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Associations of “Weekend Warrior” Physical Activity With Incident Disease and Cardiometabolic Health

Shinwan Kany, MD, MSc; Mostafa A. Al-Alusi, MD; Joel T. Rämö, MD, PhD; James P. Pirruccello, MD;
Timothy W. Churchill, MD; Steven A. Lubitz, MD, MPH; Mahnaz Maddah, PhD; J. Sawalla Guseh, MD;
Patrick T. Ellinor, MD, PhD*; Shaan Khurshid, MD, MPH*

BACKGROUND: Achievement of guideline-recommended levels of physical activity (≥150 minutes of moderate-to-vigorous physical activity per week) is associated with lower risk of adverse cardiovascular events and represents an important public health priority. Although physical activity commonly follows a “weekend warrior” pattern, in which most moderate-to-vigorous physical activity is concentrated in 1 or 2 days rather than spread more evenly across the week (regular), the effects of physical activity pattern across a range of incident diseases, including cardiometabolic conditions, are unknown.

METHODS: We tested associations between physical activity pattern and incidence of 678 conditions in 89 573 participants (62±8 years of age; 56% women) of the UK Biobank prospective cohort study who wore an accelerometer for 1 week between June 2013 and December 2015. Models were adjusted for multiple baseline clinical factors, and *P* value thresholds were corrected for multiplicity.

RESULTS: When compared to inactive (<150 minutes moderate-to-vigorous physical activity/week), both weekend warrior (267 total associations; 264 [99%] with lower disease risk; hazard ratio [HR] range, 0.35–0.89) and regular activity (209 associations; 205 [98%] with lower disease risk; HR range, 0.41–0.88) were broadly associated with lower risk of incident disease. The strongest associations were observed for cardiometabolic conditions such as incident hypertension (weekend warrior: HR, 0.77 [95% CI, 0.73–0.80]; $P=1.2\times10^{-27}$; regular: HR, 0.72 [95% CI, 0.68–0.77]; $P=4.5\times10^{-28}$), diabetes (weekend warrior: HR, 0.57 [95% CI, 0.51–0.62]; $P=3.9\times10^{-32}$; regular: HR, 0.54 [95% CI, 0.48–0.60]; $P=8.7\times10^{-26}$), obesity (weekend warrior: HR, 0.55 [95% CI, 0.50–0.60]; $P=2.4\times10^{-43}$, regular: HR, 0.44 [95% CI, 0.40–0.50]; $P=9.6\times10^{-47}$), and sleep apnea (weekend warrior: HR, 0.57 [95% CI, 0.48–0.69]; $P=1.6\times10^{-9}$; regular: HR, 0.49 [95% CI, 0.39–0.62]; $P=7.4\times10^{-10}$). When weekend warrior and regular activity were compared directly, there were no conditions for which effects differed significantly. Observations were similar when activity was thresholded at the sample median (≥230.4 minutes of moderate-to-vigorous physical activity/week).

CONCLUSIONS: Achievement of measured physical activity volumes consistent with guideline recommendations is associated with lower risk for >200 diseases, with prominent effects on cardiometabolic conditions. Associations appear similar whether physical activity follows a weekend warrior pattern or is spread more evenly throughout the week.

Key Words: accelerometry ■ cardiovascular disease ■ physical activity ■ prevention ■ weekend warrior

Physical activity is generally regarded as favorable to health and is consistently associated with lower risks of death and incident disease.[1–3] World Health Organization and American Heart Association guidelines recommend ≥150 minutes of moderate-to-vigorous physical activity (MVPA) per week but do not provide

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Correspondence to: Shaan Khurshid, MD, MPH, Demoulas Center for Cardiac Arrhythmias and Cardiovascular Research Center, Massachusetts General Hospital, 55 Fruit St, GRB 109, Boston, MA 02114. Email skhurshid@mgb.org

*P.T. Ellinor and S. Khurshid contributed equally.

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Clinical Perspective

What Is New?

- Compared with inactivity, weekend warrior physical activity measured using wrist-worn accelerometers is associated with lower risk of 264 future diseases.
- There were no conditions for which there was a significant difference in the effects of weekend warrior versus regular activity.
- Associations between physical activity and lower risk of disease were particularly prominent for cardiometabolic conditions.

What Are the Clinical Implications?

- The total volume of physical activity, rather than the pattern, appears most relevant for risk of future disease.
- Concentrated physical activity interventions may be an effective public health tool for disease prevention, particularly for cardiometabolic conditions.

Nonstandard Abbreviations and Acronyms

FDR	false discovery rate
HR	hazard ratio
MVPA	moderate-to-vigorous physical activity

specific guidance on how MVPA should be accrued.[2,4] The UK National Health Service recommends MVPA be spread "evenly over 4–5 days per week, or every day."[5]

Although the optimal pattern of MVPA remains unclear, recent data suggest that concentrating most MVPA within 1 or 2 days of the week ("weekend warrior") is common[6] and may confer similar benefits to more regular activity for selected conditions.[7,8] Using self-reported physical activity data from >350 000 individuals in a prospective cohort study, weekend warrior and regular activity were each associated with similarly lower incidence of all-cause and cardiovascular mortality.[7] In a subsequent analysis leveraging physical activity data measured using wearable accelerometers, weekend warrior activity was again associated with comparably lower risks of incident atrial fibrillation, myocardial infarction, heart failure, and stroke compared with more evenly distributed guideline-adherent physical activity.[8]

Despite previous insights, the broader effects of weekend warrior activity on incident disease, as well as potentially important consequences on cardiometabolic health, remain poorly understood. Given the robust relationship between cardiometabolic factors and future cardiovascular disease, better characterization of how varying physical activity patterns may affect cardiometabolic and overall health is needed to inform future efforts aiming to leverage physical activity to improve public health.

Here, among nearly 90 000 participants of the UK Biobank prospective cohort study providing measured physical activity data from wrist-based accelerometers, we systematically assess associations between physical activity pattern and risk of >650 incident diseases spanning a broad spectrum of conditions.

METHODS

Participants provided informed consent. The UK Biobank was approved by the UK Biobank research ethics committee (reference No. 11/NW/0382). UK Biobank data was used under application 17488. This study follows STROBE (Strengthening the Reporting of Observational Studies in Epidemiology) reporting guidelines (see checklist in Supplemental Methods).

