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FULL LENGTH MANUSCRIPT

# Independent and Joint Associations of Physical Activity and Sleep on Mental Health Among a Global Sample of 200,743 Adults

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## Abstract

**Background** Previous research has demonstrated that both sleep and physical activity (PA) are independently associated with various indicators of mental health among adults. However, their joint contribution to mental health has received limited attention. The present study used cross-sectional data from the Mental Health Million Project to examine the independent and joint effects of sleep and PA on mental health among a global sample of adults, and whether these effects differ among individuals receiving mental health treatment.

**Method** The sample included 200,743 participants (33.1% young adults, 45.6% middle-aged adults, 21.3% older adults; 57.6% females, 0.9% other) from 213 countries, territories, and archipelagos worldwide that completed a comprehensive 47-item assessment of mental health including both problems (i.e., ill-being) and assets (i.e., well-being): the Mental Health Quotient. Participants also reported their weekly frequency of PA and adequate sleep, and mental health treatment status. A series of generalized linear mixed models were computed.

**Results** Independent dose-response associations were observed, whereby greater amounts of PA and adequate sleep were each associated with better mental health. In addition, a synergistic interaction was observed in which the positive correlation of PA with mental health was strengthened with greater frequency of adequate sleep. These benefits were less pronounced among adults receiving mental health treatment.

**Conclusion** While findings suggest sleep can help to offset the negative influence of a physically inactive lifestyle (and vice versa), our results point to a "more is better" approach for both behaviors when it comes to promoting mental health.

**Keywords** Population health · Exercise · Behavior · Psychological well-being

## Introduction

Mental health is an important aspect of overall health and well-being, but evidence indicates mental disorders remain a significant concern for many people in society today. For example, results from the 2019 Global Burden of Disease study estimated that the prevalence of mental disorders is 11.7% in males and 12.8% in females, or roughly one in every eight people, with depression and anxiety disorders being the most common [1]. Emerging evidence indicates that rates of mental disorders have been exacerbated by the COVID-19 pandemic [2]. The economic impact of mental disorders is believed to be even greater than other non-communicable diseases such as cancer and diabetes [3, 4], many of which have received far greater research investment [5, 6]. These observations have sparked a growing recognition of the importance of taking preventative action to protect against and manage mental disorders [1, 7, 8].

Traditionally, the field of mental health has focused on psychopathology and distress, following a pathogenic approach rooted in the medical model that treats health as the absence of illness (e.g., depression and anxiety, in the case of mental disorders). This paradigm has been dominant in both physical and mental health fields throughout history [9]. More recently, the dual continua model of mental illness and health has been advocated [9–11]. This model recognizes that mental illness and mental health are related but

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distinct dimensions. The seminal work of Keyes [9] demonstrated strong support for the dual continua model in which individuals fall along a continuum of mental health from languishing to flourishing as well as a continuum of mental illness-based symptoms of psychopathology being present or absent. From this perspective, one's mental health is defined by jointly accounting for their position on two continua. In doing so, the dual continua model provides a more comprehensive understanding of mental health, fostering a nuanced perspective that encompasses the full spectrum from dysfunction to optimal mental flourishing.

Over a decade ago, lifestyle was recognized to play a significant role in our mental health, including the promotion of mental well-being as well as the prevention and management of mental disorders [12]. Modifiable health behaviors such as physical activity, diet, smoking, and sleep are receiving increased attention for their potential [13]. The recent release of the Canadian 24-Hour Movement Guidelines for Adults places an even greater emphasis on the importance of engaging in sufficient amounts of physical activity and sleep to achieve health benefits [14]. For instance, evidence from several meta-analyses have shown that regular physical activity engagement provides numerous mental health benefits including, but not limited to reduced risk of depression and anxiety as well as improved affect and mental well-being [15–21]. A recent study by Santos et al. [22] predicted that failure to improve physical activity levels worldwide between 2020 and 2030 would result in 215.7 million new cases of depression and anxiety, representing 43% of all new cases of preventable non-communicable diseases. It is worth noting that depression alone is expected to account for ~30% of direct health care costs attributed to physical inactivity [22]. For these reasons, physical activity is receiving considerable attention for its potential to promote mental well-being as well as in the prevention and management of mental disorders at the individual and population levels [23]. But researchers to date have largely taken a siloed approach that fails to consider the role of sleep and how these behaviors may interact to influence mental health. Only recently has there been a shift towards a new paradigm that considers the collective influence of all movement behaviors that we engage in over the course of a whole 24-h day, commonly referred to as the 24-h movement paradigm [24] or the 24-h activity cycle [25]. This shift has brought forward new analytic approaches to the field of time-use epidemiology such as compositional data analysis (CoDA) techniques. CoDA techniques consider the co-dependent nature of movement behaviors (i.e., time spent engaging in one behavior cannot be spent in another), and recent studies have demonstrated associations between 24-h movement compositions and indicators of mental health among several different populations [26]. It should be noted, however, that these models work best with 24-h time use data captured via accelerometry, thus posing challenges for collecting data to examine the interactive influence of movement behaviors on mental health using large global samples.

Beyond physical activity, emerging evidence would suggest that sleep be included as a key pillar in the path forward for addressing societal mental health concerns [27]. Specifically, reviews of the literature investigating relationships between various facets of sleep (e.g., duration, consistency, quality) with indicators of mental well-being and illness (e.g., symptoms, risk of clinical disorders) have demonstrated consistent and favorable associations [13, 28–31]. Meta-analytic findings from 72 interventions indicate that improving sleep produces small-to-medium-sized improvements across a range of mental health indicators (e.g., composite mental health, depression, anxiety, stress), including dose-response benefits for sleep quality [32].

Moreover, changes in the physiological characteristics of particular sleep stages have been linked to mental disorders, such as post-traumatic stress disorder [33]. Akin to physical inactivity, insufficient sleep poses a significant burden on the economy. The economic cost of insufficient sleep is estimated to have a combined yearly impact of $680 billion in the USA, Canada, Germany, UK, and Japan [34], representing between 1.35 and 2.92% of the included countries' gross domestic product. Moving forward, adoption of an integrative approach that considers the interplay between sleep and physical activity stands to improve our current understanding of their interactive influence on mental health.

