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Estimating changes in physical behaviour during lockdowns using accelerometry-based simulations in a large UK cohort

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Title

Estimating changes in physical behaviour during lockdowns using accelerometry-based simulations in a large UK cohort of people aged 46-48

Running Head

Lockdown: Estimated physical behaviour reductions

Keywords:

Accelerometery, Birth Cohort, COVID-19, Lockdown, Physical Behaviour, Stepping

Abstract

To contain the recent COVID-19 outbreak restrictions have been imposed, which has limited outdoor activity. These physical behaviour changes can have serious health implications, but there is little objective information quantifying these changes. This study aimed to estimate the change in physical behaviour levels during full lockdown conditions using objective data collected from a thigh-worn activity monitor. Data used was from 6,492 individuals in the 1970 British Cohort Study, collected between 2016 and 2018. Using walking bout characteristics, days were classified as either "indoor only" (n=861), "indoor and exercise" (n=167) and "outdoor active" (n=31,934). When compared to "outdoor active" days, "indoor only" days had 6,590 fewer steps per day (2,320 vs 8,876, $p < 0.001$), a longer sedentary time (1.5 hours, $p < 0.001$), longer lying time (1.4 hours, $p < 0.001$) and shorter standing (1.9 hours, $p < 0.001$) and stepping (1.3 hours, $p < 0.001$) times. The "indoor and exercise" days had a smaller number of steps compared to "outdoor active" (7,932 vs 8,876, $p < 0.05$). There is a strong relationship between reduced daily stepping, and increased sedentary time, with a range of poor health outcomes. This has important implications for public health policy and messaging during pandemics.

Introduction

There have been numerous public health strategies employed to cope with pandemics [1]. An essential approach to containing the recent SARS-CoV-2 (COVID-19) outbreak has been the requirement of communities to remain at home ("lockdown"), thereby reducing physical interaction, to control the spread of the virus. Together with the closure of leisure and community facilities, these measures are likely to have reduced physical activity and exercise opportunities for the entire population, even with lockdown rules allowing for periods of outdoor exercise. There are, however, currently a lack of detailed data to quantify physical activity reductions during a lockdown scenario. Such information is vital as a reduction in physical activity may have stark implications for health [2], thus requiring refinement of policy for future pandemics.

The benefits of regular physical activity are well documented [3]. It has been shown to reduce the risks for developing chronic conditions like type 2 diabetes [4], heart disease [5], cancer [6], depression and anxiety [7], and dementia [8], as well as a means to manage conditions by keeping symptoms under control [9] and preventing other conditions from developing [10]. Physical activity also helps to maintain and improve physical functioning [11]. The prolonged COVID-19 pandemic and subsequent lockdowns will likely exacerbate and accelerate all harmful physical inactivity consequences across the globe.

To date, several relatively small scale, mostly questionnaire-based, studies have provided early estimates of the effect of lockdown on physical activity [12-15], although these data have not been compelling due to the cross-sectional design and convenience samples. Due to limitations in the ability of subjective measures to accurately quantify levels of physical activity [16], physical activity data obtained from wearable sensors should allow a more accurate estimate of the effects of lockdown. Given the absence of large scale lockdown studies using wearable sensors, existing pre-lockdown physical activity datasets can provide valuable insight into potential changes in physical activity behaviour in lockdown by identifying days that have similar activity profiles to those seen during lockdown conditions.

Aggregated data from consumer wearable device users have suggested a worldwide reduction of 12% during the pandemic [17]. However, fitness tracker users tend to be highly active, thus unrepresentative of the general adult population. Each additional 1,000 steps per day are associated with a 6% - 36% lower risk of all-cause mortality and CVD morbidity in adults, and these benefits are present below 10,000 steps per day [18]. Thus, even relatively small daily changes in activity could impact health if sustained.

This study aimed to develop a method to differentiate 'indoor' days from 'outdoor' days using free-living data collected using state-of-the-art research-grade wearable devices. We then applied this method to free-living data collected from a population cohort of middle-aged adults before the pandemic to simulate levels of activity during a full lockdown to investigate the impact of lockdown on physical activity levels.

