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The Effect of Using Anchored Wake Time to Derive 24-h Device Measured Circadian Physical Behavior Patterns

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ABSTRACT

Introduction: Tailoring physical activity interventions to individual chronotypes and preferences by time of day could promote more effective and sustainable behavior change; however, our understanding of circadian physical behavior patterns is very limited.

Objective: To characterize and compare 24-h physical behavior patterns expressed relative to clock time (the standard measurement of time-based on a 24-h day) versus wake-up time in a large British cohort age 46.

Methods: Data were analyzed from 4979 participants in the age 46 sweep of the 1970 British Cohort Study who had valid activPAL accelerometer data across ≥4 days. Average steps and upright time (time standing plus time stepping) per 30-min interval were determined for weekdays and weekends, both in clock time and synchronized to individual wake-up times.

Results: The mean weekday steps were 9588, and the mean weekend steps were 9354. The mean weekday upright time was 6.6 h, and the mean weekend upright time was 6.4 h. When synchronized to wake-up time, steps peaked 1 h after waking on weekdays and 2.5 h after waking on weekends. Upright time peaked immediately, in the first 30-min window, after waking on both weekdays and weekends.

Conclusions: Aligning accelerometer data to wake-up times revealed distinct peaks in stepping and upright times shortly after waking. Activity built up more gradually across clock time in the mornings, especially on weekends. Synchronizing against wake-up times highlighted the importance of circadian rhythms and personal schedules in understanding population 24-h physical behavior patterns, and this may have important implications for promoting more effective and sustainable behavior change.

1 | Introduction

As public health researchers increasingly focus on behaviors that span the 24-h day, the intricate relationships between various health-enhancing behaviors over time are gaining attention. In recent years, there has been a rise in time-use research methods, particularly following the introduction of 24-h movement behavior guidelines for youth and early childhood, drawing heightened interest from physical activity researchers [1–4]. The adult guidelines issued by the United States, the United Kingdom, and WHO each deal separately with sleep, sedentary behavior, and physical activity [5–8]. The WHO's guidelines report highlighted the need for wearables to address many of the research gaps around 24-h time use [9]. This reflects that much-published data among adults examine relationships of health outcomes to time in only one

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behavior, without considering potential interrelationships of movement behaviors.

Previous research among adults has been limited by reliance on recall questionnaires, which are susceptible to bias and cannot measure total time allocated to all movement behaviors within a 24-h day [10]. The development of 24-h time-use diaries allows researchers to assess compensation across a day [11, 12]. However, constructing such accounts is problematic due to recall failures, concurrent activities, and differing interpretations. Although diaries provide an approach, more accurate and comprehensive measurements are needed.

The implementation of device-based tools such as accelerometers in cohort studies now enables accurate measurement of movement behaviors continuously across 24 h [13–16]. This has contributed to recent publications assessing time-use substitution. The proliferation of wearables providing 24-h movement data has already begun to change interpretations of sleep, sedentary behavior, and physical activity on health. Importantly, it has been indicated that this growing evidence base will be incorporated into the next iteration of national and international public health guidelines [17, 18].

Traditionally, variations in activity have been analyzed and presented in relation to clock time, typically demonstrating a gradual increase over time. However, this approach overlooks individual variances in circadian rhythms, which are crucial when aiming for enduring behavioral modifications. We know very little about physical behavior circadian rhythms due to limitations in our current methods. Interventions that align physical activity with one's circadian rhythm could have a significant edge over conventional methods. These interventions could also lead to pronounced health benefits and foster more effective, long-lasting behavioral changes.

In this analysis, we leveraged detailed accelerometer-based monitoring of both stepping and upright time patterns aligned to clock time and individual wake-up times as an indicator of intrinsic circadian rhythms. The aim of this study was to characterize and compare 24-h activity patterns expressed relative to clock time versus wake-up time in a large British cohort aged 46. Focusing on mid-aged adults minimizes confounding age-related variables, leveraging their stable routines to clarify circadian physical behavior patterns.

2 | Methods

The 1970 British Cohort Study (BCS70) is a longitudinal study following the lives of approximately 17000 individuals born in England, Scotland, or Wales during a single week in 1970 [19, 20]. The study's age 46 sweep was carried out between 2016 and 2018, with 8581 members participating. A wide range of data was captured in the sweep, including personal, social, and economic data, a range of biomedical measures, and accelerometer-derived physical behavior data. For these people, a thigh-mounted triaxial accelerometer-based device, an activPAL3 (PAL Technologies Ltd., Glasgow, UK), was used to collect objective physical behavior data over 7 days. A total of 6492 eligible participants consented to wear the activPAL.

