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# Use of Accelerometers to Track Changes in Stepping Behavior With the Introduction of the 2020 COVID Pandemic Restrictions: A Case Study

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***Introduction:*** The COVID-19 lockdown introduced restrictions to free-living activities. Changes to these activities can be accurately quantified using combined measurement. Using activPAL3 and self-reports to collect activity data, the study aimed to quantify changes that occurred in physical activity and sedentary behavior between prelockdown and lockdown. The study also sought to determine changes in indoor and outdoor stepping. ***Methods:*** Using activPAL3, four participants recorded physical activity data prelockdown and during lockdown restrictions (February–June 2020). Single events (sitting, standing, stepping, lying) were recorded and analyzed by the CREA algorithm using an event-based approach. The analysis focused on step count, sedentary time, and lying (in bed) time; median and interquartile range were calculated. Daily steps classified as taking place indoors and outdoors were calculated separately. ***Results:*** Thirty-three prelockdown and 92 in-lockdown days of valid data were captured. Median daily step count across all participants reduced by 14.8% (from 5,828 prelockdown to 4,963 in-lockdown), while sedentary and lying time increased by 4% and 8%, respectively (sedentary: 9.98–10.30 hr; lying: 9.33–10.05 hr). Individual variations were observed in hours spent sedentary (001: 8.44–8.66, 002: 7.41–8.66, 003: 11.97–10.59, 004: 6.29–7.94, and lying (001: 9.69–9.49, 002: 11.46–11.66, 003: 7.63–9.34, 004: 9.7–11.12) pre- and in-lockdown. Discrepancies in self-report versus algorithm classification of indoor/outdoor stepping were observed for three participants. ***Conclusion:*** The study quantitatively showed lockdown restrictions negatively impacted physical activity and sedentary behavior; two variables closely linked to health outcomes. This has important implications for public health policies to help develop targeted interventions and mandates that encourage additional physical activity and lower sedentary behavior. Q1

***Keywords:*** physical activity, activity monitor, lockdown

The emergence of the COVID-19 virus in 2020 has been one of the most serious public health challenges in recent times. One of the main responses, reflected worldwide, to the emerging pandemic was the introduction of significant lockdown conditions (Cabinet Office, 2020) to reduce community transmission of the disease. The lockdown rules set out by the U.K. government (Figure 1) resulted in unexpected and uncommon restrictions to movement patterns for the majority. Components of the lockdown response, including restrictions on group exercise activities, closure of gyms, and limitations on leaving home during the early stages of the lockdown significantly reduced opportunities to undertake physical activity (Stockwell et al., 2021; Strain et al., 2022) and increased sedentary behavior (Górnicka et al., 2020; Tison et al., 2020).

These changes in physical activity and sedentary behavior are known to have a negative impact on a range of physical and mental health outcomes in adults such as cardiovascular health, diabetes, and depression (Callow et al., 2020; Chandrasekaran & Ganesan, 2021; Dunstan et al., 2012; Wood et al., 2020; World Health Q2 Organization, 2020). This explains the importance of physical activity and sedentary behavior in current health policy as well Q3 as the physical activity mandate set out by the World Health Organization (2018). Measuring these factors is therefore necessary to understand the potential impact of restrictions.

Step count is a particularly useful indicator since it has been shown to correlate strongly with physical activity (Kraus et al., 2019). Interestingly, it has been highlighted that step count volume is more valuable than step intensity for improving health outcomes (Saint-Maurice et al., 2020). Studies have shown that achieving the recommended levels of moderate–vigorous physical activity (e.g., 150 min/week) may not counteract an otherwise sedentary lifestyle. Prolonged sedentarism (e.g., office work) can still have a negative impact on health despite exercise, thus time spent sedentary is justified as a separate measure (Clemes et al., 2014; González-Gross & Meléndez, 2013).

To allow the development of more targeted interventions and public health messaging that encourages additional physical activity, it is important to understand how both physical activity patterns and sedentary behavior change. This could be in response to lockdown or other events that limit physical activity including periods of ill-health or during rehabilitation.

Studies using self-report have observed a significant reduction in physical activity and an increase in sedentary behavior during lockdown compared with prepandemic levels (Robinson et al., 2021; Wood et al., 2020). However, subjective measures are limited in their ability to evaluate levels of physical activity and sedentary behavior. Self-report measures are commonly accepted as they are cost-effective and practical (Besson et al., 2010; Ishikawa-Takata et al., 2008), involving the use of questionnaires,

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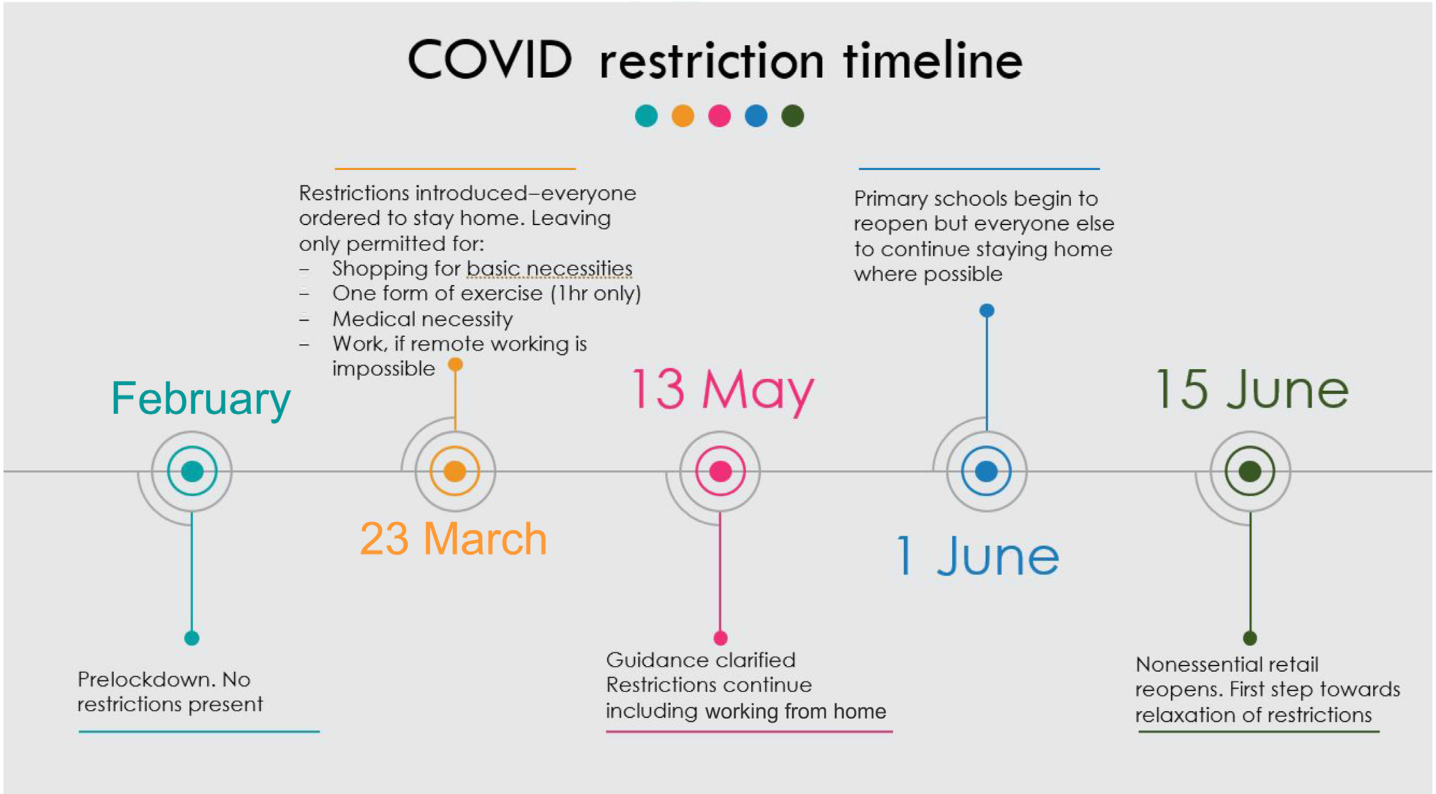