Cohort Description

The UK Biobank is a prospective cohort of 502 629 participants enrolled between 2006 and 2010.[9] Briefly, 9.2 million individuals 40 to 69 years of age living within 25 miles of 22 assessment centers in the United Kingdom were invited, and 5.4% participated in the baseline assessment. Within the physical activity measurement substudy, 103 695 participants submitted data from an Axivity AX3 (Newcastle upon Tyne, United Kingdom) wrist-based triaxial accelerometer worn for 1 week.[10] The sensor captured continuous acceleration at 100 Hz with dynamic range ±8*g*. As described previously, acceleration signals were calibrated to gravity.[10] Sample data were combined into 5-s epochs, each representing average vector magnitude. Non–wear-time was identified as consecutive stationary episodes ≥60 min in which all 3 axes had SD<13.0 mg.[10] Epochs representing non–wear-time were imputed on the basis of the average of similar time-of-day vector magnitude and intensity distribution data points on different days. We excluded individuals whose wear-time was insufficient to support imputation (ie, ≥1 1-hour period of the 24-hour cycle [eg, 0900–1000] during which no wear data were ever accrued), whose signals were insufficient for calibration or MVPA estimation, whose mean acceleration values were previously adjudicated as nonphysiological, and who contributed less than a full week of activity data.[8,11]

Activity Patterns

MVPA was classified using a published machine-learning–based method developed to categorize a broad range of activities (eg, walking, jogging, stationary cycling, elliptical, and others) and validated in a United Kingdom–based sample.[11] For our primary analysis, we defined active status at the guideline-based threshold (≥150 minutes/week).[2,4,8] Individuals were classified as inactive (below MVPA threshold), weekend warrior (at or above MVPA threshold and ≥50% of total MVPA over 1 to 2 days[6]), and regular (at or above MVPA threshold but not weekend warrior). Because optimal MVPA levels using wrist-based accelerometers are unclear,[12] in secondary analyses, we assessed alternative thresholds (outlined below).

Phenome-Wide Association Study

We investigated associations between physical activity pattern and incident disease using a phenome-wide association study approach, using Cox proportional hazards models with physical activity pattern (ie, weekend warrior, regular activity, or inactive) as the exposure of interest, and adjusted for age at activity measurement, sex, ethnic background, tobacco use, Townsend Deprivation Index, alcohol intake, educational attainment, employment status, self-reported health, and diet quality (definitions in Table S1). Covariates were selected a priori on the basis of known or suspected associations with physical activity and disease reported in previous literature as well as previous analyses of activity patterns in the UK Biobank.[1,8,11] In our models, the effect of physical activity pattern on a given disease was estimated as the hazard ratio and *P* value corresponding to the respective activity category (weekend warrior or regular) compared with the inactive referent. Subsequently, to assess whether risk of disease might differ for weekend warrior versus regular activity, we calculated hazard ratios and *P* values corresponding to weekend warrior activity using regular activity as the referent. Given baseline imbalances in total MVPA time between the weekend warrior and regular activity groups (Figure 1), and our intent to identify the potential effects of physical activity pattern for a given physical activity volume, all models directly comparing weekend warrior versus regular activity were in addition adjusted for total MVPA volume.[8] In secondary analyses, to assess whether the observed imbalance in MVPA volume may itself possess relevance for disease risk, we compared weekend warrior versus regular activity without adjustment for MVPA volume. The functional form of continuous covariates was assessed by fitting penalized splines (Supplemental Methods), and secondary models were fit to accommodate nonlinear effects when present (see below). All models used a complete case analysis (exclusions for missing data are shown in Figure 1).

To define outcomes, we used v1.2 of the Phecode Map,[13] comprising 1867 disease definitions organized into clinically relevant categories and defined using standardized sets of codes from the *International Classification of Diseases, Ninth Revision* and *Tenth Revision*. These Phecode definitions can be accessed at https://phewascatalog.org/. Sources of diagnostic codes encompassed hospital data obtained through linkage with national health-related datasets and outpatient general practitioner visit data accessed through electronic health records. To prevent model instability, only diseases with ≥120 events were tested (ie, ≥10 events per covariate), resulting in a total of 678 conditions included in association testing.[14] Given our interest in incident disease and the age distribution of the sample, we excluded Phecodes corresponding to pregnancy-related conditions and congenital anomalies. Significance thresholds were corrected for multiplicity to target a false discovery rate (FDR) of 0.01.[15] The FDR process corrects for multiple testing by controlling the expected proportion of incorrectly rejected null hypotheses (ie, false discoveries or type 1 errors). Here, we used a stringent threshold (FDR 0.01), which would be expected to result in only one false discovery per 100 associations detected. Further details are provided in the Supplemental Methods.

Follow-Up and Censoring

For analyses of incident disease, the assessment period commenced at the conclusion of physical activity measurement with accelerometry and concluded at the occurrence of an event, death, or last follow-up, whichever transpired first. Individuals were excluded from analysis of a particular incident disease if they met criteria for that disease at the time of accelerometer wear. The duration of follow-up was contingent upon the availability of linked health data, with a defined end date of March 31, 2021, for participants enrolled in England and Scotland, and February 28, 2018, for those enrolled in Wales. For reference, we tabulated the 5-year cumulative incidence, and person-time incidence rates, for all conditions included in association testing.

Secondary Analyses

To assess the robustness of our findings, we performed several secondary analyses. First, we repeated disease association testing using the sample median MVPA (≥230.4 minutes) as the threshold for activity, with the median chosen on the basis of United Kingdom national health surveys reporting that roughly half of individuals are physically active.[16] Second, to explore whether our findings may have been driven by reverse causation, we repeated association testing while excluding all events occurring within 2 years of physical activity measurement. Third, to quantify the robustness of observed associations to residual confounding, we calculated E-values, which represent the minimum strength of association on the risk ratio scale that a potential confounder would need to have with the exposure and outcome to nullify the observed association.[17] Fourth, we compared weekend warrior and regular activity without adjustment for MVPA volume. Fifth, we tested the following alternative definitions of weekend warrior activity: (1) ≥150 minutes of MVPA/week with ≥50% of total MVPA achieved over 1 or 2 consecutive days (rather than any 1 or 2 days of the week), (2) ≥150 minutes of MVPA/week with ≥50% of total MVPA achieved over 1 or 2 true weekend days, (3) ≥150 minutes of MVPA/week with ≥75% of total MVPA achieved over 1 or 2 days, and (4) ≥150 minutes of MVPA/week with ≥75% of total MVPA achieved over 1 or 2 consecutive days. Sixth, we performed analogous association testing for selected cardiometabolic factors of specific interest (ie, hypertension, diabetes, or obesity) using alternative definitions combining Phecodes with relevant anthropometric measurements, laboratory values, and medication use. Seventh, we fit models accounting for potential nonlinear relations between alcohol intake and MVPA with disease outcomes using spline terms. Eighth, to assess associations between MVPA volume and disease, we fit Cox proportional hazards models with 4 exemplar cardiometabolic factors of specific interest (ie, hypertension, diabetes, sleep apnea, and obesity) as outcomes and MVPA quartile as the main exposure, with adjustment for the same covariates as the primary analyses. Further details are provided in the Supplemental Methods.

Statistical Analysis

Analyses were performed using R v4.0. The proportional hazards assumption was assessed by performing the Grambsch-Therneau test of correlation[18] and inspecting smoothed fits of Schoenfeld residuals versus time (Supplemental Methods).