While several works have examined independent associations between sleep, physical activity, and mental health [13], or how sleep is affected by the joint effects of mental health and physical activity [35], very few have focused on the interactive associations of sleep and physical activity with mental health. Most studies to date have focused on children and youth [36–40], and only a few addressing young [41] and middle-aged to older adults [42]. Despite the dearth of evidence, existing studies point to a consistent trend: individuals who engage in low levels of physical activity and accrue inadequate amounts of sleep often report worse mental well-being and are at a higher risk of mental disorders. Moreover, these studies suggest that increased physical activity can mitigate the negative effects of poor sleep on mental health and vice versa. However, the literature is constrained by its narrow scope, often examining physical activity and sleep as binary variables characterized as adequate/inadequate amounts based on public health guideline recommendations [43–47], which fails to consider a substantial portion of the variability in these behaviors. These limitations underscore the need for future research to explore these associations among larger and more age-diverse adult samples, while also considering ranges of physical activity and sleep levels beyond binary categorizations.

The challenge of accurately assessing mental health in relation to physical activity and sleep is compounded by the limitations of current mental health instruments. Predominantly developed for diagnosing specific mental disorders [48, 49], these tools often fail to capture the complexity and heterogeneity across these constructs such as the considerable overlap in symptomatology observed across the most common disorders [50, 51]. Further, instruments developed for assessing mental disorders focus narrowly on symptoms of ill-being without considering the broader spectrum of mental health. This approach has led to a skewed understanding. Prioritizing dysfunction over well-being has made it challenging to distinguish the boundary between normal mental health and clinical disorders given that many common mental health symptoms, such as sadness, anxiety, and risk-taking, are also part of normal mental functioning [52–55]. To address this, innovative tools like the Mental Health Quotient (MHQ) have been developed for implementation among the general population, offering a more holistic view of mental health that encompasses both facets of the dual continua model—clinical dysfunction and positive mental attributes—and represents one's overall mental health as a single score spanning along a spectrum from clinical to thriving. Using instruments such as the MHQ can provide a more comprehensive understanding of the impacts of physical activity and sleep on mental health which could potentially guide the development of public health promotion strategies. Yet, the novelty of these instruments may explain their underutilization to this point.

Another existing knowledge gap relates to whether the joint effects of physical activity and sleep may provide additional benefits for individuals receiving mental health treatment compared to those who are not. Assuming individuals receiving mental health treatment have been diagnosed with a mental disorder, this relationship deserves attention given the high rates of physical inactivity [56] and poor sleep [29] observed among this population. From this perspective, these individuals may have the potential to benefit more from engaging in a healthier lifestyle compared to their non-clinical peers. A recent study by Chekroud et al. [57] supports this idea, having found a more pronounced beneficial effect of exercise on monthly mental health burden among adults who were previously diagnosed with depression than those who had not been diagnosed with depression. Such information has implications that span beyond the general population as we seek to identify alternative approaches to improve the mental health of individuals receiving treatment for psychological distress or other mental disorders.

The primary purpose of the present study was to examine the independent and joint associations of physical activity and sleep in relation to mental health among a global sample of adults. Considering individuals receiving mental health treatment may have the poorest mental health or may be most likely to experience a mental disorder, we also examined the potential interactive influence of mental health treatment status (MHTS). We hypothesized that greater frequencies of adequate sleep and physical activity engagement would be independently associated with more favorable scores for mental health and a synergistic interaction would be observed between sleep and physical activity in relation to mental health. Based on previous research that has shown exercise may be more beneficial for individuals with a previous depression diagnosis than those without [57], we predicted that the independent and interactive benefits of increasing frequencies of adequate sleep and physical activity engagement would be more pronounced among individuals currently receiving mental health treatment than those who are not.

## Methods

### Study Sample and Data Collection

This study used cross-sectional data from the Mental Health Million (MHM) project. The MHM project is an on-going study seeking to assess the mental well-being of the global population. Initial recruitment targeted the English-speaking population living in the USA, UK, Canada, South Africa, Singapore, Australia, New Zealand, and India, and later expanded to include Spanish and French speakers as well as other countries for the purpose of capturing a broader global sample. Participants were recruited through targeted advertising on Google and Facebook which sought to capture adults over the age of 18 within each age-gender demographic. Recruitment via Google Ads targeted individuals who searched for topics related to mental health assessments and tests, whereas Facebook recruitment targeted all adults on the platform with the tagline "What is your mental well-being score?" as well as individuals who searched for topics related to mental health and well-being more broadly. Data collection using the online Mental Health Quotient (MHQ) assessment took ~15 min and participation was voluntary. The sample for the present study included a total of 220,324 participants from 214 countries, territories, and archipelagos who completed the MHM from April 9, 2020, to November 21, 2021.[1] Previously established MHM data cleaning and exclusion criteria were applied [58]: individuals who found

[1] For analytic purposes, we included responses up until the release of the Arabic version of the MHQ in November 2021 as not all Arabic responses were translated into English. Pilot data collected prior to April 9, 2020, was collected using prior versions of the MHQ (versions 1.1, 1.2, 1.3) and therefore excluded. Additionally, a new version of the MHQ was launched in January 2022; and therefore, only responses on versions 2.0 through 2.8 of the MHQ were included.

the assessment hard to understand ($n$ = 6873), reported unusual or unrealistic responses such as stating they had not eaten for > 16 h ($n$ = 6187) or slept for > 16 h the previous evening ($n$ = 167), and took < 7 min or > 1 h to complete the assessment, which was viewed as an indication of limited focus on the questions and their responses ($n$ = 13,227). This resulted in a final analytic sample of 200,743 participants from 213 countries, territories, and archipelagos. Representation across the 213 countries, territories, and archipelagos ranged from one participant in 15 locations (Burundi, Congo, Eritrea, Ethiopia, Liechtenstein, Monaco, Montserrat, Saint Helena/Ascension/Tristan da Cunha, Samoa, American Samoa, Svalbard, The Gambia, Tonga, Turks and Caicos Islands, Tuvalu) to 37,910 participants in India. Informed consent was obtained from all individual participants included in the study. All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards.

## Measures

### Physical Activity

Participants responded to a single item that asked: "How regularly do you engage in physical exercise (30 minutes or more)?" Response options included "Rarely/never"; "Less than once a week"; "Once a week"; "Few days a week"; and "Every day".

### Sleep

Participants responded to a single item that asked: "In general, I get as much sleep as I need." Response options included "Hardly ever"; "Some of the time"; "Most of the time"; and "All of the time".