**Figure 1** — Timeline of lockdown restrictions in the United Kingdom.

activity diaries or logs, surveys, and interviews (Prince et al., 2008; Sylvia et al., 2014). Although insightful, these methods are often subject to error due to memory recall and response bias (i.e., activity and intensity rates are often over- or underestimated by the general population; Deliens et al., 2021; Prince et al., 2008), limiting their reliability and validity, thus compromising their usefulness for assessing how physical activity and sedentary behavior levels are quantitatively altered between prelockdown and lockdown conditions (Shook et al., 2016; Walsh et al., 2004). In comparison, objective (i.e., direct) measures are usually more expensive, intrusive, and (depending on the population age) time-consuming (Kowalski et al., 2012). They usually involve direct observation, that is, researchers monitor and record a participant's physical activity, or measurement devices such as accelerometers, pedometers, armbands or heart rate monitors are used (Aunger & Wagnild, 2022). The choice of device is dependent on the aspect of physical activity or inactivity an individual wants to measure. Such devices can provide a useful means of quantifying energy expenditure (often calculated using embedded algorithms which monitor travel speed and heart rate), movement (e.g., number of steps or stairs climbed), and sedentary behavior (time asleep, resting heart rate; Aunger & Wagnild, 2022; Sylvia et al., 2014). However, it is important to note that objective measures can sometimes capture nonphysical activity either due to their location on the body, calibration methods, or measurement error (Prince et al., 2008). For this reason, using multiple or combined methods of direct and indirect physical activity assessment is often recommended (Sylvia et al., 2014).

Lockdown posed a new restriction on everyday movement of individuals (Ammar et al., 2020) that was unlikely experienced before. This restriction in free movement was hypothesized to result in a decrease in physical activity and an increase in sedentary behavior among a healthy adult cohort. Fortuitously, physical activity within a young adult cohort was already being captured so a direct comparison between prelockdown and lockdown activity could be made.

Previous studies have been conducted which investigate the influence of COVID-19 lockdowns on physical activity and behavioral changes using both subjective and objective means. Study findings among published work largely agree that COVID-19 lockdown restrictions posed a health risk due to behavioral changes resulting from altered routines (particularly for nonessential workers), reduced amount or intensity of physical activity, and increased bouts of sedentary behavior (Barkley et al., 2021; Kingsnorth et al., 2021). However, due to the nature of lockdown restrictions, such studies possess limitations associated with one or a combination of the following: reliance on self-reported measures, memory recall and candor (Buoite Stella et al., 2021); compliance (Fernández-García et al., 2021); representative demographics among participants (Kingsnorth et al., 2021; Stockwell et al., 2021); and population size; use of multiple device types and settings used to monitor activity levels (which introduced an array of measurement error due to heterogeneity; Buoite Stella et al., 2021; Germini et al., 2022). Due to these limitations, most studies recommend further work to gain insight into how the pandemic affected activity and sedentary behavior before more definite conclusions can be drawn. Furthermore, although the majority of studies utilized both objective and subjective measures, none involved using the activPAL. The majority use commercially available smart devices, for example, smartphones or watches such as the Fitbit which, although affordable, are not research-grade devices and are typically wrist-worn. As a result, the reliability of data obtained has been called into question, particularly for moderate to high-intensity exercise (Redenius et al., 2019). Since the suitability of activity monitoring devices is highly dependent on desired outcome measures (O'Driscoll, Turicchi, Hopkins, et al., 2020), the choice of device should be study design specific wherever possible.

To this end, the aim of the study was to identify and quantify the changes occurring in physical activity and sedentary behavior between prelockdown and lockdown conditions, with a focus on sedentary time and step count in the analysis. This study used a research-grade wearable device (activPAL3) using an event-based approach. The activPAL3 was chosen because it has demonstrated improved accuracy in quantifying how free-living physical activity is accumulated (Curran et al., 2021). This is due to the relative position of the device on the body, elucidating the demonstrable impact of lockdown on physical activity and sedentary behavior (Grant et al., 2006; O'Driscoll, Turicchi, Beaulieu, et al., 2020). Placement of the device on the upper thigh reduced error related to capturing nonambulatory physical activity, thus improving the accuracy of data (Giurgiu et al., 2020; Suorsa et al., 2020). The study also sought to determine if there was any change in both indoor and outdoor stepping, classified by stepping-event duration. Recording whether an individual spent their time indoors or outdoors aids in understanding of whether location restrictions result in a lower step count in a 24 hr period.

## Materials and Methods

### Design and Participants

Six postgraduate students as part of a physical behavior module, were collecting free-living physical activity data. Upon the introduction of lockdown restrictions, the study design and protocol were modified enabling the new hypothesis to be tested. Students were approached to determine whether they consented to their data being used for a research study and if they were happy to continue collecting data for a prolonged period. Data collection for the study were approved by the University of Salford School of Health and Society Research Ethics Panel (HST1617-202). Of the six students, four agreed to participate in the study (one refused consent and one returned home overseas)—participant demographics can be found in Table 1.

Due to the rapid initiation of the study and small sample size, a case study-based approach was considered the most appropriate. This allowed for detailed information and insight that could be used for future research. It also allowed for investigation into the effects of lockdown restrictions on physical activity and sedentary behavior where it otherwise would have been impossible to carry out.

Data were collected between February 17, 2020 and March 22, 2020 as part of an observational experiment for an academic module. The participants continued collecting physical activity data for up to 3 months following the introduction of lockdown restrictions (March 23, 2020–June 22, 2020). During the lockdown period, participants kept a diary and noted the days in which they undertook physical activity outside their home.

### Physical Activity and Sedentary Time Measurement

The study used a thigh-mounted triaxial accelerometer (activPAL3 micro, PAL Technologies Ltd.), the gold standard for reliably collecting objective physical activity data (Grant et al., 2006; Lyden et al., 2017; Sellers et al., 2016), noted for its ability to measure low-intensity activity and true sedentary behaviors (Blackwood et al., 2022). The activPAL3 was waterproofed by insertion into the finger of a nitrile glove and attaching to the skin with a transparent film (e.g., Tegaderm Film). All participants were instructed by the research team on how to waterproof and fit the device and were shown how to set-up and connect the device to obtain data. Figure 2 displays waterproofing components, the activPAL3 device, and the device fitted to the midline of the anterior aspect of a participant's thigh. The mounted activPAL3 device in Figure 2c illustrates proximal–distal, medial–lateral, and anterior–posterior axes using notations *x*, *y*, and *z*, respectively. Participants were asked to wear the activPAL3 for 24 hr for 7 consecutive days before removing the device, downloading the device data using PALconnect software and electronically sending the data for analysis. The transparent film could be replaced with a fresh film if required. The participants then recharged the device for a minimum of 2 hr before repeating this process to capture additional activity data—the dates and times of the start and finish of each 7-day period were recorded.