Data Availability

Data processing scripts used to perform the analyses described herein using UK Biobank data are available at https://github.com/shaankhurshid/weekend_warrior_phewas.

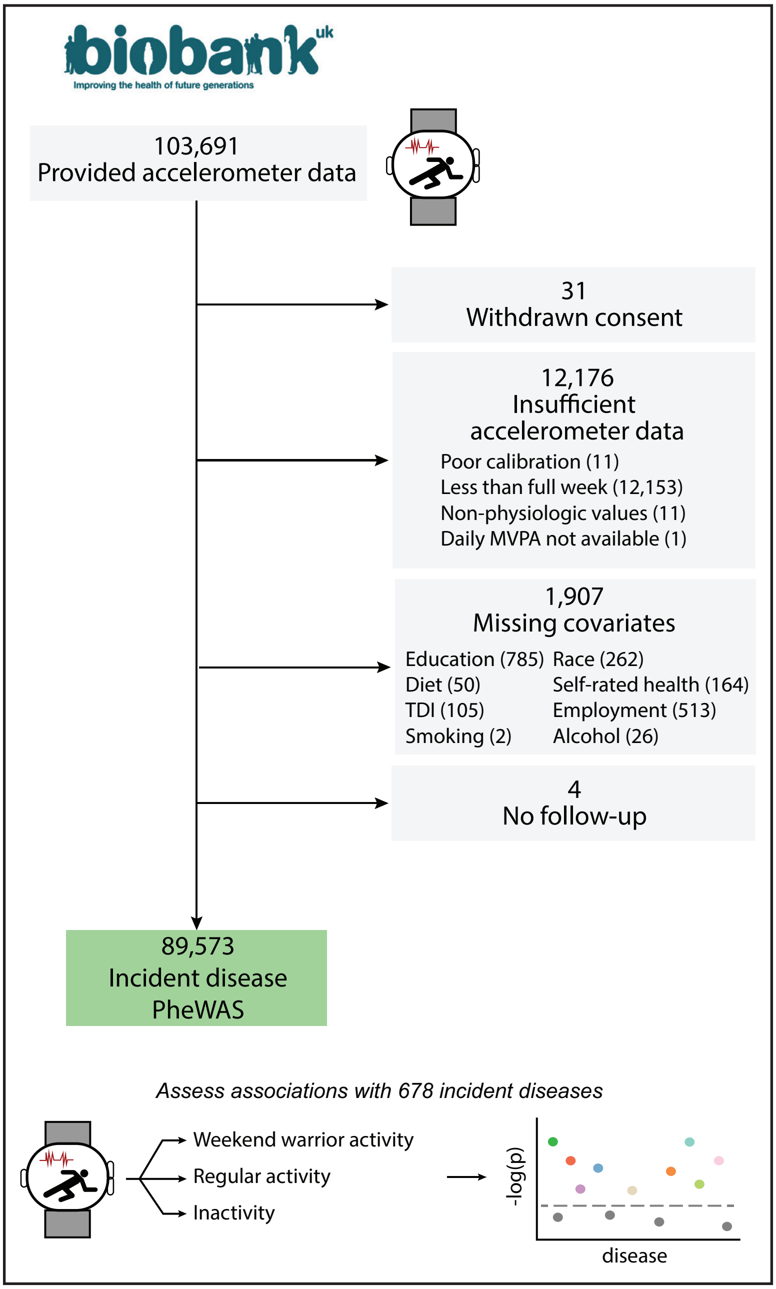

Figure 1. Study design.

Depicted is an overview of study design. In 89 573 UK Biobank participants providing 1 week of accelerometer data, we classified physical activity into 3 patterns (weekend warrior, regular activity, and inactive) using the guideline-based threshold of ≥150 minutes of moderate-to-vigorous physical activity (MVPA)/week,[2,4] and performed association testing with 678 incident diseases. PheWAS indicates Phenome-Wide Association Study; and TDI, Townsend Deprivation Index.

All UK Biobank data are available for researchers by application (https://www.ukbiobank.ac.uk/enable-your-research/apply-for-access).

RESULTS

Sample Characteristics

We performed incident disease phenome-wide association testing in 89 573 UK Biobank participants (62±8 years of age; 56% women) who underwent 1 week of physical activity measurement with a wrist-based accelerometer between June 8, 2013, and December 30, 2015 (Figure 1). Median follow-up was 6.3 years (quartile 1: 5.7, quartile 3: 6.8), and 94.2% of participants had ≥5 years of follow-up. Stratified at the guideline-based threshold of ≥150 minutes MVPA/week, a total of 30 228 participants were in the inactive group (33.7%), 37 872 were in the weekend warrior group (≥50% of total MVPA within 1 or 2 days; 42.2%), and 21 473 were in the regular group (no 1- or 2-day period with ≥50% of total MVPA; 24.0%). Total weekly MVPA achieved was highest for the regular group (median 418 minutes, quartile 1: 302, quartile 3: 605), followed by weekend warrior (288 minutes, quartile 1: 216, quartile 3: 432) and inactive (72 minutes, quartile 1: 29, quartile 3: 115; Figure 2). Weekend warriors were substantially more active on their 2 most active days of the week versus the remaining 5, whereas activity was more evenly distributed in the regular activity group (Figure 2). Baseline characteristics of the analysis sample are displayed in Table 1.

Phenome-Wide Associations of Activity Pattern With Incident Disease

Using multivariable Cox proportional hazards models testing 678 conditions (with ≥120 events, disease incidence rates provided in Table S2) and evaluated at a FDR of 0.01 (or 1%), both weekend warrior activity (267 significant associations [39% of all conditions tested], 264 with lower disease risk [99% of significant associations]; hazard ratio [HR] range, 0.35–0.89) and regular activity (209 associations [31%], 205 with lower disease risk [98%]; HR range, 0.41–0.88) were broadly associated with lower risk of incident disease (Figure 3; Table S3). Most of the significant associations represented circulatory (weekend warrior: 16.5% of all significant associations, regular: 14.4% of all significant associations), metabolic (14.2%, 13.9%), and digestive (12.0%, 13.4%) conditions, although associations spanned all 16 categories evaluated (Figure 3; Table S3). For both physical activity patterns, the small number of associations with higher disease risk primarily represented musculoskeletal conditions, injuries, and dermatologic conditions (eg, disorders of muscle, ligament, and fascia; Tables S3 and S4). Compared directly, there were no conditions for which risk differed significantly for weekend warrior versus regular activity at an FDR of 0.01, whether or not MVPA was included as an adjustment variable (Tables S5 and S6). Individual association test results for the weekend warrior and regular activity patterns, including individual effect sizes and E-values, are displayed in Tables S3, S5, and S6.