Methods

Design and participants

The 1970 British Cohort Study (BCS70) is a longitudinal study following the lives of approximately 17,000 individuals born in England, Scotland or Wales during a single week in 1970. The study's age 46 sweep was carried out between 2016 and 2018, with 8,581 members participating [19]. 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 activity data [20]. A total of 6,492 eligible participants consented to wear the activity monitor.

Physical activity measurement

The study used a thigh mounted triaxial accelerometer (activPAL3 micro; PAL Technologies Ltd., Glasgow, UK) to collect objective physical activity data [21]. The accelerometer was waterproofed and fitted to the midline of the upper thigh's anterior aspect by a trained nurse during the biomedical assessment. Cohort members were asked to wear the monitor for seven days, removing the device and returning it by post at the end of the monitoring period. If the device fell off before completing the seven days, participants were asked not to reattach the monitor before returning the device.

The activPAL data were downloaded and initially processed using PALbatch version 8.10.10.52 (PAL Technologies Ltd., Glasgow, UK). The data were exported in a format which describes an individual's physical activity using an event-based approach [21]. Using this approach, each continuous period of a specific type of activity, such as sitting, standing and taking a stride, is considered a single event. Our analysis used the CREA algorithm, which identifies a range of activity classes, including sitting, standing, stepping and lying. Each stride event determined by the algorithm comprises two steps. All adjacent 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 characterised by their duration, the number of steps and the cadence. Upright events were defined by combining continuous standing and stepping events, uninterrupted by a sedentary event. We did not consider sleeping time in our analysis as we cannot be certain that periods of lying were solely associated with sleeping behaviour. Participants were included in the analysis if they had at least four valid days with a minimum of 20 hours of physical activity data.

Classification of days by step count

Days were classified, based on daily step count and an established classification of habitual activity levels [22], into five groups (sedentary: <5,000 steps/day; low active: 5,000-7,499 steps/day; somewhat active: 7,500-9,999 steps/day; active: 10,000-12,500 steps/day; high active: 12,500-14,999 steps/day; very high active: 15,000 steps/day +).

Classification of days by the longest period of continuous stepping

The original lockdown conditions announced on the 23rd March 2020 in the UK, instructed individuals not to leave home except for a maximum of one daily outdoor exercise period. To identify days with a pattern of physical activity analogous to these lockdown conditions, we aimed to identify the key characteristics of days when individuals did not leave their home. When considering days where a person does not go outside their home, we suggest that a defining feature of these days is the absence of an extended period of continuous stepping.

To identify days where there was no stepping outside of the home, we used a heuristically derived cut-off of 60 seconds of continuous stepping, where stepping events longer than the cut-off indicated outdoor activity. However, prolonged periods of outdoor stepping are likely to be functionally associated with adjacent periods of shorter duration stepping, as seen in activities like dog-walking or navigating road crossings. To correctly classify these shorter periods of stepping, stepping events were classified based on the longest duration of stepping event in the period of upright activity containing the stepping. This would minimise any misclassification of short duration stepping associated with outdoor stepping.

Periods of upright behaviour, the upright events, were classified based on the duration of the longest continuous period of stepping within the upright event (short: < 1 minute; medium: 1 – 10 minutes; and long: >10 minutes). An example of each class of upright event is given in figure 1. The long stepping upright event classification attempts to identify periods of upright behaviour that contain stepping-based exercise activity.