We used a wear protocol previously developed [21]. The activPAL was waterproofed and affixed to the midline of the anterior aspect of the upper thigh. Participants were instructed to wear the device continuously for 7 days, after which they were to remove and return it by post. If the accelerometer became dislodged during the monitoring period, participants were instructed not to reattach the device before returning it.

Raw acceleration data from activPAL were downloaded and processed using PALbatch version 8.10.10.52 (PAL Technologies Ltd.). The event data were exported using an event-based approach [22] that considers each continuous period of sitting, standing, and taking a stride as a single event. Our study used the CREA algorithm to identify various activity classes, including sitting, standing, stepping, and lying. The algorithm defines each stride event as two steps and combines adjacent stride events into a single stepping event, with twice the number of steps as strides. Stepping events are characterized by duration, number of steps, and cadence. An upright period was characterized as a consecutive series of standing and stepping events, with sitting events marking the beginning and end. Participants with at least four valid days of activity data were included in the analysis.

The time spent out of bed was obtained from the event files for all days, and physical behavior measures such as steps per hour and upright time were calculated in relation to the time the individual got out of bed. The time in bed algorithm for the activPAL was used for detecting continuous lying events, and when conditions for this were broken, being upright (standing and stepping), they were deemed to have woken up. Subsequently, the average number of steps and percentage of time spent upright per individual were determined for each 30-min period per day.

For each individual, the average number of steps per day was calculated for both weekdays and weekends. The same was done for upright time. The average and standard deviations of these individual averages were calculated, giving an average for the group for each condition on weekdays and weekends. To generate descriptive statistics, means and standard errors were computed for the whole population across all days, separately for weekdays and weekends, for each 30-min interval.

3 | Results

Data from 4979 individuals (mean age 46.8 years, SD 0.7), out of 5569 who returned their monitors with data for at least 1 day of wear, were determined to be valid and met the requirements for the analysis. For all individuals, there was a total of 22088 valid days for weekdays and 8955 valid days for weekends.

The mean number of steps taken on a weekday was 9588 (SD 4748), and the mean number of steps taken on a weekend day was 9354 (SD 5313). The mean upright time for a weekday was 6.6 h (SD 2.2 h), and the mean upright time for a weekend day was 6.39 h (SD 2.06 h). The mean wake time for all weekdays was 7:35 (SD 3.7 h).

Figure 1 displays the daily stepping profiles for weekdays and weekends for the entire population. On weekdays, steps peaked at approximately 8:30 a.m., whereas weekends had a later peak at approximately 11:30 a.m. Stepping gradually built up across clock time in the mornings, with a more prolonged ramp on weekends. When stepping was synchronized to wake-up time, as shown in Figure 2, distinct peaks emerged approximately 1 h after waking on weekdays and 2.5 h after waking on weekends.

Figure 3 shows the upright time profiles for weekdays and weekends for the entire population. On weekdays, upright time peaked at approximately 8:00 a.m., compared with a later peak at approximately 12:30 p.m. on weekends. As with stepping, upright time built up gradually across clock time in the mornings, especially on weekends when the morning ramp was more prolonged. When upright time was normalized to wake-up time in Figure 4, a prominent peak emerged immediately after waking on both weekdays and weekends. On weekdays, the upright time declined sharply after the initial morning peak and leveled off, followed by a gradual decline. Weekends showed a secondary smaller peak approximately 3 h after waking before steadily declining. The upright time patterns complement the stepping profiles by showing similarly timed peaks and rhythms relative to wake-up. The prolonged weekend morning ramp in upright time aligns with the gradual accrual of steps over weekend mornings. Together, these findings reinforce that activity across a 24-h day follows different temporal rhythms on weekends versus weekdays when aligned to individual wake-up times.