Associations Between Activity Pattern and Cardiometabolic Conditions

Across all conditions tested, associations between both weekend warrior and regular activity patterns and incident cardiometabolic conditions were particularly prominent (Figure 3). For example, among diseases with the strongest associations (ie, smallest *P* values), we observed

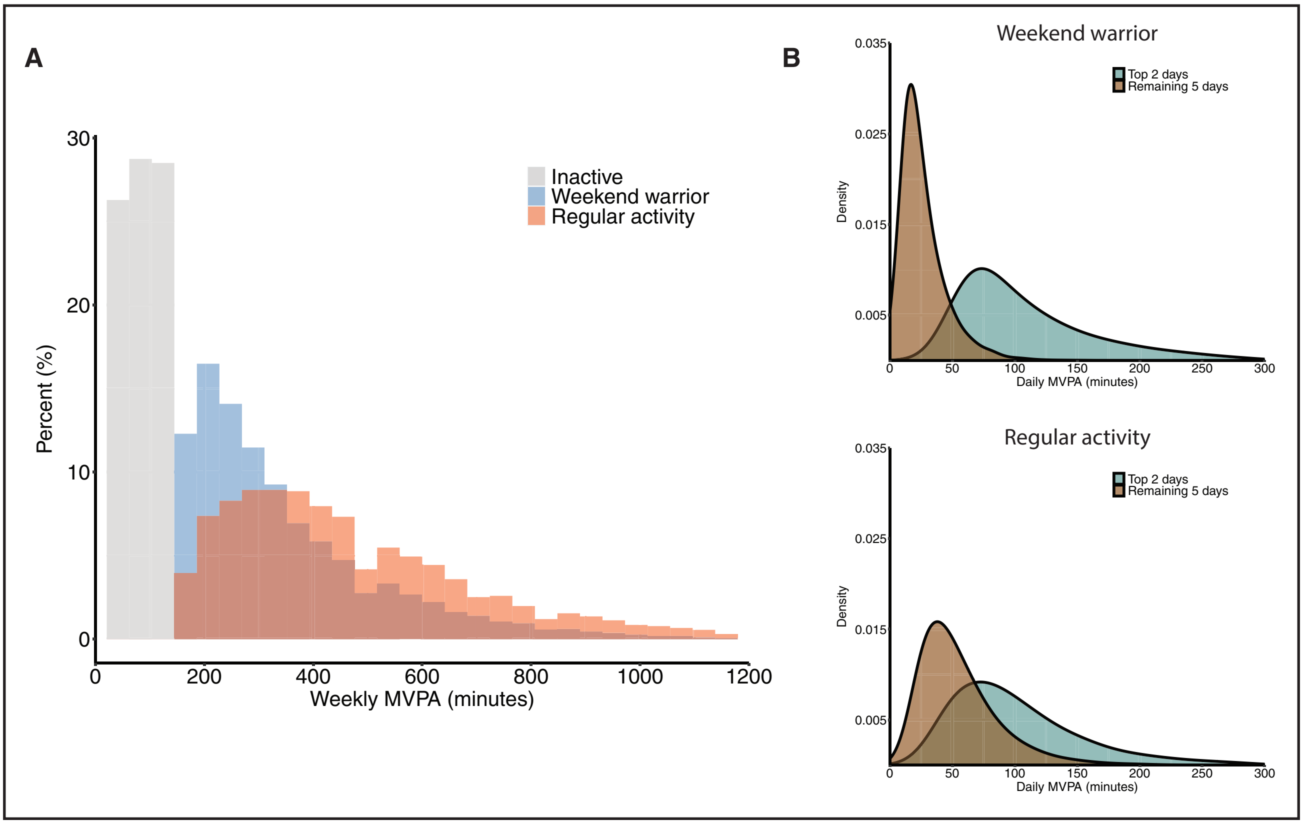

Figure 2. Distribution of MVPA time according to activity pattern.
A, Distribution of total moderate-to-vigorous physical activity (MVPA) minutes by activity pattern group measured with accelerometer (gray=inactive, blue=weekend warrior, and red=regular activity). **B**, Distribution of MVPA minutes in top 2 days (green) vs remaining 5 days (brown). **Top** depicts the weekend warrior group, and the **bottom** depicts the regular activity pattern group.

Table 1. Sample Characteristics

Baseline characteristics	Weekend warrior activity	Regular activity	Inactive*
n	37 872	21 473	30 228
Age	62.2 (7.7)	61.2 (7.9)	63.3 (7.9)
Women	19 325 (51.0)	10 964 (51.1)	20 180 (66.8)
Race and ethnicity†			
Asian	353 (0.9)	261 (1.2)	411 (1.4)
Black	247 (0.7)	177 (0.8)	305 (1.0)
Mixed	181 (0.5)	135 (0.6)	171 (0.6)
Other	182 (0.5)	150 (0.7)	131 (0.4)
White	36 909 (97.5)	20 750 (96.6)	29 210 (96.6)
Tobacco use			
Never	22 388 (59.1)	12 408 (57.8)	16 613 (55.0)
Former	13 416 (35.4)	7754 (36.1)	11 031 (36.5)
Current	2068 (5.5)	1311 (6.1)	2584 (8.5)
Alcohol intake (g/wk)‡	96 (32, 192)	96 (32, 192)	64 (8, 152)
Townsend Deprivation Index§	−1.9 (3.8)	−1.3 (3.0)	−1.8 (2.8)
Educational attainment, y	15.6 (4.6)	15.9 (4.6)	14.4 (4.7)
Employed	23 330 (61.5)	14 232 (66.3)	16 765 (55.5)
Self-reported health‖			
Good	23 105 (61.0)	12 840 (59.8)	17 791 (58.9)
Excellent	9429 (24.9)	5573 (26.0)	4334 (14.3)
Fair	4790 (12.6)	2724 (12.7)	6652 (22.0)
Poor	548 (1.4)	336 (1.6)	1451 (4.8)
Diet quality‖			
Intermediate	19 087 (50.4)	10 750 (50.1)	15 057 (49.8)
Poor	11 995 (31.7)	6386 (29.7)	10 410 (34.4)
Good	6790 (17.9)	4337 (20.2)	4761 (15.8)
Hypertension¶	7080 (18.7)	3640 (17.0)	8441 (27.9)
Hyperlipidemia¶	6153 (16.2)	3143 (14.6)	6983 (23.1)
Diabetes	1164 (3.1)	626 (2.9)	2089 (6.9)
Antihypertensive medication use	5777 (15.3)	2904 (13.5)	6903 (22.8)
Lipid-lowering medication use	4956 (13.1)	2460 (11.5)	5718 (18.9)
Body mass index, kg/m^2	26.1 (4.0)	25.6 (3.9)	27.6 (5.0)
Total weekly MVPA, min	288 (216, 432)	418 (302, 605)	72 (29, 115)

Data are mean (SD), median (quartile 1 and quartile 3), or n (%). MVPA indicates moderate-to-vigorous physical activity.

*Inactive is defined as MVPA below the guideline-based threshold of ≥150 minutes of MVPA/week.[1–3]

†Represents self-reported "ethnic background." Race classification of "Other" is defined as self-report of a race other than Asian, Black, Mixed, or White.