### Mental Health

Participants completed the MHQ, which is a 47-item web-based assessment tool that captures 47 elements of mental health, spanning both mental health problems and assets [58]. Research has shown that the MHQ is a valid and reliable tool for assessing mental health and well-being [59]. This tool was developed based on coding of symptoms from 126 commonly used mental health assessment tools for assessing 10 different disorders: depression, anxiety, bipolar disorder, attention-deficit/hyperactivity disorder, post-traumatic stress disorder, obsessive compulsive disorder, addiction, schizophrenia, eating disorder, and autism spectrum disorder [60]. Given the homogeneity in symptoms assessed by tools within (29–58%) and across specific disorders (60% in at least half of all disorders) [60], the MHQ represents a standardized assessment tool that spans the full continuum of mental health symptoms akin to the dual continuum model put forth previously by Keyes [11].

Participants' responses for the 47 items were used to create an aggregate score on a spectrum ranging from −100 to +200,[2] with negative scores representing elevated risk of a clinical disorder. Scores can be classified into six categories ranging from Clinical to Thriving: Clinical (≤−50), At Risk (−50 to <0), Enduring (0 to <50), Managing (50 to <100), Succeeding (100 to <150), and Thriving (150 to 200).

### Covariates

Covariates were selected based on known [61–65] and hypothesized associations with physical activity, sleep, and indicators of mental health. These included age (within bounded ranges), gender, employment, education level, frequency of in-person social interactions with friends, medical condition diagnoses (yes/no), whether they are currently receiving mental health treatment (yes/no), whether they have experienced major trauma in their life (yes/no), and whether they have experienced any health or financial impacts from the COVID-19 pandemic (yes/no). These variables will be referred to as the full covariate set. All items in which participants responded "Prefer not to say" were recoded as missing for multiple imputation purposes.

### Data Inspection

Missingness ranged from 0% for physical activity and mental health to 9.2% for sleep (see Table 1). Missingness for sleep was associated with other observed variables (e.g., more missingness among individuals who identify as non-binary or third gender, did not graduate high school, were unemployed), which led us to consider data missing at random and use multiple imputation to preserve our sample size.

### Data Analysis

All analyses were performed in R (Version 4.1.1) and R Studio (Version 2022.02.3).

First, we inspected the data for missingness using the *mice* package [66]. Data were considered missing at random and multiple imputation by chained equations was conducted using the *mice* package to replace missing values. Multiple

[2] A small proportion of MHQ scores fall below - 100 due to the way that the MHQ score algorithm is calculated. This procedure ensures that the negative MHQ scores are more evenly distributed across the negative score window.

**Table 1** Descriptive statistics

| Overall sample: $N = 200{,}743$ | *N* (%) | Missing |
|---|---|---|
| Gender | | 10,113 (5.0%) |
| Female | 115,684 (57.6%) | |
| Male | 73,165 (36.4%) | |
| Other | 1781 (0.9%) | |
| Age (years) | | 0 (0%) |
| 18–24 | 43,491 (21.7%) | |
| 25–34 | 23,022 (11.5%) | |
| 35–44 | 21,144 (10.5%) | |
| 45–54 | 30,016 (15.0%) | |
| 55–64 | 40,432 (20.1%) | |
| 65–74 | 31,106 (15.5%) | |
| 75–84 | 10,279 (5.1%) | |
| 85+ | 1253 (0.6%) | |
| Education | | 8742 (4.0%) |
| Less than high school | 14,172 (7.1%) | |
| High school | 60,155 (30.0%) | |
| Undergraduate degree | 56,482 (28.1%) | |
| Vocational training | 13,594 (6.8%) | |
| Graduate degree | 34,493 (17.2%) | |
| Other | 14,141 (7.0%) | |
| Employment | | 0 (0%) |
| Studying | 33,760 (16.8%) | |
| Employed | 87,628 (43.7%) | |
| Homemaker | 12,264 (6.1%) | |
| Retired | 44,549 (22.2%) | |
| Unable to work | 6041 (3.0%) | |
| Unemployed | 16,501 (8.2%) | |
| Mental health quotient[a] | 69.0 (73.3) | 0 (0%) |
| Currently receiving mental health treatment (yes) | 43,239 (21.5%) | 4750 (2.4%) |
| Weekly adequate sleep frequency | | 18,551 (9.2%) |
| Hardly ever | 25,563 (12.7%) | |
| Some of the time | 61,580 (30.7%) | |
| Most of the time | 73,832 (36.8%) | |
| All of the time | 21,217 (10.6%) | |
| Weekly exercise frequency | | 0 (0%) |
| Rarely/never | 59,290 (29.5%) | |
| Less than once a week | 27,656 (13.8%) | |
| Once a week | 19,514 (9.7%) | |
| Few days a week | 59,398 (29.6%) | |
| Every day | 34,885 (17.4%) | |
| Frequency of socializing | | 0 (0%) |
| Rarely/never | 47,040 (23.4%) | |
| 1–3 times/month | 48,592 (24.2%) | |
| Once a week | 43,430 (21.6%) | |
| Several days a week | 61,681 (30.7%) | |
| Medical condition diagnosis (yes) | 50,191 (25.0%) | 8759 (4.4%) |
| Experienced previous trauma (yes) | 151,220 (75.3%) | 14,747 (7.3%) |
| Finances affected by COVID-19 pandemic (yes) | 68,904 (34.3%) | 8491 (4.2%) |
| Health affected by COVID-19 pandemic (Yes) | 71,897 (35.8%) | 8491 (4.2%) |

[a]Mean and SD presented

imputation is considered a best practice for handling missing data [67]. A total of 10 multiply imputed datasets were created as per recommendations to set $m > 100$ times the highest fraction of missing information [68]. All variables specified in the analytical models were included in the imputation model. Life satisfaction was also included to help strengthen the imputation model based on hypothesized correlations with MHQ values.

For our primary purpose, a series of generalized linear mixed regression models were computed to examine the independent and joint effects of sleep and physical activity on mental health. All models were adjusted for the full covariate set. The *survey* package was used to handle the nested structure of the MHM dataset in all analyses (participants nested within countries, territories, and archipelagos) [69]. Since ordinary least squares regression estimates are sensitive to outliers and highly influential observations, a robust estimator was employed to reduce the influence of these observations. This approach decreases the weights of observations with large residuals to reduce their influence on model estimates and performs well when there is a strong suspicion of heteroscedasticity. Each observation (level 1) in the dataset was nested within country (level 2) and given an equivalent weight of 1. In all models, the least healthy option (e.g., "Rarely/never" for physical activity, "Hardly ever" for sleep) or a combination of options in the interaction models (e.g., "Rarely/never" for physical activity and "Hardly ever" for sleep) was set as the referent. Beta estimates and 95% confidence intervals were calculated.