ActivPAL3 data were downloaded and initially processed using PALBatch (version 8.10.11.54, PAL Technologies Ltd.). For each distinct period of device wear, the activity data were exported in a.csv format, termed an events file, which describes a participant's physical activity using an event-based approach (Granat, 2012). Using this approach, each continuous period of a specific type of activity, such as sitting, standing, and walking, is considered a single event. The CREA algorithm, verified by Montoye et al. (2022), was used for analysis. It identifies a range of activity classes: sitting (including seated transport), standing, stepping (all reciprocal leg movements), cycling, and lying. Each stride event determined by the algorithm comprises two steps. All consecutive stride events were combined into a single event, termed a stepping event; the number of steps in this event being twice the number of strides. Stepping events can then be characterized by their duration, the number of steps, and the cadence. Sedentary events include sitting, secondary lying, and seated transport, while lying covers primary lying events. Primary lying refers to time classified as being in bed, while secondary lying would cover all other lying events. Periods of nonwear were identified using the MORA algorithm, where nonwear is characterized by prolonged periods of continuous stillness (MORA—PAL Knowledge Base, n.d.). To accommodate short periods of nonwear at any time during the 24-hr wear protocol (starting and ending at midnight), such as nonwear and reattachment associated

**Table 1 Participant Demographics**

| Participant number | Age | Sex | Ethnicity | Profession |
|---|---|---|---|---|
| 001 | 28 | Female | White British | Postgraduate student |
| 002 | 23 | Female | Black African | Postgraduate student |
| 003 | 25 | Female | Mixed—White and Asian | Postgraduate student |
| 004 | 32 | Male | White British | Postgraduate student |

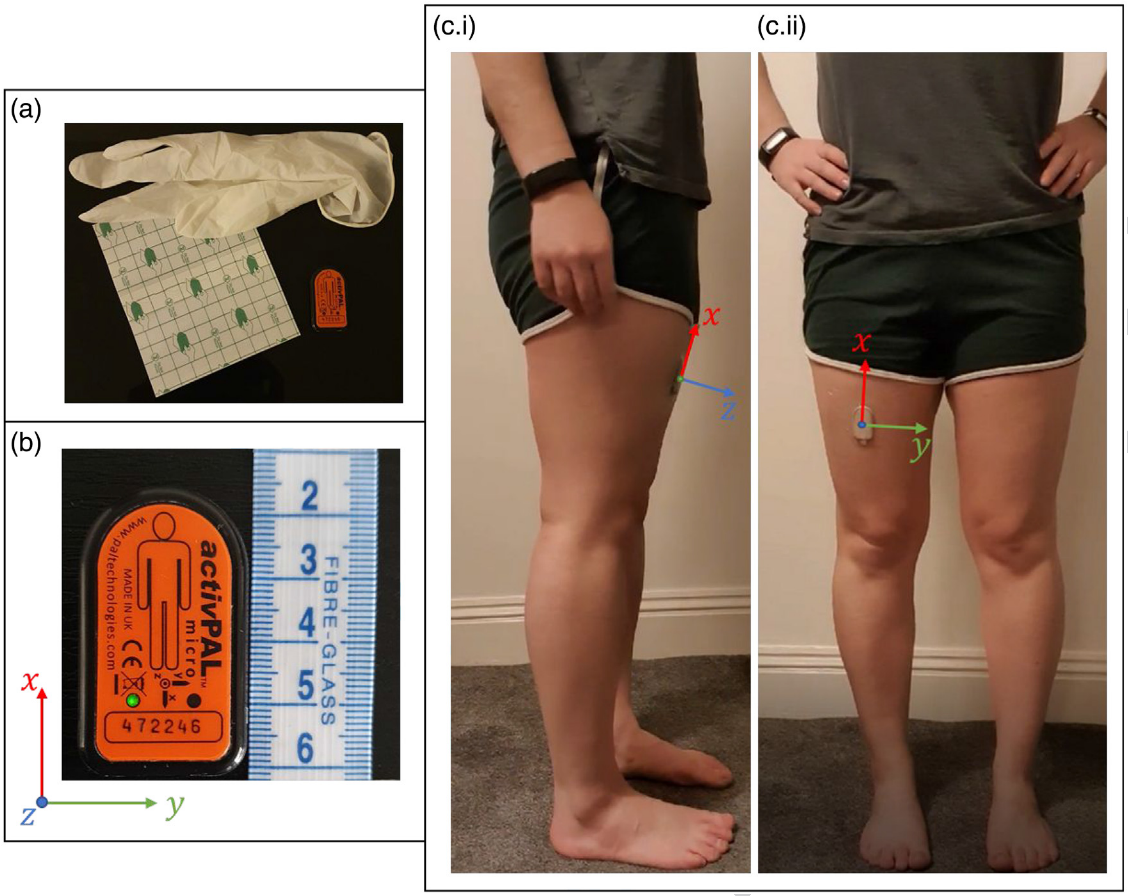



**Figure 2** — (a) Waterproofing equipment: nitrile glove and transparent film/tape, (b) activPAL3, and (c) activPAL3 placement on participant: (i) sagittal and (ii) coronal view. The *x*, *y*, and *z* axes indicate proximal–distal, medial–lateral and anterior–posterior directions, respectively.

with showering, each day with a minimum of 20 hr of valid physical activity data was considered in the analysis. This enabled incomplete days, at the start and end of the recording period, to be removed.

## Collection of Self-Reported Data

Each participant kept a diary of physical activity and sedentary behavior throughout the time of monitoring. In this, they made note of dates and times the activity monitor was worn, their wake and sleep times, specific activities (e.g., exercise), and any issues or adjustments made to the monitor. From the commencement of lockdown participants were asked to include whether, or not, they went outside for particular activities (e.g., exercise, shopping, work, etc.). Participant demographic data were gathered at the end to contribute to analysis (Table 1).

## Classification of Days by Lockdown Period

Days were initially classified based on their relationship to the introduction of lockdown restrictions (prelockdown or lockdown). "Lockdown" days were subdivided into *outdoor* versus *indoor only*, based on whether the participant reported outdoor activity on that day.

## Classification of Stepping as Indoor or Outdoor

In order to investigate differences in indoor and outdoor stepping, the approach outlined in Speirs et al. (2021) was utilized to classify periods of indoor stepping. This is based on the observation that space restrictions associated with indoor stepping are likely to place an upper limit on the maximum time an individual can step without breaks in their stepping. Thus, consecutive stepping events shorter than 60 s were classified as *indoor*, and longer stepping events were classified as *outdoor*.

## Data Cleaning and Statistical Analysis

Initially, days that fell outside of the specified observation period or did not have the required minimum valid wear time were removed using an R programming script (The R Foundation, 2022). There was no attempt to remove periods of sleeping during the analysis, as these contributed to lying time. Due to the skew of the daily step count data (skewness is 1.59), median, and interquartile range (IQR) were used to calculate daily time spent in different activity types and daily step count. The daily number of steps classified as taking place indoors and outdoors were calculated separately.

The distribution of daily stepping totals for the participants was characterized using an existing index of physical activity behavior (Tudor-Locke & Bassett, 2004). To better differentiate a large number of days with very low step counts (below 5,000 steps), a further category was added to identify days where less than 2,500 steps were taken as in Tudor-Locke et al. (2009).

For each participant, a chart was generated to display the daily breakdown of steps taken. During the lockdown period, days were labeled based on whether the participant self-reported not leaving the house.

## Results

Across the four participants that consented to wear the activPA3L, a total of 125 days' valid activity data were captured (33 prelockdown and 92 in-lockdown) and 40 days of activity were excluded (13 prelockdown and 27 in-lockdown) for having less than 20 hr of valid wear (Table 2). The remaining 125 days all had 24 hr of wear time per day. Participant adherence was high, with all individuals collecting valid activPAL3 data for at least 5 days both prelockdown, and in-lockdown, and successfully completing a daily activity diary over the same periods. Continued adherence varied due to individual circumstances during lockdown, thus resulting in a greater range in the quantity of data collected per participant.