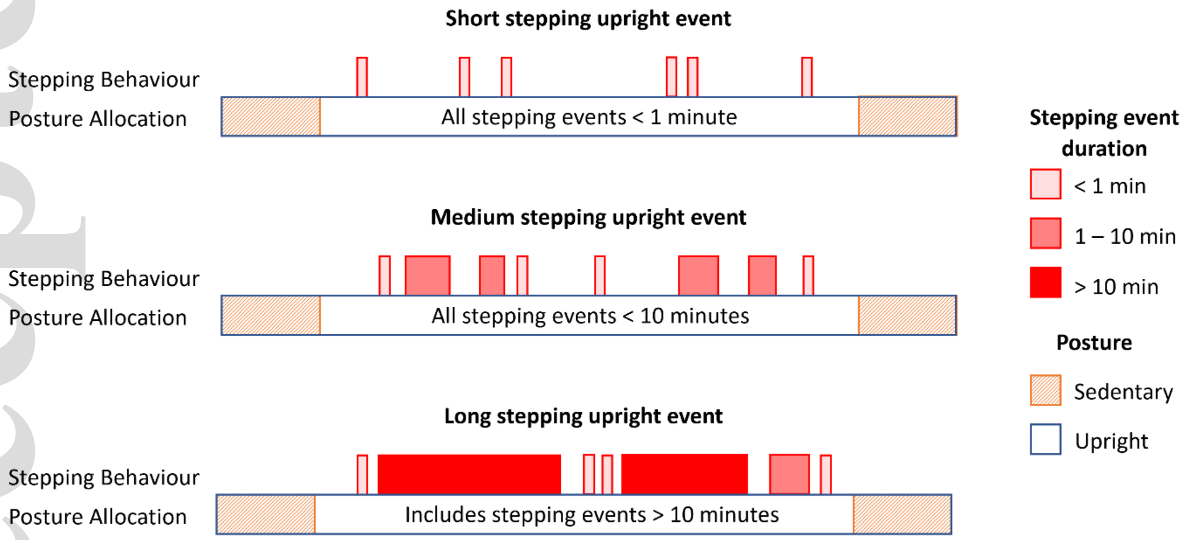

Figure 1: Examples of classification of upright events based on the longest period of continuous stepping. The lower bar shows the posture of the individual, and the upper bar gives the distribution of stepping activity within the upright event. Bar width and colour are used to denote the duration of each continuous period of stepping.

When all uprights events were classified, valid days were then divided into the following three groups based on the composition of the upright events within each day:

- **"Indoor Only"** – Days where there were only short stepping upright events.
- **"Indoor and Exercise"**– Days where there were only short stepping upright events, except for up to two upright events that contained stepping events that were longer than 10 minutes.
- **"Outdoor Active**" – All remaining days that were not classified as either "indoor only" or "indoor and exercise".

Data Cleaning and Statistical Analysis

Initial cleaning of the activity data was carried out using R [23]. For each of the defined day categories, the median and interquartile range for the daily time spent in different activity types, and the daily step count, was calculated. A one-way ANOVA was used to test for differences in daily step count, and time spent in different activity types, across the three categories of day. To determine if there was a trend in step count across the categories of upright events (based on the longest period of continuous stepping in the bout) as daily step count increase, we carried out a Mann-Kendall Monotonic Trend Test.

Results

Of the 6,492 individuals that consented to wear the activity monitor, data were analysed for the 5,797 participants with valid data (89.3%). Compliance with the wear protocol was good, with 87.1% of participants providing at least four days of valid data and 60.1% of participants providing seven days of valid data (table 1). A total of 32,962 days of valid activity data were captured.

No. of valid days	Participants		Previously Reported	
	N	%	N	%
0	220	3.80%	0	0%
1	131	2.26%	139	2.50%
2	184	3.17%	167	3.00%
3	210	3.62%	228	4.09%
4	244	4.21%	264	4.74%
5	348	5.99%	346	6.21%
6	974	16.80%	779	13.99%
7	3,486	60.15%	3,452	61.99%
8	0	0%	194	3.48%
Total	**5,797**		**5,569**	

Table 1: Distribution of the number of valid days of activity data for the study participants. The distribution of valid days using the inclusion criteria used by the BCS70 study group [6] are provided for reference

The median daily step count across all days was 8,718 steps. “Indoor only” days had a lower step count than “outdoor active” days (2,320 vs 8,876, $p < 0.001$) (table 3). This lower step count was accompanied by longer sedentary time (1.5 hours, $p < 0.001$), longer lying time (1.4 hours, $p < 0.001$) and shorter standing (1.9 hours, $p < 0.001$) and stepping (1.3 hours, $p < 0.001$) times when compared to "outdoor active" days.

