of p < 0.05.

3. Results

Overall, 65% of participants (n = 1,456) were women with an average age of 57.5 (SD = 9.7) years (Table 1). Participants who remained active (i.e., met physical activity guidelines) in 2018 and during the COVID-19 pandemic (n = 660, 29.5%) were more likely to be men and were also more likely to report better sleep quality during the pandemic. Approximately 67% of participants (n = 1509) increased sedentary time between the two time points.

3.1. Associations of changes in physical activity with psychological distress

Compared to participants who remained active, participants who became inactive or remained inactive were more likely to have worse psychological distress after multivariate adjustment (model 2 OR =

1.32, 95% confidence intervals [CI] = 1.02–1.70; OR = 1.30, 1.04–1.63, respectively; Table 2). Participants who became active did not differ in psychological distress compared to those who remained active (OR = 0.89, 0.62–1.28).

Changes in physical activity were not associated with anxiety symptoms; however, participants who remained inactive were twice as likely to experience worse depressive symptoms (OR = 2.07, 1.34–3.22) compared to those who remained active.

3.2. Associations of changes in sedentary time with psychological distress

After multivariate adjustment, including adjustment for 2018 (baseline) sedentary time, participants who increased the amount of time spent sedentary during the pandemic had higher odds of worse psychological distress compared to those with consistent sedentary time between the two time points (model 3 OR = 1.26, 1.00–1.59; Table 3). Participants who increased sedentary time were also significantly more likely to report worse depressive symptoms (OR = 1.78, 1.13–2.81).

3.3. Joint assseociations of changes in physical activity and sedentary time with psychological distress

Compared to participants who remained active and also maintained sedentary time between 2018 and the COVID-19 survey, participants who increased sedentary time and also became inactive (OR = 1.64,
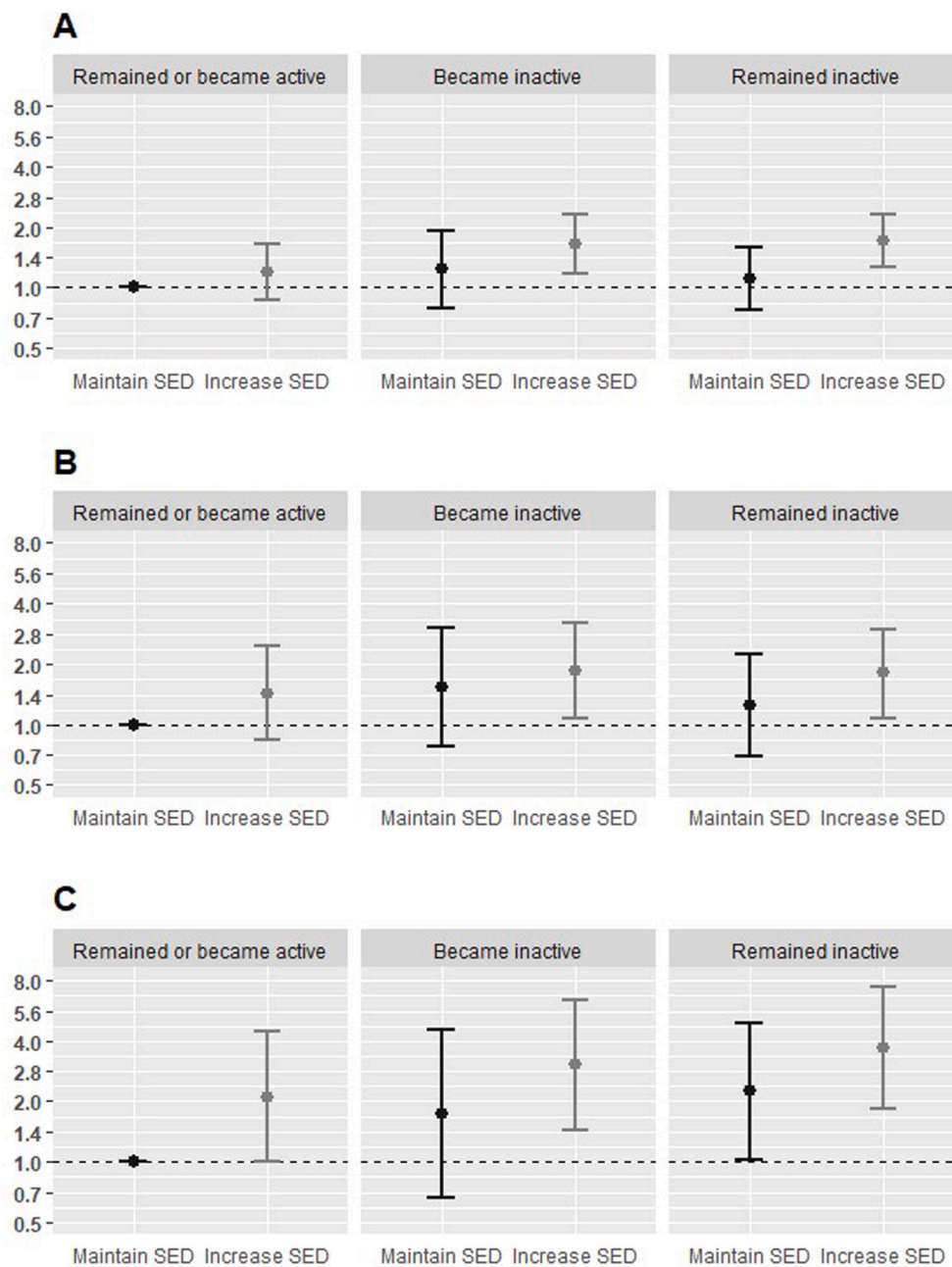
Fig. 1. Associations of pandemic-related (2018 to June 2020) changes in physical activity and sedentary time with odds of a) psychological distress, b) anxiety symptoms, c) depressive symptoms.