Across all participants, the median daily step count was 5,828 (IQR 4,902–12,860) prelockdown and 4,963 (IQR 3,370–6,232) during lockdown. This shows a 14.8% reduction in step count following the introduction of restrictions and a significantly reduced IQR. For three participants, the daily step count was lower in-lockdown than prelockdown (001: −16.9%, 002: −73.5%, 004: −54.4%). An exception to this was Participant 003, for whom prelockdown and lockdown median step counts were similar (5,074 and 5,068, respectively).

### Participant 001

Figure 3 shows a broadly consistent distribution of daily step counts across prelockdown (red 4,118) and lockdown (green/blue 4,808) data, but with lockdown data centered about a lower median (prelockdown 9,313, lockdown 7,742). It is observed that for "all stepping" events combined, there are 5 days (27.8% of days) with a very low step count (< 5,000 steps) during lockdown which are not present prelockdown (0% of days).

The indoor and outdoor stepping breakdowns in Figure 3 are described in Table 3, showing that indoor stepping was limited to < 5,000 steps in both prelockdown and lockdown conditions. During lockdown there was a slight change in the distribution of steps such that 22.2% of days rather than 16.7% were over 2,500. Outdoor stepping saw a greater change, with days ≥10,000 dropping from 33.3% of the total days prelockdown to 5.6%. In contrast, the 7,500–9,999 step group increased from 16.7% to 27.8%. The 5,000–7,499 and 2,500–4,999 groups were consistent between pre- and lockdown conditions, but days with <2,500 steps only occurred during lockdown. Figure 3 shows no indoor-only days (i.e., no blue markers). During lockdown, Participant 001 reported in their activity diary going outdoors at least once every day; this was consistent with the output from the classification system.

Considering daily duration of sedentary behavior and lying activity, Figure 3 shows that the median overall time spent sedentary remains relatively consistent during the whole observation period (8.44 hr before and 8.66 hr during lockdown). Although lying time overall is consistent between prelockdown and the complete lockdown data set (median 9.69 hr prelockdown and 9.49 hr lockdown), the initial recordings at the start of lockdown did show a significantly smaller range and lower median (median: 8.97, IQR: 0.37 hr in April) compared with later in-lockdown (median: 9.88, IQR: 2.16 hr in May).

### Participant 002

Figure 4 illustrates a large overall reduction in daily step count during lockdown (prelockdown median step count 4,557 to lockdown median step count of 1,208), with a reduced variation in daily step count compared with prelockdown days (prelockdown IQR step count 4,274 to lockdown IQR step count of 480).

The most prominent difference was observed in steps classified as occurring outdoors. From Table 4, 94.4% of recorded days in-lockdown featured < 2,500 steps for outdoor stepping, compared with only 50% of prelockdown days. During lockdown there was only 1 day which deviated from the <2,500 group (≥10,000 5.6%), whereas, during prelockdown there were days across the range of groups (<2,500 50%, 2,500–4,999 16.7%, 5,000–7,499 16.7%, ≥10,000 16.7%). The step counts for indoor stepping remain consistent for prelockdown and lockdown conditions (medians 865 and 1,121, respectively) with all indoor step counts at <5,000 and the majority (83.3% prelockdown, 94.4% in-lockdown) at <2,500 (Table 4). For Participant 002, 11 of 18 days (61.1%) in-lockdown were self-reported as taking place indoors only; while of the 7 days self-reported as outdoors, three were identified by the classification algorithm as having no periods of outdoor stepping. These days were characterized by extremely low step counts (<1,500 steps).

Although the sedentary and lying time ranges decrease slightly from prelockdown to lockdown (sedentary: 2.99–1.75 hr respectively, lying: 2.93–1.29 hr, respectively), the median daily duration spent sedentary increases slightly (7.41 and 8.66 hr respectively) while lying time was found to be similar (11.46 and 11.66 hr, respectively) across the prelockdown and lockdown periods for Participant 002.

### Participant 003

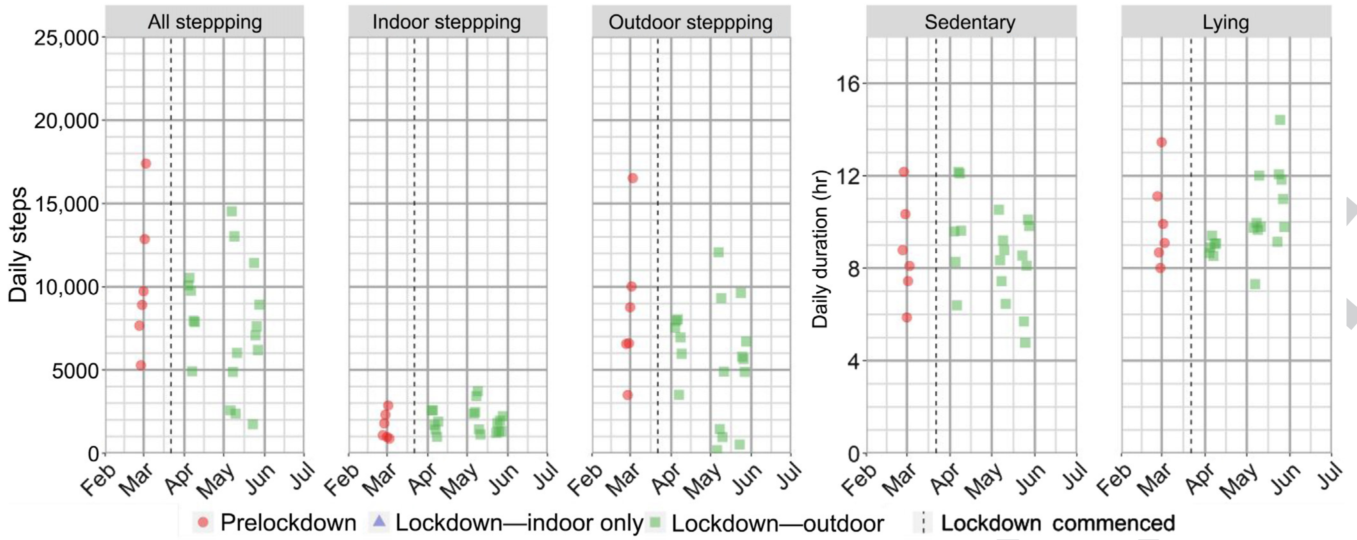
A similar median of daily stepping was observed in Participant 003 during prelockdown and lockdown periods (5,074 and 5,068 steps, respectively). However, for variation in daily step count, a drastic reduction was observed during lockdown conditions (prelockdown IQR: 4,887 steps, lockdown IQR: 1,494 steps; Figure 5).

The most notable change in step count is seen in outdoor stepping, in which both range and median decreased significantly from prelockdown to lockdown (median 3,374–2,022 steps and IQR 3,501–941, respectively). A corresponding increase in median stepping classified as taking place indoors (prelockdown 1,528 steps, lockdown 2,952 steps) was also observed. The data in

**Table 2 Characteristics of Daily Step Count in Relation to the Classification of Days by Lockdown Period**

| | Prelockdown | | Lockdown | |
|---|---|---|---|---|
| Participant number | Days | Daily steps | Days | Daily steps |
| 001 | 6 | 9,313 (7,960–12,078) | 18 | 7,742 (5,190–9,998) |
| 002 | 6 | 4,557 (2,422–6,696) | 18 | 1,208 (1,052–1,532) |
| 003 | 15 | 5,074 (1,573–6,460) | 51 | 5,068 (4,344–5,838) |
| 004 | 6 | 18,787 (8,882–20,444) | 5 | 8,564 (5,430–8,674) |

*Note*. [a]Values are median (interquartile range), unless otherwise indicated.