‡Can be converted to standard US drinks per week by dividing by 14 g.

§The Townsend Deprivation Index is a measure of material deprivation standardized by geographic area. Numerically greater values indicate more deprivation. The sample range is −6.2 to 10.1, with values around −2 and −1 indicating somewhat less deprivation compared with the average on the basis of geographic location.

‖Definitions of self-reported health and diet quality are provided in Table S1.

¶Defined as parent Phecode (ie, 401 for hypertension and 272.1 for hyperlipidemia) or respective medication use.

similarly lower risks of incident hypertension (weekend warrior: HR, 0.77 [95% CI, 0.73–0.80], $P=1.2\times10^{-27}$; regular: HR, 0.72 [95% CI, 0.68–0.77], $P=4.5\times10^{-28}$), diabetes (weekend warrior: HR, 0.57 [95% CI, 0.51–0.62], $P=3.9\times10^{-32}$; regular: HR, 0.54 [95% CI, 0.48–0.60], $P=8.7\times10^{-26}$), obesity (weekend warrior: HR, 0.55 [95% CI, 0.50–0.60], $P=2.4\times10^{-43}$, regular: HR, 0.44 [95% CI, 0.40–0.50], $P=9.6\times10^{-47}$), and sleep apnea (weekend warrior: HR, 0.57 [95% CI, 0.48–0.69], $P=1.6\times10^{-9}$; regular: HR, 0.49 [95% CI, 0.39–0.62], $P=7.4\times10^{-10}$;

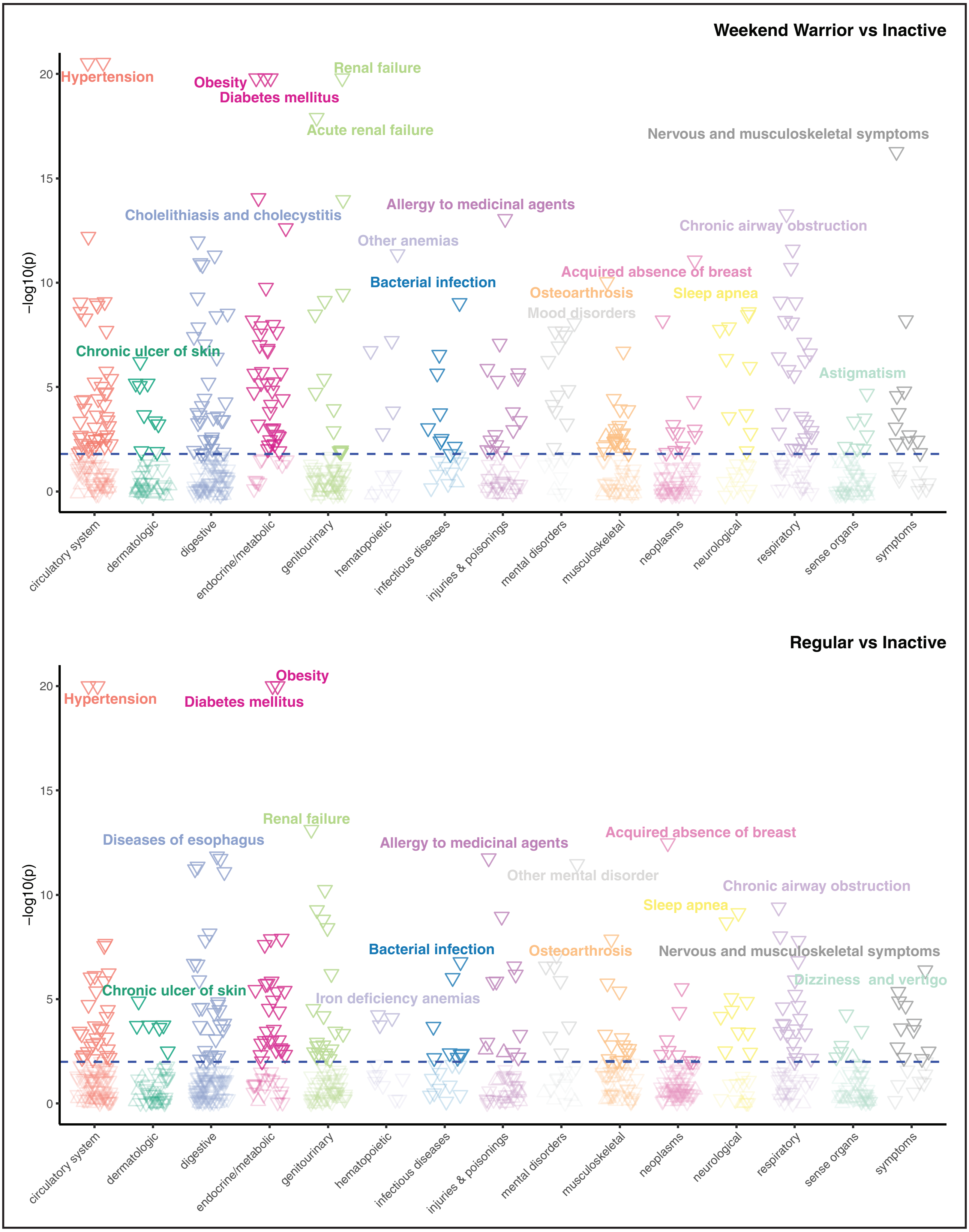

Figure 3. Associations between physical activity pattern and incident disease.
Incident disease phenome-wide association study comparing people with regular activity vs inactive pattern in the **top** and weekend warrior vs inactive pattern in the **bottom**. In each plot, every point depicts the negative log10 *P* value for the association between accelerometer-measured activity group and one incident disease (grouped by category on the *x* axis) in Cox proportional hazards models adjusted for adjusted for age at physical activity measurement, sex, ethnic background, tobacco use, Townsend Deprivation Index, alcohol intake, educational (*Continued*)

Figure 3 Continued. attainment, employment status, self-reported health, and diet quality, with darker shaded points meeting a significance level of $P<0.01$ (corresponding approximately to false discovery rate 0.01, blue dotted line). Upward-facing triangles represent higher risk (hazard ratios >1), whereas downward-facing triangles represent lower risk (hazard ratio <1). In each plot, the top association (ie, smallest *P* value) for each disease category is annotated. Additional conditions were also annotated if −log10(*P*) was >15. Some annotation names are shortened for readability. For graphical display purposes, the "other" category is not displayed. The plot is truncated at −log(*P*) of 20 (with diseases having larger values listed at 20). Full results are available in Table S3.