Days classified as "indoor and exercise" also had a significantly lower step count when compared to days classified as "outdoor active" (7,932 vs 8876, $p < 0.05$). "Indoor and exercise" days compared to "indoor only" days also had significantly shorter lying time (9.08 hours against 9.88 hours, $p < 0.001$), significantly longer standing (2.76 hours against 2.42 hours, $p < 0.05$) and stepping (1.48 hours against 0.60 hours, $p < 0.001$) times but similar sitting time (9.80 hours against 10.24 hours, $p = 0.74$) (table 3). Of the 607 individuals with at least one day classified as indoor only, 452 (74.5%) have a single day, and 95 (15.7%) have two days classified as indoor only. Of the 5,052 individuals considered in our analysis, only six individuals (0.12%) had all their valid days classified as indoor-only. Four individuals (0.08%) had only a single day classified as outdoor active or indoor and exercise.

	Valid Days	Step Count	Daily time in posture (hours)				
			Lying	Sitting	Upright	Standing	Stepping
Indoor Only	861	2,320* (1,480, 3,258)	9.88* (8.3 , 11.95)	10.24^ (7.61 , 12.21)	3.05* (1.84 , 4.8)	2.42* (1.42 , 3.94)	0.60* (0.39 , 0.83)
Indoor and Exercise	167	7,932+ (5,938 , 10,755)	9.08+ (7.98 , 10.76)	9.80^ (7.69 , 11.33)	4.48+ (3.23 , 6.11)	2.76+ (1.83 , 4.22)	1.48+ (1.11 , 1.95)
Outdoor Active	31,934	8,876 (6,266 , 12,214)	8.41 (7.32 , 9.67)	8.70 (6.75 , 10.59)	6.38 (4.77 , 8.27)	4.29 (3.12 , 5.78)	1.91 (1.38 , 2.55)
Total	32,962	8,718 (6,036, 12,098)	8.44 (7.34 , 9.73)	8.73 (6.77 , 10.6)	6.31 (4.67 , 8.21)	4.24 (3.06 , 5.75)	1.88 (1.33 , 2.52)

†Values are the median (Interquartile Range), unless otherwise indicated.

* Significantly different from Indoor and Exercise and Outdoor Active ($p < 0.05$)

^ Significantly different from Outdoor Active only ($p < 0.05$)

+ Significantly different from Outdoor Active ($p < 0.05$)

Table 2: Characteristics of daily activity profile in relation to the classification of days by stepping composition within upright events.