Q10 **Figure 3** — Physical activity profile for Participant 001 during prelockdown and lockdown period. *Note*. Recordings are color-coded depending on self-reported daily activity: prelockdown days (red circles); lockdown days where all time is spent indoors (blue triangles); lockdown days where the participant self-reports going outdoors that day (green squares).

**Table 3 Prelockdown and Lockdown Step-Count Distributions for Participant 001**

| | Indoor | | Outdoor | |
|---|---|---|---|---|
| **Step count** | **Prelockdown** | **Lockdown** | **Prelockdown** | **Lockdown** |
| 0–2,499 (days, %) | 5 (83.3) | 14 (77.8) | — | 4 (22.2) |
| 2,500–4,999 (days, %) | 1 (16.7) | 4 (22.2) | 1 (16.7) | 3 (16.7) |
| 5,000–7,499 (days, %) | — | — | 2 (33.3) | 5 (27.8) |
| 7,500–9,999 (days, %) | — | — | 1 (16.7) | 5 (27.8) |
| ≥10,000 (days, %) | — | — | 2 (33.3) | 1 (5.6) |

Table 5 emphasizes these changes, where the proportion of days falling within the lowest (<2,500 steps) group for indoor step count decreases from prelockdown to lockdown conditions (93.3%–19.6%, respectively) while higher categories increase (2,500–4,999 from 6.7% to 76.5% of days, respectively, and 5,000–7,499 from 0% to 3.9%, respectively). Outdoor stepping demonstrates the reverse trend, with days of <2,500 steps rising from 33.3% prelockdown to 70.6% during lockdown. The margins of higher daily outdoor step-counts all decrease from prelockdown to lockdown conditions or are not found in the latter at all (2,500–4,999 from 40.0% to 27.5%, 5,000–7,499 from 13.3% to 2.0%, 7,499–9,999 no change at 0%, and ≥10,000 from 13.3% to 0%). There was 1 day where the participant reported outdoor activity, but the classification algorithm identified no periods of outdoor stepping.

The median daily duration spent sedentary was observed to decrease from prelockdown to lockdown conditions (prelockdown 11.97 hr, lockdown 10.59 hr); in contrast median lying time increased during lockdown (prelockdown 7.63 hr, lockdown 9.34 hr).

## Participant 004

Figure 6 shows a large overall reduction in daily step count during lockdown (median 8,564 steps) compared with prelockdown activity (median 18,787 steps). Similar to Participant 003, stepping classified as occurring outdoors decreased notably (median 17,366–3,760 steps) while a smaller increase in stepping classified as occurring indoors (from a median of 1,736–2,884 steps) was found.

The most prominent change from prelockdown to lockdown was observed in outdoor stepping, with a large decrease in both range (11,219 steps prelockdown to 3,000 steps in-lockdown) and median (17,366 steps prelockdown to 3,760 steps in-lockdown). From Table 6, where 66.7% of outdoor step counts reached ≥10,000 prelockdown, high outdoor step counts were completely absent in-lockdown; yet, the number of days in every other category is higher. This results in a more varied distribution than prelockdown where days were either 2,500–4,999 steps (33.3%) or ≥10,000 (66.7%). The proportion of days with <2,500 indoor steps dropped from 83.3% prelockdown to 0% in-lockdown while the 2,500–4,999 group increased from 16.7% to 100% over the same period. The majority of days during the lockdown period were self-reported as being spent indoors only, which was not reflected in the classification of daily steps for Participant 004 where all days were classified as having outdoor stepping (80% self-reported, 0% classification).

Median duration in both sedentary and lying time increased slightly during lockdown (sedentary 7.94 hr [IQR: 1.79 hr], lying 11.12 hr [IQR: 0.48]) compared with their prelockdown behavior (sedentary 6.29 hr [IQR: 1.87], lying 9.70 hr [IQR: 2.12 hr]).

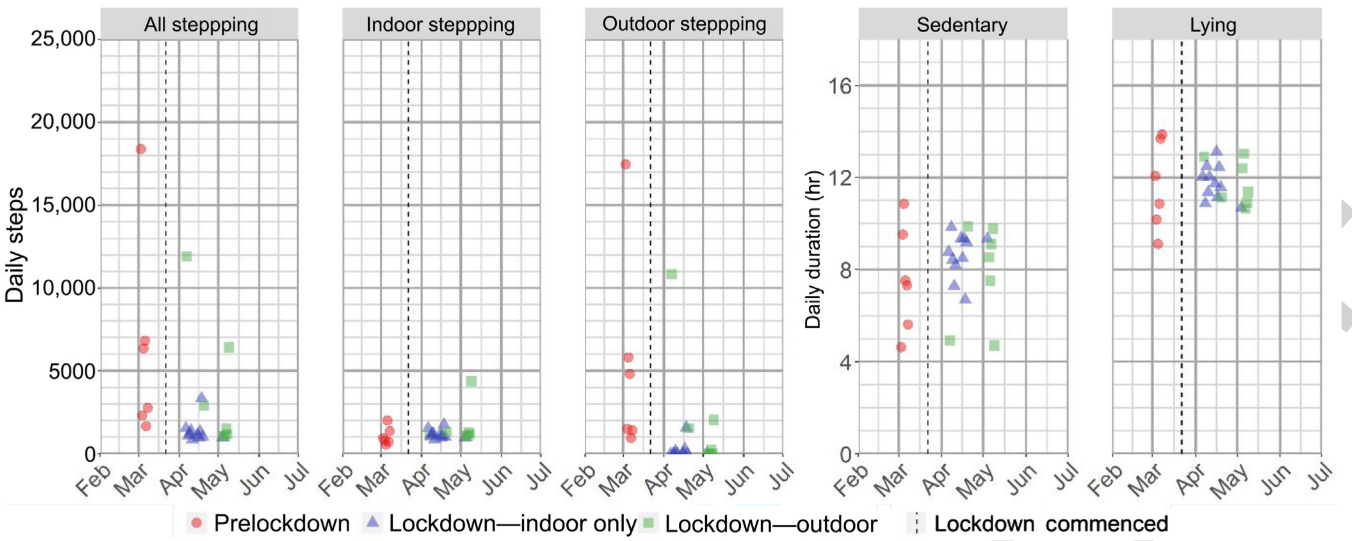



**Figure 4** — Physical activity profile for Participant 002 during prelockdown and lockdown period. *Note*. Recordings are color coded depending on self-reported daily activity: prelockdown days (red circles); lockdown days where all time is spent indoors (blue triangles); lockdown days where the participant self-reports going outdoors that day (green squares).

**Table 4 Prelockdown and Lockdown Step-Count Distributions for Participant 002**

| | Indoor | | Outdoor | |
|---|---|---|---|---|
| **Step count** | **Prelockdown** | **Lockdown** | **Prelockdown** | **Lockdown** |
| 0–2,499 (days, %) | 5 (83.3) | 17 (94.4) | 3 (50) | 17 (94.4) |
| 2,500–4,999 (days, %) | 1 (16.7) | 1 (5.6) | 1 (16.7) | — |
| 5,000–7,499 (days, %) | | — | 1 (16.7) | — |
| 7,500–9,999 (days, %) | — | — | — | — |
| ≥10,000 (days, %) | — | — | 1 (16.7) | 1 (5.6) |

## Discussion

This study investigated the use of an activPAL3 activity monitor to measure changes in physical activity and sedentary time arising from lockdown conditions. The four participants successfully recorded the variables over 5 months encompassing the period prior to the introduction of COVID-19 lockdown restrictions in the United Kingdom and the first 3 months of lockdown conditions.

Importantly, the activPAL3 allowed identification of individual-specific behavioral changes which would not have been apparent from volume-based measures of physical activity and sedentary behavior (Bassett et al., 2015). This is because an event-based approach allows the composition of activity to be looked at to ascertain how stepping was accumulated.