Table 2; Tables S3 and S7). The 5-year cumulative risks of these 4 exemplar cardiometabolic conditions were similar for both regular activity and weekend warrior activity, and substantially lower than those observed among inactive individuals (Figure 4). The relative hazard of all 4 conditions was progressively lower with increasing quartile of MVPA (Figure S1). Results were similar when conditions were ranked by effect size, with comparably large associations with lower risk observed for cardiometabolic conditions (eg, chronic renal failure: weekend warrior: HR, 0.64 [95% CI, 0.58–0.72], $P=6.8\times10^{-15}$; regular: HR, 0.65 [95% CI, 0.56–0.74], $P=5.4\times10^{-10}$), as well as a range of other diseases (eg, cholelithiasis: weekend warrior: HR, 0.64 [95% CI, 0.56–0.73], $P=7.2\times10^{-12}$; regular: HR, 0.57 [95% CI, 0.48–0.67], $P=5.9\times10^{-12}$). The top 5 associations by disease category are shown in Table S8.

Alternative Activity Definitions

Association results were similar in analyses using the sample median (≥230.4 minutes) as the threshold for physical activity (Figure S2; Tables S9 through S11), and when events within 2 years of physical activity measurement were blanked (Tables S12 and S13). Across increasingly stringent definitions of weekend warrior activity, both the number of individuals meeting criteria for a weekend warrior pattern and the number of significant disease associations identified at FDR 0.01 decreased (≥50% of total MVPA on 1 or 2 consecutive days: n=26 032, with 218 associations; ≥50% of total MVPA on 1 or 2 weekend days: n=8002, with 79 associations; ≥75% of total MVPA on 1 or 2 days: n=6333, with 19 associations; ≥75% of total MVPA on 1 or 2 consecutive days: n=2978, with 1 association; Tables S14 through S21). Yet effect sizes for the 4 exemplar cardiometabolic diseases remained consistent, suggesting fewer associations identified at our stringent multiplicity threshold were a result of decreasing statistical power rather than changes in the effect of weekend warrior activity across varying definitions (Table 2). Using each of the alternative weekend warrior definitions tested, there were again no diseases for which effects differed significantly between weekend warrior and regular activity at an FDR of 0.01 (Table 2). Our observations about cardiometabolic conditions remained consistent when incorporating physical measurements taken at systematic assessments after physical activity measurement such as blood pressure, glycated hemoglobin, and body mass index into outcome definitions of hypertension, diabetes, and obesity (Table S22). Associations were similar in models including spline terms to account for potential nonlinearity in the effects of alcohol and MVPA (Tables S23 through S25).

DISCUSSION

In this study, we leverage a unique resource of nearly 90 000 UK Biobank participants providing measured physical activity data from a wrist-based accelerometer to comprehensively assess associations of weekend warrior and regular activity patterns with risk of >650 future diseases. We observe that guideline-adherent physical activity volumes, irrespective of how they are achieved, are linked to lower risk of >200 incident diseases. We noted particularly strong associations with incident cardiometabolic conditions such as hypertension, diabetes, obesity, and sleep apnea, with up to 50% lower risk observed with both weekend warrior and regular activity. Despite testing hundreds of diseases, as well as a variety of definitions of weekend warrior activity, we observed no conditions for which the effect of activity on disease differed for weekend warrior versus regular activity.

Our observations have several implications for initiatives aiming to leverage physical activity to improve public health. First, efforts to optimize physical activity may be expected to have wide-ranging health benefits that extend beyond previously published associations with cardiovascular disease.[8] Here, after correcting for multiple testing, we observed strong associations between physical activity and lower risk of up to 264 incident conditions over 6 years, with diseases spanning all 16 categories analyzed. Although >98% of associations represented a lower risk of incident disease, we did observe a small number of associations implying a higher risk for both physical activity groups, with conditions representing musculoskeletal and dermatological disorders. Future work is warranted to identify methods to reduce the risk of conditions potentially related to overuse,[19] although we note that physical activity was also associated with a lower risk of over a dozen musculoskeletal conditions, including osteoarthrosis and degenerative spinal conditions. On balance, our findings suggest that physical activity possesses potential for positive public health impact spanning a wide spectrum of disease.

Second, our results suggest that the achievement of guideline-adherent physical activity volumes (ie, minutes of MVPA/week) is the key factor relevant to incident disease risk, as opposed to the pattern by

Table 2. Effect Sizes of Exemplar Cardiometabolic Conditions Across Varying Definitions of Weekend Warrior Activity

	Weekend warrior vs inactive*		Regular activity vs inactive*		Weekend warrior vs regular activity*	
Disease	**Hazard ratio (95% CI)**	***P* value**	**Hazard ratio (95% CI)**	***P* value**	**Hazard ratio (95% CI)**	***P* value†**
≥150 minutes MVPA/week with ≥50% in 1 or 2 days						
Hypertension	0.77 (0.73–0.80)	1.2×10^{-27}	0.72 (0.68–0.77)	4.5×10^{-28}	1.00 (0.95–1.07)	0.88
Obesity	0.55 (0.50–0.60)	2.4×10^{-43}	0.44 (0.40–0.50)	9.6×10^{-47}	1.09 (0.96–1.23)	0.17
Diabetes	0.57 (0.51–0.62)	3.9×10^{-32}	0.54 (0.48–0.60)	8.7×10^{-26}	0.97 (0.86–1.10)	0.64
Sleep apnea	0.57 (0.48–0.69)	1.6×10^{-9}	0.49 (0.39–0.62)	7.4×10^{-10}	1.04 (0.82–1.33)	0.73
≥230.4 minutes MVPA/week (median) with ≥50% in 1 or 2 days						
Hypertension	0.80 (0.76–0.84)	3.7×10^{-19}	0.75 (0.71–0.80)	5.2×10^{-22}	1.01 (0.94–1.08)	0.82
Obesity	0.60 (0.54–0.65)	9.5×10^{-27}	0.47 (0.42–0.53)	3.9×10^{-36}	1.11 (0.97–1.27)	0.13
Diabetes	0.56 (0.51–0.63)	5.0×10^{-26}	0.59 (0.52–0.66)	2.0×10^{-18}	0.89 (0.77–1.03)	0.11
Sleep apnea	0.62 (0.51–0.75)	1.4×10^{-06}	0.52 (0.41–0.66)	5.3×10^{-08}	1.06 (0.81–1.39)	0.66
≥150 minutes MVPA/week with ≥50% on 2 consecutive days						
Hypertension	0.77 (0.73–0.81)	4.9×10^{-23}	0.74 (0.70–0.78)	6.1×10^{-32}	0.99 (0.94–1.04)	0.68
Obesity	0.57 (0.52–0.63)	3.8×10^{-31}	0.46 (0.42–0.51)	2.6×10^{-58}	1.11 (0.99–1.24)	0.07
Diabetes	0.59 (0.52–0.66)	9.9×10^{-20}	0.49 (0.44–0.55)	1.6×10^{-35}	1.04 (0.92–1.17)	0.55
Sleep apnea	0.56 (0.46–0.69)	$3.0\times10^{-0.8}$	0.53 (0.44–0.64)	7.0×10^{-11}	0.96 (0.77–1.21)	0.74
≥150 minutes MVPA/week with ≥50% on true weekends						
Hypertension	0.74 (0.68–0.81)	6.9×10^{-12}	0.75 (0.72–0.79)	3.6×10^{-35}	0.96 (0.88–1.04)	0.30
Obesity	0.54 (0.46–0.63)	1.6×10^{-14}	0.51 (0.47–0.55)	2.1×10^{-62}	1.00 (0.85–1.17)	0.97
Diabetes	0.48 (0.39–0.58)	2.6×10^{-14}	0.57 (0.52–0.62)	1.1×10^{-37}	0.81 (0.67–0.98)	0.03
Sleep apnea	0.55 (0.39–0.76)	3.4×10^{-04}	0.54 (0.46–0.64)	1.3×10^{-12}	0.94 (0.68–1.32)	0.74
≥150 minutes MVPA/week with ≥75% of total MVPA on 1 or 2 days						
Hypertension	0.80 (0.73–0.87)	1.5×10^{-07}	0.74 (0.71–0.78)	2.8×10^{-37}	1.02 (0.94–1.11)	0.64
Obesity	0.65 (0.56–0.76)	9.8×10^{-08}	0.49 (0.46–0.53)	8.3×10^{-67}	1.19 (1.01–1.39)	0.04
Diabetes	0.65 (0.54–0.77)	7.7×10^{-07}	0.50 (0.50–0.59)	5.2×10^{-42}	1.11 (0.93–1.32)	0.25
Sleep apnea	0.51 (0.35–0.73)	3.1×10^{-04}	0.55 (0.46–0.65)	2.0×10^{-12}	0.83 (0.58–1.21)	0.34
≥150 minutes MVPA/week with ≥75% of total MVPA on 2 consecutive days						
Hypertension	0.80 (0.70–0.90)	2.3×10^{-04}	0.75 (0.72–0.78)	3.3×10^{-37}	1.01 (0.90–1.14)	0.83
Obesity	0.65 (0.52–0.82)	1.7×10^{-04}	0.50 (0.47–0.54)	6.5×10^{-66}	1.16 (0.93–1.45)	0.20
Diabetes	0.63 (0.49–0.81)	2.9×10^{-04}	0.55 (0.51–0.60)	9.1×10^{-42}	1.06 (0.82–1.36)	0.66
Sleep apnea	0.59 (0.36–0.96)	3.3×10^{-02}	0.54 (0.46–0.64)	3.7×10^{-13}	0.97 (0.60–1.59)	0.92