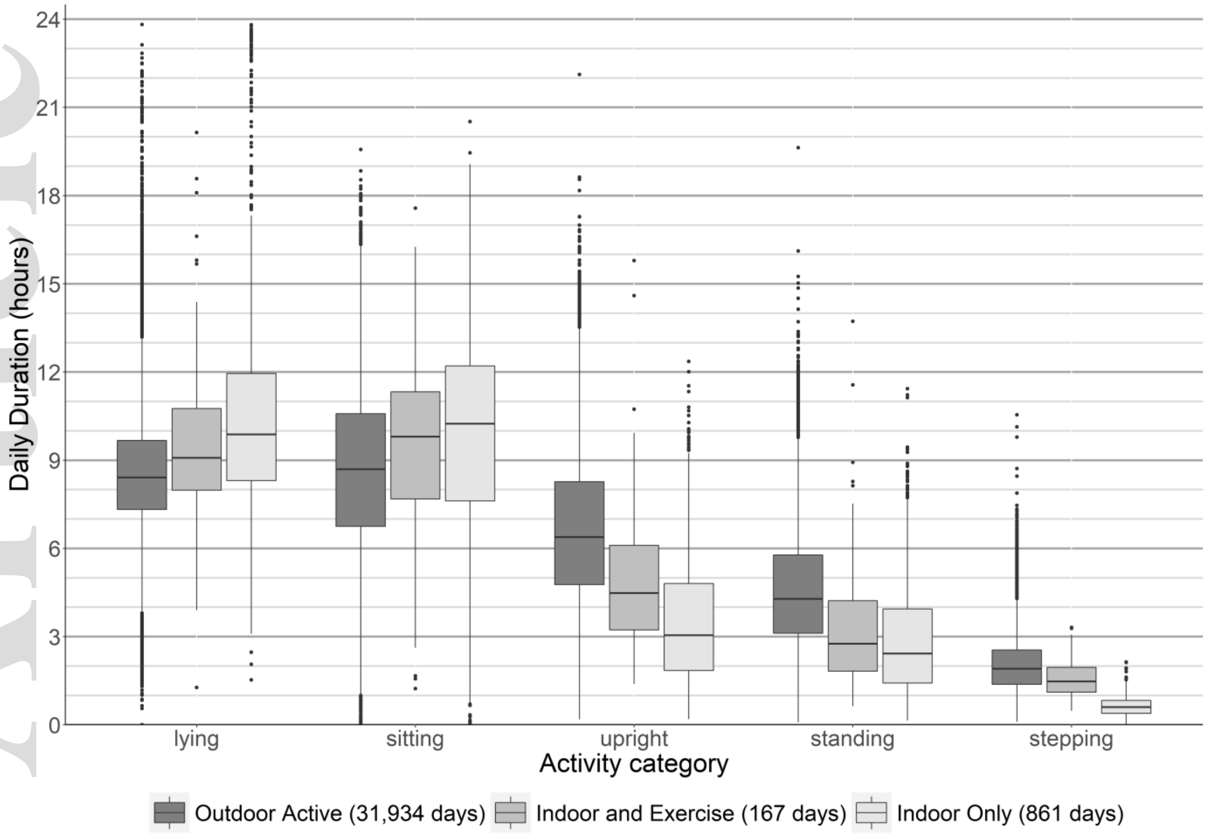

Figure 2: Distribution of time spent in different classes of activity, based on the classification of days by the composition of upright bouts within each day.

When all days were grouped by total daily step volume, the number of steps accumulated in medium stepping upright events increased ($p < 0.01$) (figure 3). There was no trend seen in the number of steps accumulated in long stepping upright events as daily step count increased ($p = 0.24$). The median number of steps accumulated in long stepping upright events is zero for all groups up to the >15k steps per day group. There was no trend in the number of steps accumulated for short stepping upright events as the number of steps per day increased ($p = 0.26$). The number of steps accumulated in these upright events appeared to level off at approximately 3,750 steps.