The study's findings indicated that lockdown negatively impacted physical activity and sedentary behavior, although observed changes on an individual basis varied. For example, while the volume of steps decreased for all participants the distribution of step count remained consistent for Participant 001 as they continued to leave their house daily. In contrast, Participants 002, 003, and 004 all exhibited a significant reduction in walking for continuous bouts lasting over 60 s, implying very little outdoor walking. The data for the latter two participants report increased *indoor* walking, but not enough to match the reduced volume of outdoor walking. For self-reported data, some discrepancies—particularly for Participants 002 and 004—indicated a level of recall bias (Deliens et al., 2021; Prince et al., 2008; Shook et al., 2016; Walsh et al., 2004) or that the algorithm used is not suitable for assessing free-living movements in restrictive conditions. This highlights the value of combining both objective and subjective measurement reports (Sylvia et al., 2014) to mitigate method limitations.

## Step Count

### *Participant 001*

For Participant 001, though the distribution of step count remained consistent the overall volume of steps reduced during lockdown, including 3 days with very low step count values of less than 2,500 steps. This suggests that the participant was restricted in their physical activity upon the introduction of lockdown rules. Considering the lockdown mandate that people could only leave the home for essential errands or 1 hr of exercise per day (Prime Minister's Office, 2020), this may explain why the data show substantial changes only in stepping classified as outdoors. Because of the 1-hr mandate, Participant 001 may have taken full advantage and been outdoors and active for the full hour. This may indicate why there are still higher levels of step counts (5 days at 7,500–9,999) for outdoor stepping.

Every day during lockdown conditions, Participant 001 undertook stepping classified as outdoor, which matches with their self-

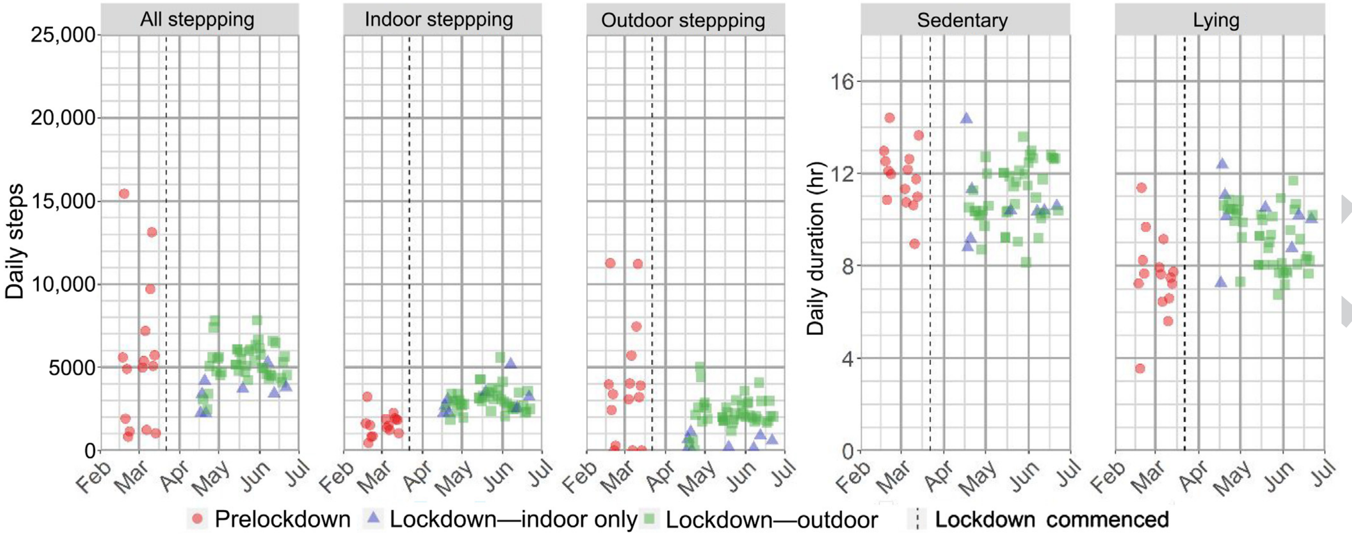



**Figure 5** — Physical activity profile for Participant 003 during prelockdown and lockdown period. *Note*. Recordings are color-coded depending on self-reported daily activity: prelockdown days (red circles); lockdown days where all time is spent indoors (blue triangles); lockdown days where the participant self-reports going outdoors that day (green squares).

**Table 5 Prelockdown and Lockdown Step-Count Distributions for Participant 003**

| | Indoor | | Outdoor | |
|---|---|---|---|---|
| **Step count** | **Prelockdown** | **Lockdown** | **Prelockdown** | **Lockdown** |
| 0–2,499 (days, %) | 14 (93.3) | 10 (19.6) | 5 (33.3) | 36 (70.6) |
| 2,500–4,999 (days, %) | 1 (6.7) | 39 (76.5) | 6 (40) | 14 (27.5) |
| 5,000–7,499 (days, %) | | 2 (3.9) | 2 (13.3) | 1 (2.0) |
| 7,500–9,999 (days, %) | — | — | — | — |
| ≥10,000 (days, %) | — | — | 2 (13.3) | — |

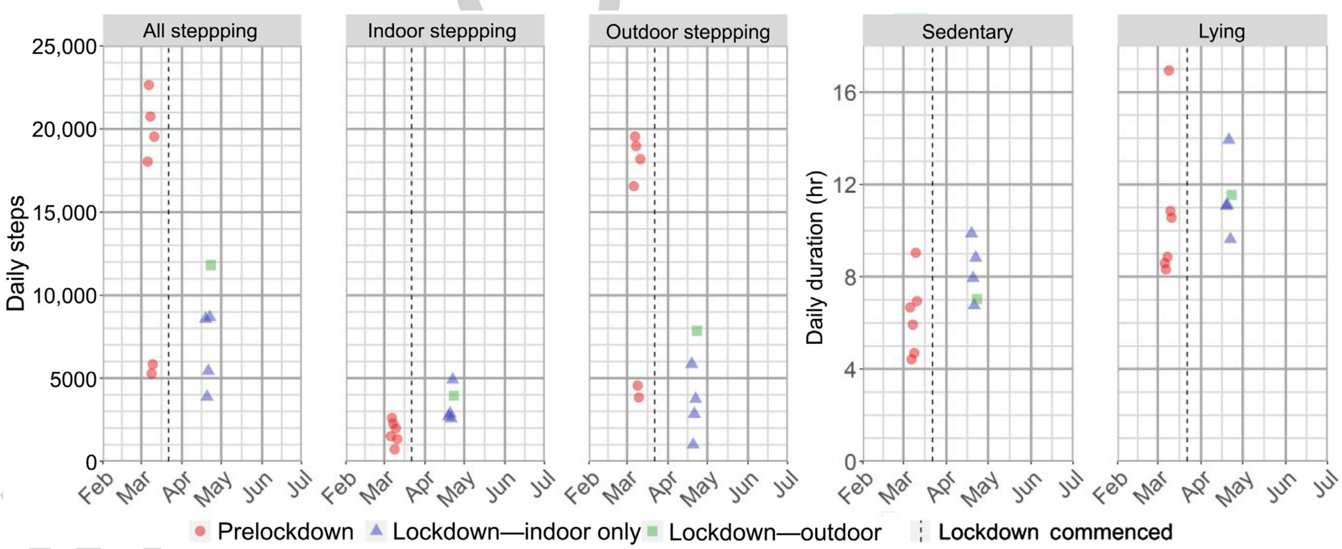



**Figure 6** — Physical activity profile for Participant 004 during prelockdown and lockdown period. *Note*. Recordings are color-coded depending on self-reported daily activity: prelockdown days (red circles); lockdown days where all time is spent indoors (blue triangles); lockdown days where the participant self-reports going outdoors that day (green squares).