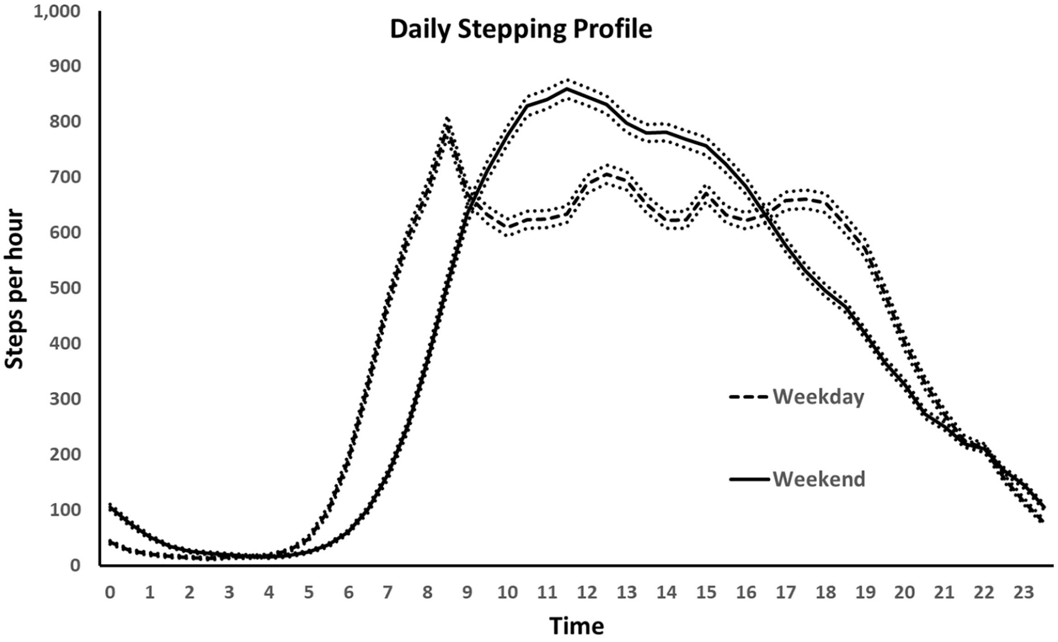

FIGURE 1 | Daily stepping profiles for both weekdays and weekends. The lines show the mean and two standard errors.

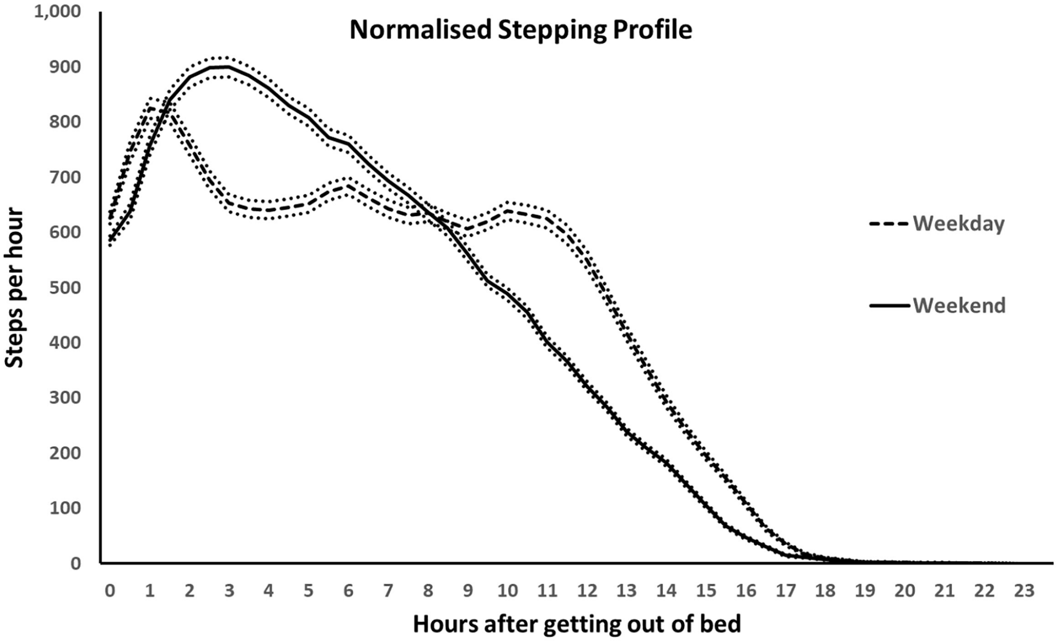

FIGURE 2 | Daily normalized stepping profiles for both weekdays and weekends. The lines show the mean and two standard errors.