1.17–2.29) or remained inactive (OR = 1.69, 1.25–2.30) had higher odds of worse psychological distress (Fig. 1a); these same two groups of participants also had higher odds of anxiety symptoms (OR = 1.86, 1.08–3.21 and OR = 1.80, 1.08–2.99, respectively; Fig. 1b). Participants who became inactive and also maintained sedentary time did not differ in depressive symptoms compared to those who remained or became active and also maintained sedentary time (Fig. 1c). However, all other groups were more likely to report high depressive symptoms, ranging from a borderline association among those who became active but increased sedentary time (OR = 2.09, 0.99–4.40) to a three-fold higher likelihood of depression among those who increased sedentary time while remaining inactive (OR = 3.67, 1.83–7.38) or becoming inactive (OR = 3.02, 1.44–6.34).

3.4. Effect modification by sex and pre-pandemic depression/anxiety

Sex did not appear to modify the association between changes in physical activity and overall psychological distress (Supplemental Table 2). Additionally, history of pre-pandemic depressive and anxiety symptoms did not modify associations between physical activity or sedentary time with psychologic distress. Conversely, sex did modify the association between sedentary time and psychologic distress (p-interaction = 0.042), such that men (compared to women) who increased sedentary time (compared to those who maintained) were more likely to experience overall psychologic distress (OR = 1.99, 1.17–3.40).

4. Discussion

Using data from a prospective cohort, results from this study suggest

that, compared with participants who remained active, those who became or remained physically inactive during (compared to before) the pandemic were more likely to experience depressive symptoms. Similarly, those who became more sedentary during the pandemic were more likely to report depressive symptoms than those who maintained sedentary time, with as much as a three-fold higher likelihood of symptoms of depression for those who increased sedentary time while remaining or becoming inactive. Although the associations between physical activity and sedentary time (separately) with feelings of anxiety were not statistically significant in the current study, analyses of the joint association revealed that, compared to participants who remained active and maintained sedentary time, participants who increased sedentary time and became inactive had 80–86% higher odds of anxiety symptoms.

Many prior studies of the associations between physical activity, sedentary time, and mental health during the pandemic are cross-sectional and only assess physical activity or sedentary time during the pandemic (Callow et al., 2020; Jacob et al., 2020; López-Bueno et al., 2020; Qin et al., 2020; Schuch et al., 2020), or ask participants to report their perceived change in behavior since the pandemic started (i.e., increased, decreased, or stayed the same), triggering concerns around recall bias and reverse causality (Cross et al., 2021; Duncan et al., 2020; Stanton et al., 2020). Further, a recent commentary on studies of perceived changes in physical activity during the pandemic reported that 66% of studies assess physical activity with non-validated measures (Cross et al., 2021). Results of this study, therefore, uniquely contribute longitudinal data (including data collected before the pandemic began) from a validated questionnaire to the rapidly growing literature.

Consistent with the current study, one of the stronger cross-sectional studies of 3,052 U.S. adults found that, compared to those who reported that they remained active, participants who reported becoming inactive during the pandemic had significantly worse depression, but anxiety symptoms were not significantly different between those remaining active and becoming inactive (Meyer et al., 2020). More broadly, many of the existing studies corroborate the findings from the current study and Meyer et al. regarding the inverse relationship between physical activity and symptoms of depression during the pandemic. On the other hand, previous studies of physical activity and anxiety during the pandemic have yielded equivocal results, with some studies reporting a statistically significant inverse association with physical activity and anxiety during the pandemic (Duncan et al., 2020; Jacob et al., 2020; López-Bueno et al., 2020; Schuch et al., 2020; Stanton et al., 2020), and others reporting no association (Anyan, Hjemdal, Ernstsen, & Havnen, 2020; Callow et al., 2020). There are fewer studies of the relationship between sedentary time and mental health during the pandemic. Nevertheless, these studies suggest that a reported increase in screen-based sedentary time may be associated with more symptoms of depression (Meyer et al., 2020) and less positive affect (Maher et al., 2021), but may not be associated with anxiety (Meyer et al., 2020). More studies on the joint association of physical activity and sedentary time with mental health during the pandemic are greatly needed.