MVPA indicates moderate-to-vigorous physical activity.

*All models adjusted for age at physical activity measurement, sex, ethnic background, tobacco use, Townsend Deprivation Index, alcohol intake, educational attainment, employment status, self-reported health, and diet quality. Comparisons between weekend warrior activity and regular activity in addition adjusted for total MVPA.

†No *P* values comparing weekend warrior vs regular activity are significant at the prespecified false discovery rate (FDR) of 0.01.

which physical activity may be accrued. Specifically, both regular and weekend warrior activity exhibited nearly identical associations with lower risk of hundreds of diseases, and when compared directly, we did not identify a single condition for which risk appeared substantively different for one pattern versus the other. Our results support previous investigations focused on concentrated activity.[8] Using survey data from 60 000 adults, O'Donovan et al reported similarly lower rates of all-cause, cardiovascular-related, and cancer-related mortality with weekend warrior versus regular activity.[20] Similar observations were reported in a larger study by Dos Santos et al including >350 000 participants in the US National Health Interview Survey from 1997 to 2013.[7] Acknowledging the limitations of self-reported physical activity data (eg, recall bias and tendency for overestimation),[21] we recently leveraged physical activity measured using accelerometry to assess associations between physical activity pattern and cardiovascular events, observing similarly lower risks of atrial fibrillation, heart failure, myocardial infarction, and stroke with both weekend warrior and regular activity. In the context of previous findings, the current study provides important reassurance that concentrated physical activity patterns, objectively measured by accelerometer, appear to retain broad and salutary

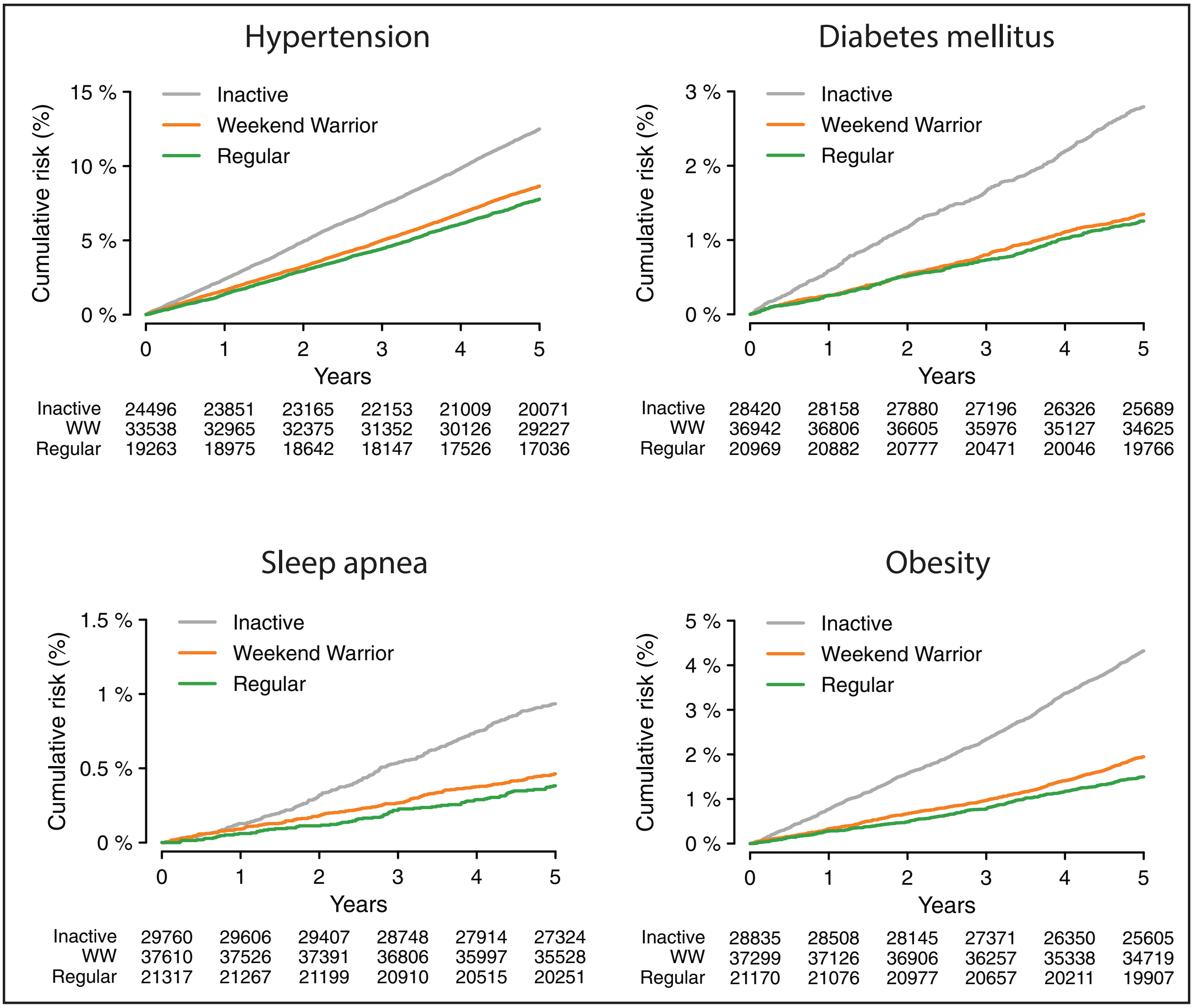

Figure 4. Cumulative risk of cardiometabolic conditions stratified by activity pattern.