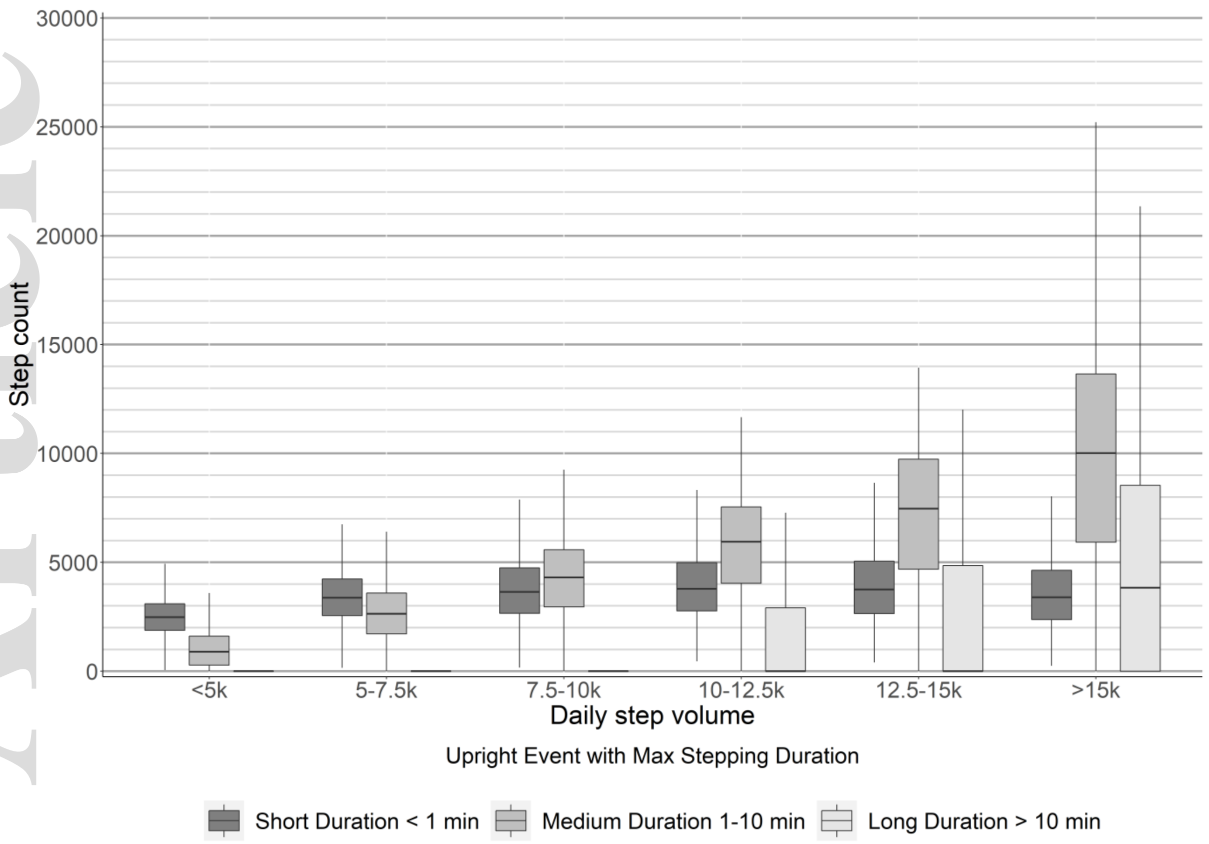

Figure 3: Step count distribution for the different classes of upright events, based on the longest stepping event within the bout, as daily step count increases

To confirm that our cut-off choice solely did not drive the observed differences in step count, we repeated our analysis using a revised cut-off of 90 seconds (table 3). We then carried out a series of unpaired t-tests using Bonferroni's correction to test if the change in daily step count is different when using the different stepping bout duration thresholds. Using the revised cut-off, there was a significant increase in median step count (from 2,320 steps to 3,874 steps) for days classified as "indoor only". However, there continued to be a substantial deficit in the number of steps compared to days classified as either "indoor and exercise" or "outdoor active". A significant difference in step count was also observed for days classified as "indoor and exercise" and "outdoor active" when using different stepping bout duration thresholds.

	Indoor Stepping Threshold			
	60 seconds		**90 seconds**	
	Valid Days	**Step Count**	**Valid Days**	**Step Count**
Indoor Only	861	2,320	3,285	3,874*

		(1,480, 3,258)		(2,658, 5,474)
Indoor and Exercise	167	7,932 (5,938 , 10,755)	737	9,384* (7,222, 12,276)
Outdoor Active	31,934	8,876 (6,266 , 12,214)	28,940	9,284* (6,688 , 12,552)
Total	32,962	8,718 (6,036, 12,098)	32,962	8,718 (6,036, 12,098)

†Values are the median (Interquartile Range), unless otherwise indicated.

* Significantly different between 60 second and 90 seconds mean step count ($p < 0.01$)

Table 3: Sensitivity analysis of daily step count across different classes of days using a 90-second threshold for indoor stepping

Discussion

This study simulated the potential impact of lockdown conditions on physical behaviour patterns using real-world data derived from a large population of middle-aged adults. Using a classification scheme based on the longest duration of stepping during an upright period, we found that days classified as solely indoors had, on average, 6,590 fewer steps per day than days that were characteristic of spending time outdoors. We also found that days with a similar stepping profile to days spent indoors, but which included one or two long stepping upright events indicative of exercise activity, had on average 5,612 more steps than days indoor days.

As we did not consider the health profile of our sample entered in the analyses, we acknowledge that functional limitations within a subset of the population may account for some of the observed decrease in daily step count. For these individuals, low daily step counts would be a consequence of health-based limitations on physical activity as opposed to the impact of remaining indoors. Given that almost all of the population (99.8%) had at least two days classified as being spent outdoors, we believe this suggests few individuals have functional limitations that significantly limit their physical activity capacity and that the contribution of physical limitations to the observed reduction in daily step count is likely to be limited.

There is strong evidence that reduced daily stepping is associated with a range of poor health outcomes, including increased risk of cardiovascular disease [28], elevated blood pressure [27] and increased all-cause mortality [25-26]. In particular, research looking at the relationship between daily step count and all-cause mortality in older adults in the USA found that a decrease from 8,000 steps per day to 4,000 steps per day is associated with a twofold increase in the risk of all-cause mortality (adjusted hazard ratio, 2.04) [26]. A similar relationship was observed in a study investigating the relationship between daily step count and all-cause mortality in older women, where individuals with a low daily step count (median step count - 2,718) had a significantly increased risk (72% to 203%) of all-cause mortality compared to individuals with a higher step count (median step count – 8,442) (adjusted hazard ratio, 1.72 - 3.03) [25]. These findings highlight the serious long-term negative health consequences that are likely to arise from the reduced levels of stepping we suggest are associated with the lockdown conditions implemented in response to the COVID-19 pandemic.