Estimated marginal means were computed from the regression models and Tukey's post hoc tests were used to compare each level of sleep and physical activity to the levels below and above it (e.g., "Rarely/never" versus "Less than once a week"; "Less than once a week" versus "Once a week") for each behavior independently, and each level physical activity to the levels below and above it within each level of sleep for the interaction models (see Supplementary Files 1). Given that regression models specifying an interaction between two ordinal predictors simply provide beta coefficients for all possible combinations of the variables (a total of 20 in the case of the present study) in contrast to a single referent level, we computed an ANOVA of each regression model (e.g., physical activity, sleep, physical activity × sleep), which treats each predictor as continuous to enhance interpretation. Doing so aided with the interpretation of the main and interaction effects by providing a single statistical value (term) to determine whether these effects met the criteria for statistical significance, which was set at $\alpha < .05$. It should be noted, however, that visual inspection of the residuals versus fitted plots suggested potential violations of the linearity assumption for the ANOVA models, which led us to compute *F*-tests to determine whether models with a quadratic term provided a superior fit over the linear models for physical activity and sleep. Findings indicated the models with non-linear (i.e., quadratic) terms provided a significantly better fit for the physical activity and sleep data; and thus, quadratic terms were specified for physical activity and sleep in the ANOVA of each regression model.

Our secondary purpose related to the potential influence of MHTS on the independent and joint associations between sleep and physical activity in relation to mental health. We conducted a series of follow-up analyses in which MHTS was added as an interactive term in each of the aforementioned models and followed the same analytical procedures.

## Results

### Descriptive Statistics

Descriptive statistics for the sample demographic characteristics, physical activity, sleep, and mental health are presented in Table 1. Skewness (− 0.34) and kurtosis (2.07) for the MHQ were within acceptable standards (± 3) [70].

### Physical Activity

Figure 1 visually displays the beta coefficients for each level of physical activity engagement in relation to overall MHQ values. The regression table with beta coefficients and 95% CIs is presented in Supplementary Materials Table 1. An ANOVA of the generalized linear mixed model for the independent effect of physical activity on overall MHQ demonstrated a significant main effect ($F_{(2,\ 200{,}686)} = 2565.45$, $p < 0.001$), in which increasing frequency of physical activity engagement was associated with more favorable scores. Tukey's post hoc tests revealed significant differences between each level of physical activity (all $p$'s $< 0.001$), except for "Few days a week" and "Every day" ($p = 0.20$), thus suggesting a plateau effect.

Figure 2 visually displays the beta coefficients for each level of physical activity engagement in relation to overall MHQ values by MHTS. The regression table with beta coefficients and 95% CIs is presented in Supplementary Materials Table 2. An ANOVA of the physical activity × MHTS generalized linear mixed model revealed significant main effects of physical activity ($F_{(2,\ 200{,}694)} = 602.70$, $p < 0.001$) and MHTS ($F_{(1,\ 200{,}696)} = 1719.38$, $p < 0.001$) as well as a significant physical activity × MHTS interaction ($F_{(1,\ 200{,}680)} = 31.03$, $p < 0.001$) in relation to overall MHQ. Greater frequency of physical activity engagement was associated with more favorable scores for overall MHQ across both groups, although scores for overall MHQ were considerably lower among those currently receiving mental health treatment. The beneficial association between physical activity and mental health

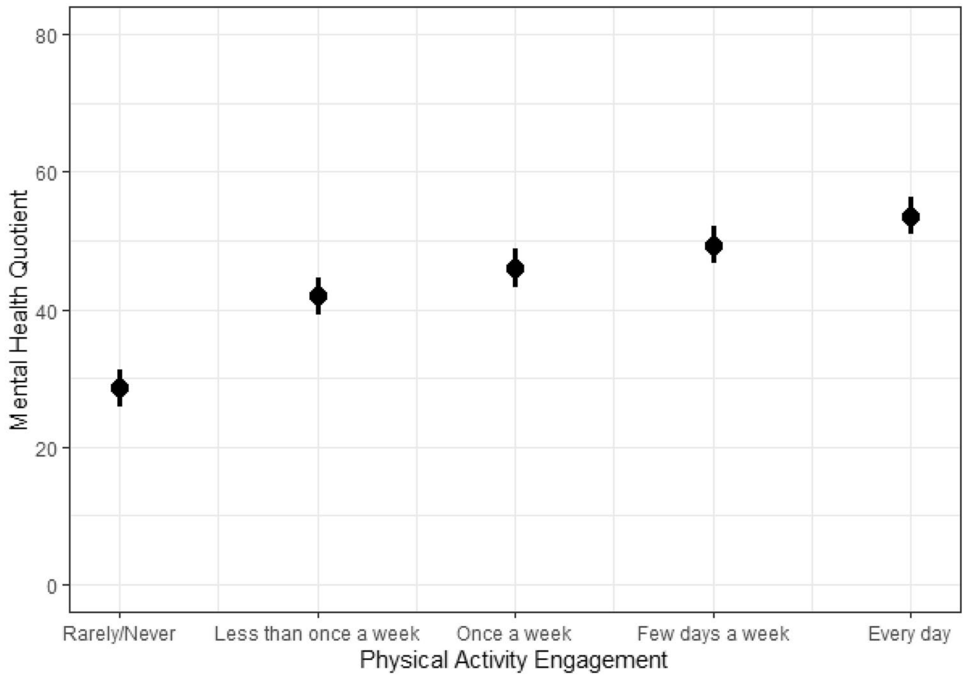


**Fig. 1** Beta coefficients with 95% CIs for the regression model examining each level of physical activity engagement in relation to the Mental Health Quotient. Values are based on adjustment for age (18–24), gender (female), education (undergraduate degree), employment (employed), frequency of socialization (once a week), medical condition (no), mental health treatment (no), major life trauma (no), health impacted by COVID-19 (no), and financially impacted by COVID-19 (no)

appears to be stronger for individuals not currently receiving mental health treatment. Tukey's post hoc contrasts revealed significant differences between each level of physical activity regardless of MHTS (all $p$'s $< 0.001$), although a plateau effect was observed for those currently receiving mental health treatment in that increasing physical activity beyond "Less than once a week" appears to provide minimal additional benefit.