**Table 6 Prelockdown and Lockdown Step-Count Distributions for Participant 004**

| | Indoor | | Outdoor | |
|---|---|---|---|---|
| **Step Count** | **Prelockdown** | **Lockdown** | **Prelockdown** | **Lockdown** |
| 0–2,499 (days, %) | 5 (83.3) | — | — | 1 (20) |
| 2,500–4,999 (days, %) | 1 (16.7) | 5 (100) | 2 (33.3) | 2 (40) |
| 5,000–7,499 (days, %) | | — | — | 1 (20) |
| 7,500–9,999 (days, %) | — | — | — | 1 (20) |
| ≥10,000 (days, %) | — | — | 4 (66.7) | — |

reported physical activity indicating that they left their house daily to take their dog for a walk. This implies that by classifying stepping events, in this case indoor versus outdoor stepping, it is possible to identify individuals that may have essential activities in their daily schedule which require them to leave the restricted confines of their home. Dog owners have been shown to have higher levels of physical activity due to the neccessity to take their dogs on regular walks (Christian et al., 2013; Westgarth et al., 2019).

#### *Participant 002*

For Participant 002, the decrease in-lockdown step count was driven mainly by the absence of stepping periods greater than 60 s (“outdoor” stepping). The data imply they did not leave their house frequently during lockdown (11 of 18 days self-reported as being indoor only). The activPAL3 data were classified as having an additional 3 days as indoor only with an extremely low step count on these days of <1,500. The disparity could be down to recall bias in the self-report diary (Deliens et al., 2021; Prince et al., 2008; Shook et al., 2016) and may be in part be due to the impact of lockdown conditions on the subjective experience of the passage of time (Kosak et al., 2022; Ogden, 2020; Wittmann, 2020).

Many individuals in the United Kingdom do not have access to a garden or have green spaces in close proximity (Barbosa et al., 2007; Brindley et al., 2018; Jassi & Dutton, 2020). This could seriously limit the type and/or amount of physical activity possible for an individual when restrictions or limitations on daily excursions are enforced. This poses serious physical and mental health risks related to reduced physical activity for individuals who must experience confinement or isolation for any reason (Ammar et al., 2020; Ghram et al., 2021).

#### *Participant 003*

For Participant 003, during lockdown an increase in stepping classified as taking place indoors compared with prelockdown levels was observed. This could be evidence of an attempt to increase movement in response to the lack of opportunity to undertake nonessential outdoor activity. Kaur et al. (2020), Lim and Pranata (2021), and Newbold et al. (2021) showed that home/online workouts, for example, increased in popularity during lockdown. While it may be theorized that spending longer indoors will inevitability result in increased indoor stepping due to an individual’s need to complete their daily activities, this was not consistently observed across the cohort. External variables that are individual-specific, for example, size of property, caring for dependents, or a tendency to undertake domestic work have all been shown to affect physical activity levels (Chambers & Fuster, 2012; Oliver & Kemps, 2018; Piercy et al., 2018; Rhodes et al., 2014), and thus alterations to indoor step counts is likely highly dependent on individual-specific variables. These variables were not gathered during this study; therefore, future studies would benefit from collection of broader demographic information.

#### *Participant 004*

As with Participant 003, Participant 004 demonstrated the same increase in indoor stepping that may have resulted from the same factors previously mentioned. In addition, Participant 004 showed the most prominent decrease in stepping classified as outdoor as well as a lower variation in step count ranges. A large proportion of daily step count has been shown to come from nonexercise activity thermogenesis, including activities such as commuting (Levine, 2002; Yang et al., 2012). Considering this, the requirement to work from home, in addition to the closure of services, and reduction in social engagements will have resulted in a substantial decrease in physical activity: this is supported by other findings in the literature (Bin et al., 2021; Castañeda-Babarro et al., 2020; Kass et al., 2021). The effects caused by changes in legislation and services are likely to have impacted a large number of individuals nationally—as a result of lockdown, the United Kingdom saw the volume of individuals who work from home increase from 5.7% (January/February 2020) to 43.1% (April 2020; Felstead & Reuschke, 2020).

Considering the data of all four participants, the overall reduction in step count per day suggests that introduction of lockdown conditions has a negative impact on physical activity levels, which is supported by the literature (Martínez-de-Quel et al., 2021; Stockwell et al., 2021; Strain et al., 2022; Tison et al., 2020). Little variation in daily step count during lockdown was observed, particularly for Participants 002 and 003, compared with prelockdown where the range in daily step count was much greater. It is unclear whether this reduced variation in daily stepping was solely driven by external factors, such as lockdown restrictions removing opportunities to vary daily routine, or whether it was the participants’ method of adaption or coping strategy to reinforce positive mental well-being during lockdown conditions (Public Health England, 2021). Additionally, there are indications that the government directive to only leave the house for a single period of exercise contributed to the development of artificial routines (Buckaloo et al., 2009; Cashin et al., 2008) which could account for the observed low variation in daily stepping. Overall, considering the recommended step count of 10,000 steps/day (or more flexibly 8,000–11,000 steps/day) for healthy adults as set out in Tudor-Locke et al. (2011), only one of the participants (004) achieved this successfully during lockdown (median: 8,564 steps). Of the four participants, two experienced a step count reduction great enough to classify them at a lower activity level (002: “limited activity” to “basal activity,” 004: “highly active” to “somewhat active”), while a third (001) went from being at the top of the “active” category (7,500–9,999 steps/day) during prelockdown to the very bottom during lockdown (from 9,313 to 7,772 steps). In support of the literature (Martínez-de-Quel et al., 2021), this indicates the negative impact lockdown restriction may have had on physical activity-based health outcomes.

## Sedentary Time

Since all the participants were postgraduate students, their desk-based employment contributed to a baseline of sedentary hours (often higher than office workers; Castro et al., 2018) which were not expected to have changed during the "working from home" period of lockdown. Given that sedentary behavior is most commonly influenced by intrinsic motivation and least by extrinsic regulation (Gaston et al., 2016), it is likely that changes in sedentary time are influenced most by choices outside of work-based sedentary hours.

### *Participants 001*

Participant 001 exhibited little change in daily sedentary time compared with prelockdown levels. Their self-report noted daily dog walks and regular home workouts thus Participant 001 appears to have adapted their behaviors to suit the lockdown restraints.

### *Participant 003*

Interestingly, Participant 003 saw a slight decrease in sedentary time (prelockdown 11.97 hr, lockdown 10.59 hr). This may have been due to domestic circumstances (e.g., responsibilities in the household) or restlessness induced by work-related stress or inability to venture outdoors and separate work and home environments (Åkerstedt et al., 2015; Xiao et al., 2021).

### *Participants 002 and 004*

These participants both saw a notable increase in sedentary time from prelockdown to lockdown (002: 7.41–8.66 hr, respectively; 004: 6.29–7.94 hr, respectively). For Participant 004, sedentary time was higher on self-reported lockdown days spent solely indoors with an accompanying reduction in day-to-day variation. This supports other studies (Celorio-Sardà et al., 2021; Sadarangani et al., 2021; Stockwell et al., 2021) that have found an increase in sedentarism during lockdown compared with prelockdown conditions. The reduced diversity in sedentary behavior may highlight the importance social amenities and commitments play in contributing to weekly variation and motivation to maintain a balanced and active lifestyle (Bin et al., 2021).