Only two longitudinal studies have assessed associations of pandemic-related changes in physical activity and sedentary time with mental health. In one of these studies, total physical activity (including MVPA and lighter intensity activities of daily living) was assessed with a general rank-order survey (on a scale from 1 to 6) approximately two years prior to, and again during, the pandemic. The study found no correlation between change in physical activity and overall mental wellbeing (measured via the Warwick-Edinburgh Mental Wellbeing Scale; Spearman correlation = −0.035) in 137 Scottish older adults with an average age of 84 years (Okely et al., 2020). The other investigation, which included 214 university students based in the U.K., reported a borderline significant positive association between change (from October 2019 to April 2020) in sedentary time and change in perceived stress ($r = 0.18$, $p < 0.010$), but found no statistically significant associations between change in physical activity or sedentary time with

change in mental well-being (Savage et al., 2020). The lack of agreement between these two and the current longitudinal studies likely reflects a combination of differences in sample sizes, average participant ages, study site (including country-specific differences in COVID-19-related restrictions), physical activity surveys, and mental health measures.

Possible biologic mechanisms of the inverse association between physical activity and depressive symptoms broadly include the promotion of neurogenesis and neural activation, decreased neuro-inflammation and oxidative stress, and increased brain-derived neurotropic factor (BDNF), norepinephrine, and serotonin (Hu, Tucker, Wu, & Yang, 2020; A. Kandola, Ashdown-Franks, Hendrikse, Sabiston, & Stubbs, 2019). It is also possible that recovery experiences during physical activity, including higher psychological detachment from the pandemic/lockdown, higher levels of relaxation, greater experience of mastery, and greater experience of control, may mediate the relationship between physical activity and mental well-being during the pandemic specifically (Ginoux et al., 2021). The potential mechanisms for the relationship with sedentary behavior are less understood, but it is possible that the specific nature of the sedentary behavior may be relevant. For example, recent studies suggest that mentally passive sedentary behaviors, such as watching television, may be more highly associated with depressive symptoms than mentally active sedentary behaviors, such as working on a computer (Hallgren, Dunstan, & Owen, 2020). This level of detail regarding the nature of time spent sedentary unfortunately could not be obtained from CPS-3 surveys and therefore could not be explored in the current study. More research is needed to fully understand these relationships, not just to benefit people during the remainder of the COVID-19 pandemic, but also for any potential future pandemics, natural disasters, or similar events associated with a number of employment, life, and financial stressors.

It is certainly possible that greater depressive symptomology during the pandemic resulted in less physical activity and more sitting time compared to 2018. To address this potential for reverse causality, we demonstrated that the association between change in physical activity and depressive symptoms during the pandemic remained significant even among participants who reported little or no depressive symptoms before the pandemic. On the other hand, some studies suggest that the physical activity-depression relationship may truly be bidirectional in nature (Da Silva et al., 2012). Consequently, we cannot completely rule out that part of the associations seen in the current study are not a result of reverse causality and/or a true bidirectional association. It is also possible that the average decrease in physical activity from 2018 to 2020 reported in this study reflects a trend towards less physical activity with aging and was not necessarily caused by the pandemic. However, there was a relatively short time period – 2.2 years on average - between surveys and an average decrease in MVPA time of 19% from the 2018 to the COVID-19 survey. For context, the average change in reported physical activity from the 2015 to 2018 CPS-3 surveys in these same participants (average of 2.9 years apart) was +2%. Given the vast differences in reported physical activity over a short period of time in the current study, it seems likely that these differences are indeed a reflection of the pandemic.

Strengths and Limitations: In addition to the potential for reverse causality or bidirectional associations discussed above, this study relied on self-reported physical activity and sedentary time. Importantly, validation studies have confirmed that the CPS-3 physical activity and sedentary time measures have good one-year reliability and are correlated with accelerometer-measured data (Rees-Punia et al, 2019a, 2019b; Subbiah et al., 2020). Further, CPS-3 participants are generally more physically active than the U.S. population, which may limit generalizability. Strengths of this study include the use of prospective data, with data collected before and during the pandemic. This study also included both men and women of varying ages residing throughout the United States.

Identifying adaptable strategies for easing feelings of psychological distress, including anxiety and depression, associated with the COVID-

19 pandemic remains a public health priority. The current study suggests that those who became inactive and/or increased sedentary time during the pandemic were much more likely to experience symptoms of depression compared to those who maintained or adapted an active lifestyle. These findings support the value of promoting physical activity and limiting sedentary time during stress-inducing public health events that require physical distancing, limited person-to-person contact, and social isolation.

Declarations of competing interest

None

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.mhpa.2021.100425.

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