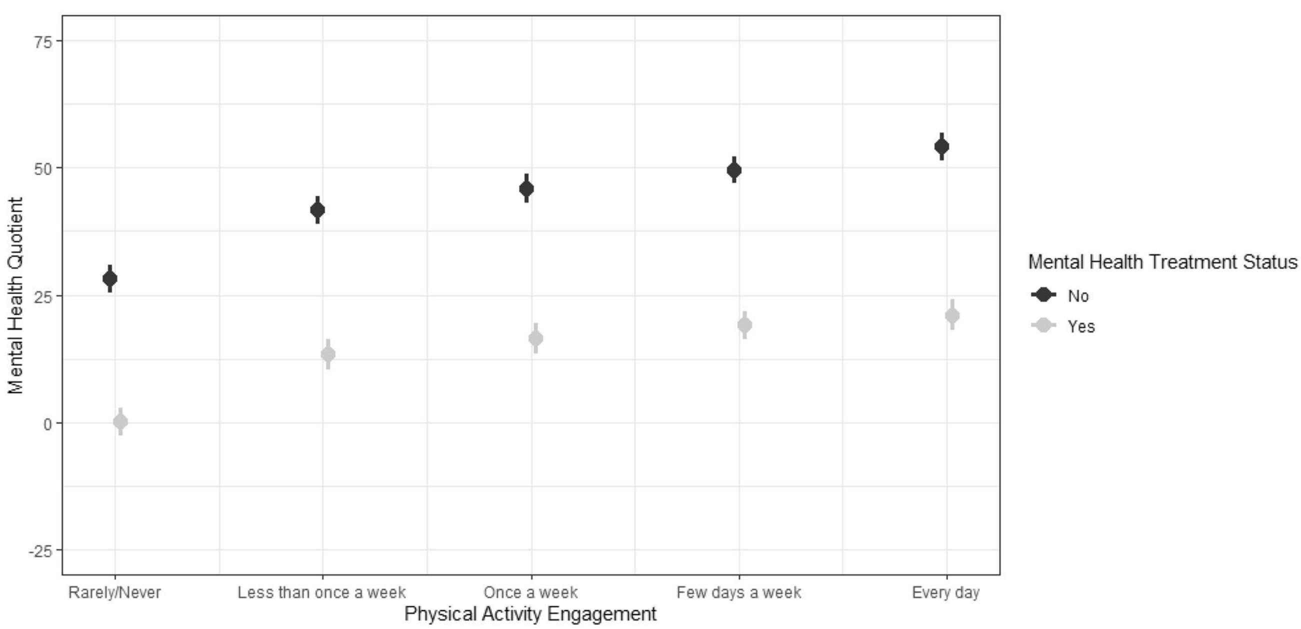


**Fig. 2** Beta coefficients with 95% CIs for the regression model examining each level of physical activity engagement in relation to the Mental Health Quotient by mental health treatment status. Values are based on adjustment for age (18–24), gender (female), education (undergraduate degree), employment (employed), frequency of socialization (once a week), medical condition (no), major life trauma (no), health impacted by COVID-19 (no), and financially impacted by COVID-19 (no)

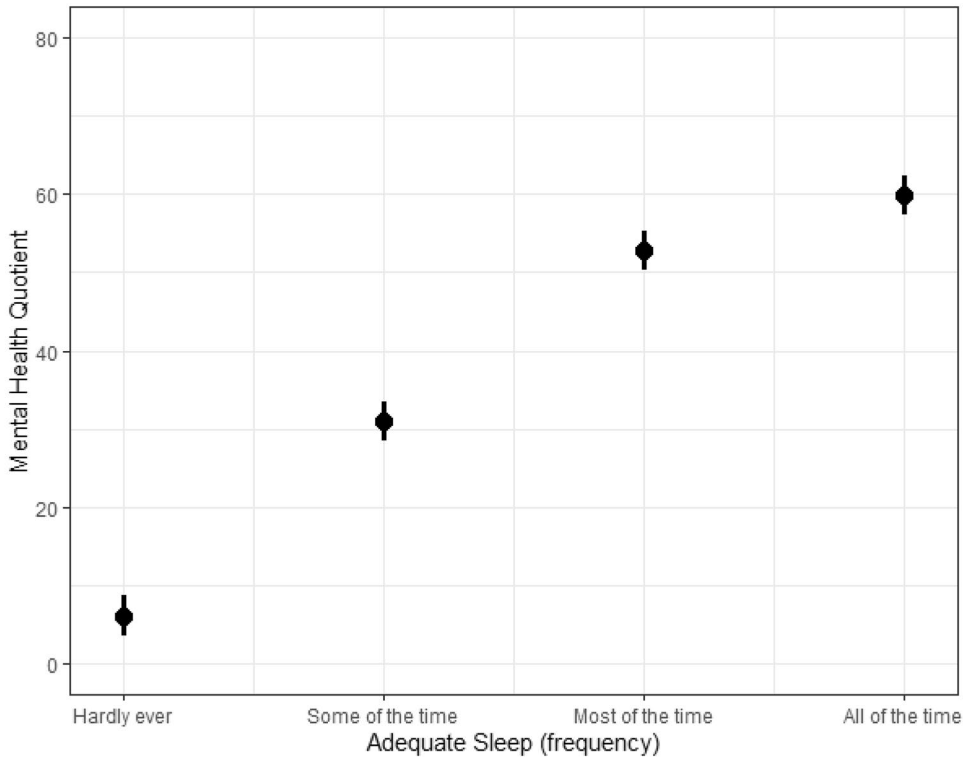


**Fig. 3** Beta coefficients with 95% CIs for the regression model examining each level of adequate sleep frequency in relation to the Mental Health Quotient. Values are based on adjustment for age (18–24), gender (female), education (undergraduate degree), employment (employed), frequency of socialization (once a week), medical condition (no), mental health treatment (no), major life trauma (no), health impacted by COVID-19 (no), and financially impacted by COVID-19 (no)

## Sleep

Figure 3 visually displays the beta coefficients for each level of adequate sleep frequency in relation to overall MHQ values. The regression table with beta coefficients and 95% CIs is presented in Supplementary Materials Table 3. An ANOVA of the generalized linear mixed model for the independent effect of sleep on overall MHQ demonstrated a significant main effect ($F_{(2, 200,698)}$= 9038.90, $p < 0.001$), in which greater frequency of adequate sleep was associated with more favorable scores. Tukey's post hoc tests revealed significant differences between each level of sleep (all $p$'s < 0.001).

Figure 4 visually displays the beta coefficients for each level of adequate sleep frequency in relation to overall MHQ values by MHTS. The regression table with beta coefficients and 95% CIs is presented in Supplementary Materials Table 4. An ANOVA of the sleep × MHTS generalized linear mixed model revealed significant main effects of sleep ($F_{(2, 200,686)} = 2428.03$, $p < 0.001$) and MHTS ($F_{(1, 200,685)} = 583.75$, $p < 0.001$) as well as a significant sleep × MHTS interaction ($F_{(1, 200,678)} = 84.73$, $p < 0.001$) in relation to overall MHQ. Greater frequency of adequate sleep was associated with more favorable scores for overall MHQ across both groups, although scores were considerably lower among individuals currently receiving mental health treatment. The beneficial association between sleep and overall MHQ appears to be stronger for individuals not currently receiving mental health treatment. Tukey's post hoc tests revealed significant differences between each level of sleep regardless of MHTS (all $p$'s < 0.001), although a plateau effect was observed for those currently receiving mental health treatment at the highest levels of sleep (i.e., going from "Most of the time" to "All of the time").