## Lying Time

### *Participant 002*

Unlike the others, Participant 002 had no discernible increase in lying time between lockdown and prelockdown. Holtermann et al. (2014) showed that individuals who experience a lying time of 11 hr or more per day, regardless of whether they are active or inactive the rest of the time, have a significantly increased risk of cardiovascular disease. It may be that the human body naturally tries to ensure staying within the "optimum" range (7 hr minimum to 11 hr maximum). Having the highest (and only) lying time median to exceed 11 hr prelockdown (001: 9.69, 002: 11.6 hr, 003: 7.6 hr, 004: 10.7 hr), this may explain why there was no further increase despite the introduction of lockdown restrictions. Furthermore, all participants continued working throughout the lockdown period, limiting the time available for lying. Postgraduate research students are often shown to work long hours (Bartlett et al., 2021; Woolston, 2019), and it has been shown that those in academia were recorded as spending more time working than before lockdown (Celorio-Sardà et al., 2021). Additionally, many students have part-time jobs alongside their studies (Hovdhaugen, 2015), thus the number of hours left for lying is limited in this cohort. Number of hours worked including part-time jobs was not captured in this study, but future studies would look to benefit from capturing such data.

### *Participants 001, 003, and 004*

The remaining participants (001, 003, and 004) were all observed to have an increase in lying time. Potential reasons for these increases are discussed below both generally and specifically for each participant.

Previous research (Christian, 2012) identified that in the absence of a need to travel to work or education, people tend to increase overall time spent in bed. This may contribute to increases in lying time observed during lockdown, even within a population who were still able to work from home. Students have also been shown to work flexibly (Lei, 2015; Sang et al., 2015) and the absence of structured attendance at university may have further increased their tendency to work in nonstandard patterns, which could also account for the changes in physical activity and sedentary behavior observed during lockdown. Within the U.K. general population, Adams-Prassl et al. (2020) showed that 15% of individuals lost their jobs and a further 43% were furloughed during the initial period of lockdown, inevitably resulting in rising unemployment levels (Watson, 2020). Literature reports that people have different activity and sleep patterns when not working during weekends and holidays (Drenowatz et al., 2016), which suggests the changes in lying behavior seen in this population may reflect changes in lying behavior within the general population during lockdown.

An alternative or additional factor which could increase lying time is the imposed restrictions resulting in excess free time. Additionally, many expected holidays were canceled (Competition and Markets Authority, 2021; Davies, 2020; Kourgiantakis et al., 2021) as a result of the restrictions; with no alternative options, individuals—including the study participants—were likely forced to use this time as a surrogate holiday. Participant 001 reported a significant amount of time spent sunbathing as the weather improved toward the end of the recording period. Many people are shown to exhibit changes in lifestyle between seasons (Noonan et al., 2017) which may account for their increase in lying time toward the latter half of lockdown. This hypothesis is supported by evidence that during the lockdown many individuals experienced more personal recovery and relaxation time (Grandey et al., 2021).

# Strengths

The use of a thigh-worn sensor and the event-based approach in the analysis was a major strength of this study. As this device is particularly known for its accuracy when measuring sedentary behavior (Blackwood et al., 2022; Sylvia et al., 2014), it was appropriate for the given environmental conditions, that is, constraints imposed by lockdown. This was advantageous compared with a wrist-worn device as it decreased the likelihood of mistaking upper body movement for locomotion (Suorsa et al., 2020). It was successfully used to monitor changes over 5 months to obtain a significant amount of data, particularly on an individual basis, without researcher intervention. This approach enables physical activity and sedentary behavior to be quantitively measured, supporting subjective data by providing more objective information as to how physical activity and sedentary behavior is altered during restrictive periods such as that imposed by lockdown.

With lockdown preventing any direct intervention from researchers, the accuracy and user-friendly aspects of the activPAL3 (Berendsen et al., 2014; Harvey et al., 2016) meant that this device was particularly appropriate for a study during lockdown conditions. The high battery life and data collection capabilities of activPAL3 easily enabled a continuous wear protocol which is likely to result in high user compliance (Edwardson et al., 2017; Fukuoka et al., 2015; Xu et al., 2018). This allowed for easier collection of valid data sets.

## Limitations

A limitation of this study is the modification of the data collection protocol from an existing study to rapidly adapt to the unexpected emergence of the COVID-19 pandemic. The fast transition meant working with what was available at the time, resulting in some important variables not being captured for more effective analysis. Development and use of a more comprehensive activity diary, including variables such as property size, dependents, and part-time jobs would therefore be advantageous in future studies. The modification, nevertheless, did allow capturing and assessment of changes to physical activity and sedentary behavior imposed by lockdown, where it otherwise would not have been possible.

The unknown enforcement of lockdown and its rules resulted in data capture being disproportionate between prelockdown and lockdown (33 + 13 and 92 + 27 valid plus excluded days, respectively). This skew makes it more difficult to accurately compare the two situations. In addition, the fortuitous nature of the study limited participant recruitment to individuals already collecting appropriate data prelockdown. For this reason, sample size was small, and the study population was composed of young, healthy adults who may not display behavior representative of the general population both before and during lockdown.

Using a case study method had benefits, especially for assessing such a small sample size in an unexpected project, but it also has drawbacks. Case studies are often difficult to replicate and lack the necessary scientific rigor to allow for generalization of the result to the wider population (Crowe et al., 2011; Yin, 2009). It does, however, enable insight into an area of research and gives precedence to future work in the area.

The participants were aware they were being monitored; this may have influenced activity levels (i.e., increased measurement reactivity), particularly in the early stages of the study (Baumann et al., 2018). Though this would be mitigated by the relatively long period of continuous wear (McGrath et al., 2017), it is possible that the increase in sedentary time during lockdown may be partially attributable to decreased participant awareness as they became more accustomed to the device. However, participants were familiar with using activPAL3 and its protocols for an extended period prelockdown which likely mitigated any reactivity during lockdown. In addition, most participants already used some form of activity monitoring device (e.g., a smart watch), which potentially means participant reactivity may have reduced more rapidly compared with a different group of individuals. Furthermore, since 20 hr of data were required for a valid day, typically recording did not start on the day of application (Pontt et al., 2015). Pontt et al. (2015) also showed that the thigh-worn nature of the activPAL3 means its intrusion is less noticeable compared with other methods. Though participants were exposed to a visual representation of their data retrospectively during the download process, this is likely to have less influence than devices which provide instant feedback (Imboden et al., 2018). Furthermore, this was relevant during both prelockdown and lockdown conditions, thus any associated margin of uncertainty was consistent throughout the study.

Although the self-report measure provided some insight through subjective- to objective-measure comparison, subjective- and objective-measure mismatches were observed. This was potentially due to a common limitation of subjective measurements, that is, recall bias (Deliens et al., 2021; Shook et al., 2016). However, the activPAL3 is not able to provide the context for free-living movement behaviors without subject reporting, thus using the combined method is the best option (Sylvia et al., 2014). Future studies could look to incorporate participant reminders for subjective data capture or include another form of objective measure such as a smart watch that captures additional information such as sleep times, heart rate, or exercise types (Aunger & Wagnild, 2022; Sylvia et al., 2014).

## Conclusion

This study quantitively demonstrated lockdown restrictions had a negative impact on physical activity and sedentary behavior; two variables which are closely linked to health outcomes. Overall, step count decreased among the participants with the introduction of lockdown restrictions and sedentary behaviors increased. Individual variations were observed such as consistency in step count distribution, indoor and outdoor stepping ratios, and lying time frequency. These differences pointed toward links to individual circumstances like pet ownership and home environment, highlighting the importance of comprehensive demographic information in the interpretation of activity monitor data.

In general, the results highlighted the importance of objectively monitoring physical activity and sedentary behaviors in times of activity restrictions. Furthermore, more extensive studies are required to expand on the presented data to offer an improved representative depiction of physical activity and sedentary behavior in the context of isolation for a wider population. This work has implications for public health policies which aim to encourage additional physical activity and lower sedentary behavior through targeted interventions.

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