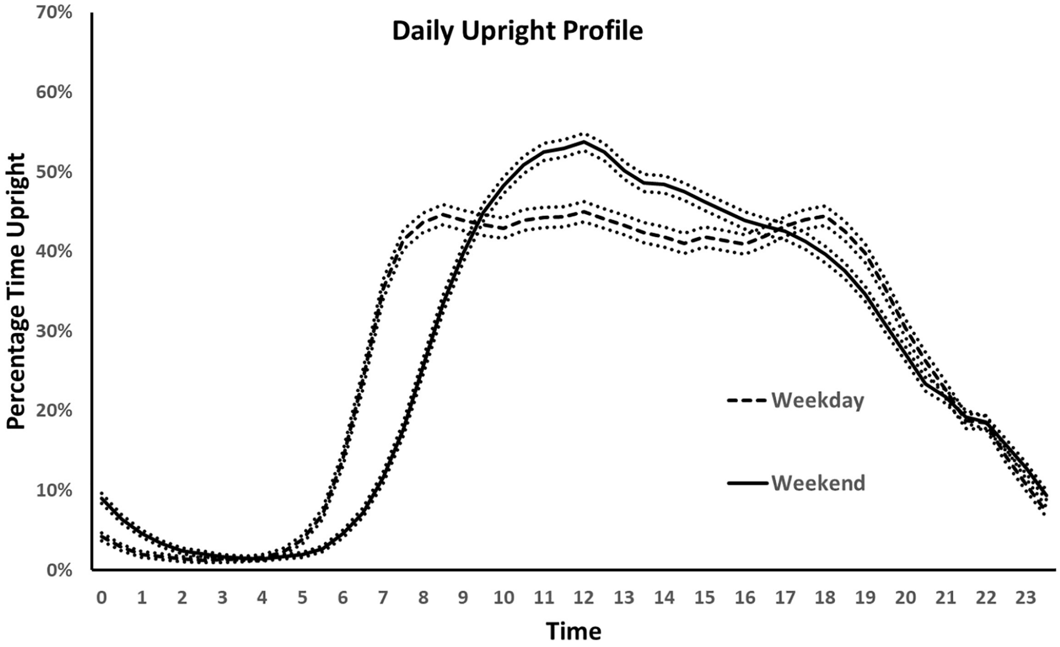

FIGURE 3 | Daily upright profiles for both weekdays and weekends. The lines show the mean and two standard errors.

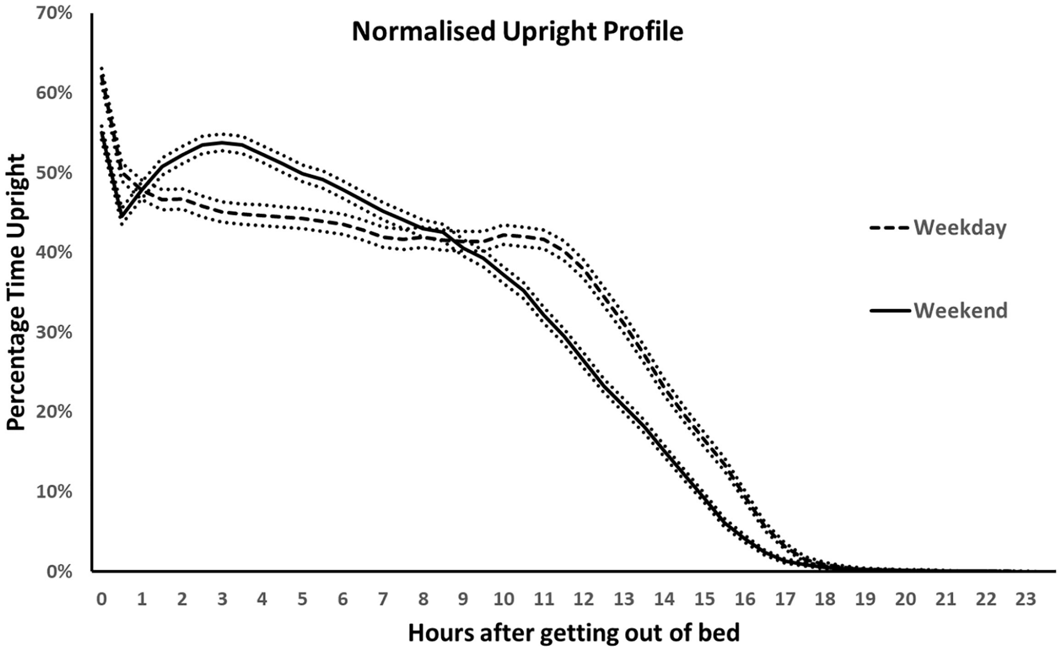

FIGURE 4 | Daily normalized upright profiles for both weekdays and weekends. The lines show the mean and two standard errors.