## Physical Activity × Sleep Interaction

Figure 5 visually displays the beta coefficients for each level of physical activity engagement in relation to overall MHQ values by each level of sleep. The regression table with beta coefficients and 95% CIs is presented in Supplementary Materials Table 5. Results from an ANOVA of the physical activity × sleep generalized linear mixed model revealed significant main effects of physical activity ($F_{(2, 200,683)} = 212.64$, $p < 0.001$) and sleep ($F_{(2, 200,681)} = 2082.61$, $p < 0.001$) as well as a significant sleep × physical activity interaction ($F_{(1, 200,673)} = 129.12$, $p < 0.001$) in relation to overall MHQ. Greater frequencies of adequate sleep and physical activity were associated with more favorable scores for overall MHQ and these associations appear to become more beneficial with healthier combinations of sleep and physical activity behavior. For the most part ($p < 0.05$ for 162/190 contrasts), healthier combinations of sleep and physical activity were associated with greater MHQ scores. Non-significant contrasts were generally observed when one behavior was held constant and the other increased one level (e.g., physical activity = "Rarely/never" and sleep = "Most

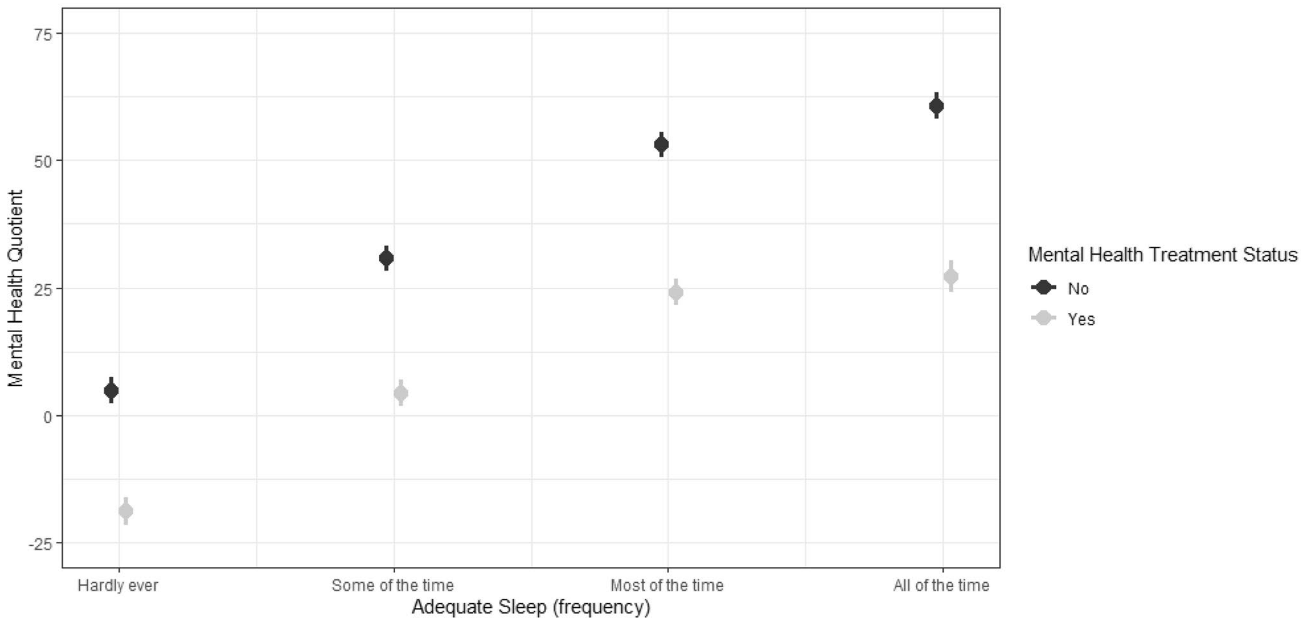


**Fig. 4** Beta coefficients with 95% CIs for the regression model examining each level of adequate sleep frequency in relation to the Mental Health Quotient by mental health treatment status. Values are based on adjustment for age (18–24), gender (female), education (undergraduate degree), employment (employed), frequency of socialization (once a week), medical condition (no), major life trauma (no), health impacted by COVID-19 (no), and financially impacted by COVID-19 (no)

of the time" versus physical activity = "Rarely/never" and sleep = "All of the time").

Figure 6 visually displays the beta coefficients for each level of physical activity engagement and sleep in relation to overall MHQ values by MHTS. The regression table with beta coefficients and 95% CIs is presented in Supplementary Materials Table 6. An ANOVA of the physical activity × sleep × MHTS generalized linear mixed model revealed significant