Depicted is the 5-year cumulative incidence of 4 exemplar cardiometabolic conditions (see label above each plot), stratified by activity pattern (gray=inactive, orange=weekend warrior, and green=regular). The number remaining at risk at each year is depicted below each plot.

effects across the spectrum of health and disease, and that such effects appear similar to the benefits observed with more regular activity. Especially because the weekend warrior pattern appears common, and may be more feasible for certain contemporary lifestyles,[16] our findings compel future work to assess the effectiveness of concentrated physical activity interventions for reducing the risk of future disease.

Third, although we noted beneficial associations across a wide range of diseases, our findings suggest that physical activity may be particularly effective for modifying risk of cardiometabolic conditions, including hypertension, obesity, diabetes, and sleep apnea. For example, we observed roughly 50% lower hazard of incident diabetes with both weekend warrior and regular activity patterns, after adjustment for multiple potential confounders. It is important to note that although our primary analysis applied the most common definition of weekend warrior activity proposed using wrist-based accelerometers (ie, ≥50% of total MVPA in 1 or 2 days), which clearly separated individuals with a tendency to be far more active on 1 or 2 days of the week compared to the remaining 5, our observations remained consistent when applying up to 6 alternative definitions. Of note, we did observe that the regular activity group tended toward higher total MVPA, suggesting that greater MVPA volumes may be more commonly achievable through regular activity. Nevertheless, we observed no differences between the effects of weekend warrior versus regular activity on disease, whether or not we adjusted for total MVPA, implying that observed imbalances in MVPA volume (in excess of the guideline-based threshold) were not sufficiently substantive to affect disease risk. We submit our findings are particularly relevant in light of recent positive studies of drugs targeting metabolic pathways (sodium-glucose cotransporter-2 inhibitors) and weight loss (glucagon-like peptide 1-receptor agonists), which may demonstrate synergy with physical activity.[22] Future studies are warranted to investigate the potential effectiveness of comprehensive approaches combining medical therapy with lifestyle modification, including concentrated physical activity interventions, to improve population-level cardiometabolic health.

Limitations

Several limitations should be taken into consideration. First, this study is observational and cannot be used to infer causal relationships. Nevertheless, we adjusted for multiple potential confounders and took steps to mitigate reverse causation (eg, 2-year blanking analysis), in which our observations remained robust. Furthermore, E-values for key outcomes suggested that the effects of unmeasured confounders would need to be very large to nullify observed associations. Second, physical activity was assessed over a single week, and participants may have altered their behavior during observation. Third, our methodology relied on a previously validated MVPA classification method encompassing various activities like walking, jogging, stationary cycling, elliptical, and others,[10,11] yet the accuracy of MVPA classification may vary depending on physical activity type. Fourth, although optimal MVPA thresholds using wrist-based accelerometers remain uncertain, our results remained consistent when using the 150 minutes/week threshold endorsed in consensus guidelines, as well as the sample median threshold and alternative definitions of weekend warrior activity. Fifth, the UK Biobank is predominantly White, which may limit the generalizability of our findings to other ethnic or racial groups. Sixth, we defined diseases using Phecodes, which are a validated diagnosis code–based framework for ascertaining hundreds of conditions. We submit that use of a publicly available system for principled association testing will facilitate reproduction and comparison of our results to future analyses, and, to this end, we plan to return our Phecode-based definitions to the UK Biobank for future use. At the same time, we acknowledge that accuracy for individual conditions is likely lower than curated disease-specific definitions drawing from multiple sources, which are impractical to develop and apply across all conditions. Reassuringly, we observed similar findings for key cardiometabolic outcomes when incorporating physical measurements, medications, and laboratory results into our definitions. Seventh, although detailed hospital diagnoses were available for the whole cohort, primary care data were only available in roughly 45% of participants and only through 2017, which may limit sensitivity for certain conditions less likely to result in the generation of inpatient codes (eg, obesity). It is important to note that incidence rates for other major cardiometabolic conditions (eg, hypertension or diabetes) appeared comparable with estimates from other relatively healthy research samples,[23–26] and results remained similar when additional data (ie, body mass index) were used to identify obesity. Eighth, follow-up time is limited in duration, and therefore, the long-term impact of habitual exercise on health outcomes is incompletely elucidated. Ninth, we focused on quantifying disease associations. Future work is warranted to assess the potential value of measured activity pattern within a prediction model framework.

Conclusions

In a cohort of nearly 90 000 individuals with wrist-based physical activity tracking, we found that both physical activity concentrated within 1 or 2 days and more regular activity patterns were each associated with a similarly lower risk of >200 diseases spanning the full spectrum of disease. Both physical activity patterns had particularly prominent associations with lower risk of cardiometabolic conditions. Future studies are warranted to assess the potential value of concentrated physical activity interventions to improve public health.

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Affiliations

Department of Cardiology, University Heart and Vascular Center Hamburg-Eppendorf, Hamburg, Germany (S. Kany). German Center for Cardiovascular Research (DZHK), Partner Site Hamburg/Kiel/Lübeck, Hamburg, Germany (S. Kany). Cardiovascular Disease Initiative (S. Kany, M.A.A.-A., J.T.R., J.P.P., S.A.L., P.T.E., S. Khurshid), Data Sciences Platform (M.M.), Broad Institute of MIT and Harvard, Cambridge. Cardiovascular Research Center (S. Kany, M.A.A.-A., J.T.R., T.W.C., S.A.L., J.S.G., P.T.E., S. Khurshid), Cardiovascular Performance Program (T.W.C., S.G.), Demoulas Center for Cardiac Arrhythmias (S.A.L., P.T.E., S. Khurshid), Cardiology Division (M.A.A.-A.), Massachusetts General Hospital, Boston. Institute for Molecular Medicine Finland, Helsinki Institute of Life Science, University of Helsinki (J.T.R.). Division of Cardiology (J.P.P.), Institute for Human Genetics (J.P.P.), University of California, San Francisco.

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Supplemental Material

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