4 | Discussion

Understanding individual differences in daily routines and wake-up times is crucial when examining daily activity patterns, as these factors can influence physical activity levels throughout the day, and this could impact how we design physical activity interventions. The significance of taking individual differences in daily routines into account is supported by research on circadian rhythms, which are biological processes that operate on an approximately 24-h cycle and regulate various aspects of our physiology and behavior, including sleep–wake cycles [23, 24].

Circadian rhythms help synchronize our bodily functions to match the Earth's natural light–dark cycle. However, people's intrinsic circadian cycles differ, categorized into “chronotypes” of morning larks, night owls, and intermediates [24]. Chronotype impacts the timing of sleep and activity preferences. By synchronizing physical activity data to individual wake-up times, researchers can align movement patterns to biological time rather than external clock time [25]. This accounts for differences in chronotypes and schedules across a population. For instance, consider two individuals—one waking at 6:00 a.m. and another at 8:00 a.m. At 9:00 a.m., the first had been awake for 3 h, whereas the second had been awake for only 1 h. Any activity at 9:00 a.m. represents different points in their personal circadian cycle. Synchronizing to wake-up time places their activity patterns on the same timescale aligned to their intrinsic rhythms.

Tailoring physical activity interventions to individual chronotypes and preferences by time of day could also promote more effective and sustainable behavior change. For example, morning people may be most receptive to scheduled morning walks or exercise classes, whereas evening types may prefer later afternoon or evening activities. Understanding these individual differences can help design personalized activity planning that fits individual circadian rhythms and preferences. This approach could improve the adoption and maintenance of physical activity routines for broader public health, rather than a "one size fits all" recommendation. Matching activity timing to innate chronotype and personal preferences may lead to greater satisfaction, adherence, and overall activity levels. It has been shown that structured exercise aligned with chronotype can enhance health outcomes in Type 2 diabetes patients [26] and that exercising at the right time could help synchronize circadian rhythms with daily schedules, potentially improving overall health [27, 28].

This study has several strengths, including the use of thigh-worn activPAL devices to objectively measure movement behaviors with high resolution continuously across multiday periods, providing a robust quantification of stepping and upright time. The large nationwide British cohort of nearly 5000 adults provided a population-based, roughly representative sample in a critical for chronic disease prevention narrow age range, removing the confounding factor of age-related differences and national differences. The main limitation was that the sample was restricted to British adults, potentially reducing generalizability to other populations. It is important to note the potential selection bias from analyzing a subset ($n = 4979$) of the larger 1970 British Cohort Study. In addition, we have only 1 week of data from each individual and assume that it represents their normal week. Our analysis focused on looking at circadian physical behavior patterns within this cohort, and future studies might use this approach to compare these patterns across different population subtypes, both sex and socio-economic.

5 | Conclusions

This study revealed insights into 24-h activity patterns in a large British cohort when accelerometer data were aligned to individual wake-up times rather than clock time. Clear peaks in stepping and upright time emerged shortly after waking on both weekdays and weekends. However, activity built up more gradually across clock time in the mornings, especially on weekends. These findings demonstrate the importance of accounting for individual differences in circadian rhythms and wake-up schedules when studying relationships between movement behaviors across a population. The results highlight implications for future revisions to 24-h activity guidelines and personalized activity planning tailored to individual chronotypes.

Conflicts of Interest

MHG is a co-inventor of the activPAL3™ physical activity monitor and a director of PAL Technologies Ltd.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

References

1. M. S. Tremblay, J. P. Chaput, K. B. Adamo, et al., "Canadian 24-Hour Movement Guidelines for the Early Years (0–4 Years): An Integration of Physical Activity, Sedentary Behaviour, and Sleep," *BMC Public Health* 17, no. Suppl 5 (2017): 874, https://doi.org/10.1186/s12889-017-4859-6.

2. M. S. Tremblay, V. Carson, J. P. Chaput, et al., "Canadian 24-Hour Movement Guidelines for Children and Youth: An Integration of Physical Activity, Sedentary Behaviour, and Sleep," *Applied Physiology, Nutrition, and Metabolism* 41, no. 6 Suppl 3 (2016): S311–S327, https://doi.org/10.1139/apnm-2016-0151.