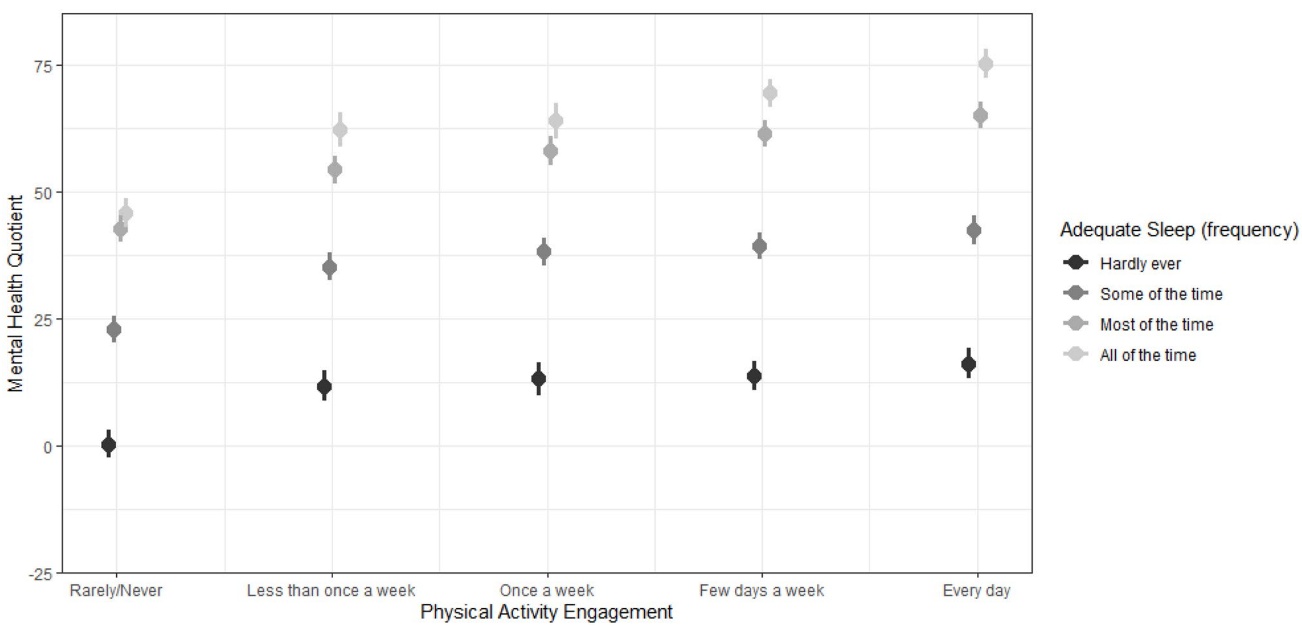


**Fig. 5** Beta coefficients with 95% CIs for the regression model examining each level of physical activity engagement in relation to mental health quotient by sleep. Values are based on adjustment for age (18–24), gender (female), education (undergraduate degree), employment (employed), frequency of socialization (once a week), medical condition (no), major life trauma (no), mental health treatment (no), health impacted by COVID-19 (no), and financially impacted by COVID-19 (no)

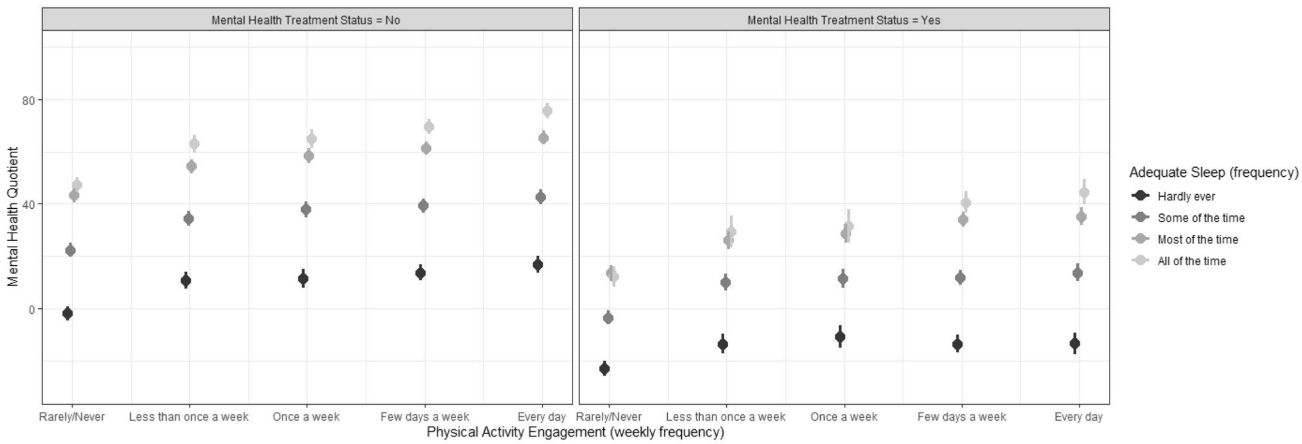


**Fig. 6** Beta coefficients with 95% CIs for the regression model examining each level of physical activity engagement in relation to mental health quotient by adequate sleep frequency and mental health treatment status. Values are based on adjustment for age (18–24), gender (female), education (undergraduate degree), employment (employed), frequency of socialization (once a week), medical condition (no), major life trauma (no), health impacted by COVID-19 (no), and financially impacted by COVID-19 (no)

main effects of physical activity ($F_{(2, 200,678)} = 229.29$, $p <$ 0.001), sleep ($F_{(2, 200,677)} = 1884.78$, $p <0.001$), and MHTS ($F_{(1, 200,675)} = 64.36$, $p < 0.001$) on overall MHQ. The results also demonstrated significant interactive effects of physical activity × sleep ($F_{(1, 200,665)} = 47.71$, $p < 0.001$), sleep × MHTS ($F_{(1, 200,669)} = 65.91$, $p < 0.001$), physical activity × MHTS ($F_{(1, 200,662)} = 32.03$, $p < 0.001$), and physical activity × sleep × MHTS ($F_{(1, 200,664)} = 25.53$, $p < 0.001$) in relation to overall MHQ. In brief, greater frequencies of adequate sleep and physical activity were associated with more favorable scores for overall MHQ, which was generally supported by the post hoc contrasts, although the benefits of healthier combinations of sleep and physical activity appear to be stronger for individuals not receiving mental health treatment.

Post hoc contrasts revealed minimal additional benefits of greater physical activity engagement beyond "Less than once a week" for those currently receiving mental health treatment who get the lowest levels of adequate sleep (i.e., "Hardly ever" or "Some of the time). Further, the favorable benefits of greater physical activity engagement were less pronounced at the highest levels of adequate sleep frequency among those currently receiving mental health treatment.

## Discussion

The present study was the first to examine the interactive effect of physical activity and sleep in relation to mental health among a global sample of adults using a novel comprehensive mental health instrument that captures both dimensions of Keyes' [11] dual continua model of mental health and illness within a single score. Findings revealed independent dose-response associations whereby greater amounts of physical activity and frequency of adequate sleep were each associated with better mental health. Furthermore, a synergistic interaction was observed in which increasingly healthier combinations of physical activity and adequate sleep were associated with more favorable mental health scores, and these benefits appear to be more pronounced among adults not currently receiving mental health treatment. These findings were consistent across each subdomain of the MHQ. While results suggest that greater frequency of adequate sleep can help to offset the negative influence of a physically inactive lifestyle on mental health (and vice versa), evidence points to a "more is better" approach for both behaviors when it comes to promoting mental health. Collectively, these findings contribute to the dearth of studies investigating the interactive influence of sleep and physical activity on mental health and provide further support for the potential of behavioral medicine to buffer the toll on mental health experienced by many in our society.

Sleep and physical activity together have garnered more recent attention for their potential joint effects on mortality [71–74], risk of chronic disease [75–77], and other outcomes such as academic achievement [78]. The present study contributes to the dearth of evidence investigating these associations with mental health and well-being using the largest sample to date. Using a global sample of over 200,000 adults from 213 countries, our results support the synergistic effect from physical activity and sleep on mental health. Specifically, mental health scores were positively associated with greater weekly physical activity and that these relationships were strengthened with greater frequency of adequate sleep, which support previous findings [36–40, 42]. Also consistent with these studies is that the lowest scores for mental health were observed among adults who were physically inactive and hardly ever accrued adequate sleep (i.e., the least healthy combination). Accruing adequate sleep each night and exercising everyday (i.e., the healthiest combination), in contrast, was associated with an 71-point increase in mental health, which on the MHQ spectrum would be equivalent to improving by two categories (e.g., from At Risk to Managing). These findings speak to the potency of healthy active lifestyles and highlight the potential value of developing interventions that adopt integrative whole day approaches to improve mental health through physical activity and sleep concurrently.

Contrary to our hypothesis based on previous research [57], the interactive benefits of physical activity and sleep were more pronounced among adults not currently receiving mental health treatment than those receiving treatment. Closer inspection of the data revealed a plateau effect for the benefits of adequate sleep frequency at “most nights” among adults enrolled in mental health treatment, whereas a dose-response relationship was observed among those not receiving mental health treatment. Beyond the inclusion of sleep as an interaction term in the present study, one reason for the discrepancy in findings to those of Chekroud et al. [32] is the characterization of the poor mental health groups. Chekroud et al. used previous diagnosis of depression to identify this group based on the assumption that it would be strongly associated with mental health burden. Comparatively, the MHQ survey did not include measures of previous mental health disorder diagnosis, and therefore based a mental health disorder from whether an individual reported they are currently receiving mental health treatment. However, it is estimated that only 40% of people diagnosed with a mental health disorder seek treatment in the 12 months around the time of the disorder or distress [79, 80]. Furthermore, it is plausible that accessing treatment might be a sign of symptom severity in that seeking help is increasingly likely among the most severe cases [81]. From this perspective, our sample of individuals receiving mental health treatment may not be representative of all those who have been diagnosed with a mental disorder, and potentially skew to more severe cases. Considering physical activity is recognized by several national guidelines as an alternative treatment for less severe forms of depression [82–85], the effects among individuals receiving mental health treatment in the present study may have been buffered due to the potential severity of their symptomology, or perhaps they are already experiencing benefits from their treatment and ceiling effects are occurring. Moving forward, researchers are strongly encouraged to include items pertaining to the presence and severity of mental disorders in future survey design. Such information will help to better understand who stands to benefit the most from engaging in healthier patterns of lifestyle behaviors.

Independent associations observed between physical activity and sleep with mental health also support what has been found in their respective bodies of literature in that dose-response relationships were found [15, 32]. It is important to note that the most significant improvements for mental health were observed when increasing from never/hardly ever engaging in physical activity or getting adequate rest to the next amount (e.g., some of the time for sleep, less than once a week for physical activity). Further benefits were observed with increasing amounts of sleep and physical activity, but the magnitude of the improvements began to dissipate. These findings align with previous work investigating associations between physical activity and morbidity and mortality [86]; supporting the notion that more is better not only for physical activity, but also when it comes to getting enough sleep. Moreover, it is well established that certain crucial sleep stages, such as slow-wave sleep (“deep sleep”), get priority over other important stages (e.g., rapid eye movement (REM) sleep) when the total amount of sleep an individual gets is less than the recommended daily amount [87]. In that respect, it is possible that participants reporting the least amount of adequate sleeping time have been especially lacking sufficient REM sleep— which, in turn, has long been associated with various mental disorders [33, 88, 89]. In light of these findings, public health messaging campaigns should also consider developing content specific to the importance of even slight increases in the frequency of nights that adults accrue adequate sleep. Small changes in frequency of adequate sleep and physical activity at the population-level could have significant ramifications in terms of reducing the economic impacts attributed to mental disorders [3, 4].

Despite the many strengths of the current study, it is not without limitations. First, a cross-sectional design was employed, which limits our understanding of the causal nature of the relationships between physical activity and sleep with mental health. While the present study focused on physical activity and sleep as correlates of mental health, it would be remiss to not acknowledge an alternative interpretation of the data—people with mental disorders tend to avoid physical activity [56] and report poorer sleep [29]. Longitudinal studies have provided insight into the temporal nature of the relationship between physical activity and sleep [90], but this work needs to be extended to include indicators of mental health to further unpack these potential bi-directional associations. For instance, network-based modeling approaches could be employed to examine how physical activity, sleep, and mental health interact over time as a complex dynamic system [91]. Second, sleep and physical activity were self-reported, which may introduce recall errors or social desirability bias [92]. Future large-scale studies could consider capitalizing on technology as consumer wearables that provide estimates of physical activity and sleep become increasingly ubiquitous in society. Third, the MHM project did not assess sedentary behavior; and therefore, we were unable to include the third component of the 24-h movement paradigm, which is also known to independently influence indicators of mental health [93–95]. Fourth, participants receiving mental health treatment were able to indicate the type(s) of treatment they were receiving (e.g., Cognitive Behavioral Therapy, Antidepressant/Anti-anxiolytic Medication, Yoga and/or Meditation); however, there was considerable variability in responses (i.e., 262,144 combinations of 18 possible responses) and missingness (> 20%). Further, many individuals who need mental health treatment worldwide lack access to high-quality services [96]; and thus, we decided to pool responses into a binary variable (yes/no) which fails to consider how physical activity and sleep may interact differently with various mental health treatments. Fifth, despite the strengths of multiple imputation as it relates to handling missing data, it is important to acknowledge that as the amount of missingness increases, estimates are more likely to become biased [97]. Finally, although the sample included a diverse global participant pool which included individuals from 213 countries, territories, and archipelagos, it should be acknowledged that convenience sampling through Google and Facebook was employed, which may limit the generalizability of the findings to the global population due to selection bias. Moreover, all data for the study was collected during the peak of the COVID pandemic, which potentially could further limit its generalizability.

In sum, the present study represents the first to explore joint associations between physical activity and sleep in relation to mental health among a broad sample of adults from 213 countries. Results demonstrated that inadequate amounts of physical activity and sleep are each inversely associated with mental health. Engaging in increasing amounts of physical activity is associated with favorable benefits for mental health and this relationship can be further strengthened with greater frequency of adequate sleep; however, these effects are less pronounced for adults receiving mental health treatment. Collectively, these findings highlight the potential potency for public health interventions to adopt approaches rooted in behavioral medicine to improve the overall mental health of the population.

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## Declarations

**Competing Interests** The authors declare no competing interests.

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