3. A. D. Okely, D. Ghersi, K. D. Hesketh, et al., "A Collaborative Approach to Adopting/Adapting Guidelines—The Australian 24-Hour Movement Guidelines for the Early Years (Birth to 5 Years): An Integration of Physical Activity, Sedentary Behavior, and Sleep," *BMC Public Health* 17, no. Suppl 5 (2017): 869, https://doi.org/10.1186/s12889-017-4867-6.

4. J. Willumsen and F. Bull, "Development of WHO Guidelines on Physical Activity, Sedentary Behaviour, and Sleep for Children Less Than 5 Years of Age," *Journal of Physical Activity and Health* 17, no. 1 (2020): 96–100, https://doi.org/10.1123/jpah.2019-0457.

5. F. C. Bull, S. S. Al-Ansari, S. Biddle, et al., "World Health Organization 2020 Guidelines on Physical Activity and Sedentary Behaviour," *British Journal of Sports Medicine* 54, no. 24 (2020): 1451–1462, https://doi.org/10.1136/bjsports-2020-102955.

6. K. L. Piercy, R. P. Troiano, R. M. Ballard, et al., "The Physical Activity Guidelines for Americans," *Journal of the American Medical Association* 320, no. 19 (2018): 2020–2028, https://doi.org/10.1001/jama.2018.14854.

7. R. Ross, J. P. Chaput, L. M. Giangregorio, et al., "Canadian 24-Hour Movement Guidelines for Adults Aged 18–64 Years and Adults Aged 65 Years or Older: An Integration of Physical Activity, Sedentary Behaviour, and Sleep," *Applied Physiology, Nutrition, and Metabolism* 45, no. 10 (2020): S57–S102, https://doi.org/10.1139/apnm-2020-0467.

8. Department of Health and Social Care, "Physical Activity Guidelines: UK Chief Medical Officers' Report" (2019), https://www.gov.uk/government/publications/physical-activity-guidelines-uk-chief-medical-officers-report.

9. H. P. Van Der Ploeg, D. Merom, J. Y. Chau, M. Bittman, S. G. Trost, and A. E. Bauman, "Advances in Population Surveillance for Physical Activity and Sedentary Behavior: Reliability and Validity of Time Use Surveys," *American Journal of Epidemiology* 172, no. 10 (2010): 1199–1206, https://doi.org/10.1093/aje/kwq265.

10. L. DiPietro, S. S. Al-Ansari, S. J. H. Biddle, et al., "Advancing the Global Physical Activity Agenda: Recommendations for Future Research by the 2020 WHO Physical Activity and Sedentary Behavior Guidelines Development Group," *International Journal of Behavioral Nutrition and Physical Activity* 17, no. 1 (2020): 143, https://doi.org/10.1186/s12966-020-01042-2.

11. S. R. Gomersall, T. S. Olds, and K. Ridley, "Development and Evaluation of an Adult Use-of-Time Instrument With an Energy Expenditure

Focus," *Journal of Science and Medicine in Sport* 14, no. 2 (2011): 143–148, https://doi.org/10.1016/j.jsams.2010.08.006.

12. C. E. Matthews, D. Berrigan, B. Fischer, et al., "Use of Previous-Day Recalls of Physical Activity and Sedentary Behavior in Epidemiologic Studies: Results From Four Instruments," *BMC Public Health* 19, no. Suppl 2 (2019): 1–13, https://doi.org/10.1186/s12889-019-6763-8.

13. S. F. M. Chastin, D. E. McGregor, J. Palarea-Albaladejo, et al., "Joint Association Between Accelerometry-Measured Daily Combination of Time Spent in Physical Activity, Sedentary Behaviour and Sleep and All-Cause Mortality: A Pooled Analysis of Six Prospective Cohorts Using Compositional Analysis," *British Journal of Sports Medicine* 55, no. 22 (2021): 1277–1285, https://doi.org/10.1136/bjsports-2020-102345.

14. K. M. Whitaker, K. P. Gabriel, M. P. Buman, L. R. Tobar, J. L. Sheats, and J. P. Reis, "Associations of Accelerometer-Measured Sedentary Time and Physical Activity With Prospectively Assessed Cardiometabolic Risk Factors: The CARDIA Study," *Journal of the American Heart Association* 8, no. 1 (2019): e009892, https://doi.org/10.1161/JAHA.118.009892.

15. A. Kandola, D. Vancampfort, M. Herring, et al., "Moving to Beat Anxiety: Epidemiology and Therapeutic Issues With Physical Activity for Anxiety," *Current Psychiatry Reports* 20, no. 8 (2018): 1–9, https://doi.org/10.1007/s11920-018-0923-x.

16. J. Grgic, D. Dumuid, E. G. Bengoechea, et al., "Health Outcomes Associated With Reallocations of Time Between Sleep, Sedentary Behaviour, and Physical Activity: A Systematic Scoping Review of Isotemporal Substitution Studies," *International Journal of Behavioral Nutrition and Physical Activity* 15, no. 1 (2018): 69, https://doi.org/10.1186/s12966-018-0691-3.

17. E. Stamatakis, M. Ahmadi, M. H. Murphy, et al., "Journey of a Thousand Miles: From 'Manpo-Kei' to the First Steps-Based Physical Activity Recommendations," *British Journal of Sports Medicine* 57 (2023): 1227–1228, https://doi.org/10.1136/bjsports-2023-106869.

18. J. M. Gill, T. J. Chico, A. Doherty, et al., "Potential Impact of Wearables on Physical Activity Guidelines and Interventions: Opportunities and Challenges," *British Journal of Sports Medicine* 57 (2023): 1223–1225, https://doi.org/10.1136/bjsports-2023-106822.

19. A. Sullivan, M. Brown, M. Hamer, and G. B. Ploubidis, "Cohort Profile Update: The 1970 British Cohort Study (BCS70)," *International Journal of Epidemiology* 52, no. 3 (2023): e179–e186, https://doi.org/10.1093/ije/dyac148.

20. M. Hamer, E. Stamatakis, S. Chastin, et al., "Feasibility of Measuring Sedentary Time Using Data From a Thigh-Worn Accelerometer," *American Journal of Epidemiology* 189, no. 9 (2020): 963–971, https://doi.org/10.1093/aje/kwaa047.

21. P. M. Dall, D. A. Skelton, M. L. Dontje, et al., "Characteristics of a Protocol to Collect Objective Physical Activity/Sedentary Behaviour Data in a Large Study: Seniors USP (Understanding Sedentary Patterns)," *Journal for the Measurement of Physical Behaviour* 1, no. 1 (2018): 26–31, https://doi.org/10.1123/jmpb.2017-0034.

22. M. H. Granat, "Event-Based Analysis of Free-Living Behaviour," *Physiological Measurement* 33, no. 11 (2012): 1785–1800.

23. E. R. Stothard, A. W. McHill, C. M. Depner, et al., "Circadian Entrainment to the Natural Light-Dark Cycle Across Seasons and the Weekend," *Current Biology* 27, no. 4 (2017): 508–513, https://doi.org/10.1016/j.cub.2016.12.041.

24. T. Roenneberg and M. Merrow, "The Circadian Clock and Human Health," *Current Biology* 26, no. 10 (2016): R432–R443, https://doi.org/10.1016/j.cub.2016.04.011.

25. F. Patterson, S. K. Malone, A. Lozano, M. A. Grandner, and A. L. Hanlon, "Smoking, Screen-Based Sedentary Behavior, and Diet Associated With Habitual Sleep Duration and Chronotype: Data From the UK Biobank," *Annals of Behavioral Medicine* 50, no. 5 (2016): 715–726, https://doi.org/10.1007/s12160-016-9797-5.

26. M. Y. Menek and M. Budak, "Effect of Exercises According to the Circadian Rhythm in Type 2 Diabetes: Parallel-Group, Single-Blind, Crossover Study," *Nutrition, Metabolism, and Cardiovascular Diseases* 32, no. 7 (2022): 1742–1752, https://doi.org/10.1016/j.numecd.2022.04.017.

27. J. M. Thomas, P. A. Kern, H. M. Bush, et al., "Circadian Rhythm Phase Shifts Caused by Timed Exercise Vary With Chronotype," *JCI Insight* 5, no. 3 (2020): e134270, https://doi.org/10.1172/jci.insight.134270.

28. B. M. Gabriel and J. R. Zierath, "Circadian Rhythms and Exercise—Re-Setting the Clock in Metabolic Disease," *Nature Reviews Endocrinology* 15 (2019): 197–206, https://doi.org/10.1038/s41574-018-0150-x.