It has been shown that even modest increases in daily step count (1,000 – 2,000 steps) can significantly reduce a range of adverse health outcomes [25-27]. Therefore encouraging individuals to increase their step count can substantially mitigate the negative health consequences arising from lockdown conditions. This study found that days classified as "indoor with exercise" had a median of 5,612 more steps more than "indoor only" days. This suggests that introducing one or two periods of prolonged stepping (e.g., an indoor exercise class) during a lockdown scenario could significantly reduce these adverse health outcomes.

Considering our findings and the proven health benefits of more physical activity in lockdown circumstances, we believe that the messaging surrounding undertaking exercise during lockdown condition should be more explicit. For example, people could be specifically encouraged to be physically active on a dailybasis for a given period. We observed that days with greater step counts were characterised by longer periods of stepping, which suggests that outdoor exercise may be the most appropriate method to increase daily step count as it best matches examples of real-world behaviour on days with greater step volumes.

When we consider the composition of step accumulation as daily step count increased, we found that increases in step count were primarily driven by upright events containing periods of continuous stepping longer than one minute in duration. In particular, we observed a levelling off in the number of steps accumulated in short stepping upright events, which we associate with indoor stepping, with a ceiling of approximately 3,750 steps. Current public health guidelines highlight the health benefits arising from increased physical activity, irrespective of the activity duration. However, the distribution of stepping in days with higher step counts suggests that it may be easier to achieve an increase in physical activity from a small number of longer upright events (i.e., structured, purposeful exercise) than a larger number of shorter duration stepping upright events. These findings suggest that it is likely to be challenging to accumulate sufficient additional stepping within the home to attenuate the negative health impact arising from remaining indoors throughout the day. This is particularly important when individuals have limited opportunities to leave their home, such as during the current COVID-19 restrictions. The significant positive health benefits that arise from increasing daily step count are most likely to be achieved by encouraging people to undertake a small number of prolonged periods of outdoor exercise.

In addition to the health impact of low daily step counts there is evidence suggesting that increases in sedentary time are associated with an increased risk of all-cause mortality [35-36] and cardiovascular and metabolic disease [35], independent of accompanying decreases in physical activity. Our analysis found "indoor only" days had longer sedentary time (1.54 hours per day) than "outdoor active" days. This would suggest that the potential negative health impact of reduced stepping during lockdown conditions would be worsened by the increase in sedentary time.

Since the introduction of lockdown restrictions in response to the COVID-19 pandemic, research has started to emerge looking at the change in physical activity patterns resulting from the lockdown. Several studies have used self-report to measure post-lockdown changes in physical activity and sedentary behaviour within the general population [29-32]. While the studies reported on different measures of physical activity (e.g. time in different classes of physical activity, the proportion of individuals meeting WHO physical activity guidelines, number of individuals reporting an increase or decrease in physical activity levels) there was a general consensus that lockdown conditions have led to individuals undertaking less daily physical activity and increasing their sedentary time.

A limited number of studies have also used accelerometer data to investigate physical activity changes within small clinical populations during lockdown [33-34]. In these studies, there was a significant reduction in daily step count (15% and 16% respectively), which was smaller than the reduction observed in the present analysis. An increase in sedentary time was also observed in one of the studies (29 minutes per day) [33]. However, these studies did not discuss participant compliance with lockdown conditions, so the reported reduction in daily step count during lockdown may be attenuated by the presence of periods of outdoor stepping. Findings from these studies support our finding that lockdown conditions are likely to lead to a significant reduction in daily stepping that is accompanied by an increase in daily sedentary time.

This study's main strengths include the size of the population-based sample, which is roughly representative of the general population. Unlike wrist-worn devices, using a research-grade thigh-based accelerometer allows us to distinguish between upright and non-upright activity, while the activity classification algorithm used lets us separate lying activity from sitting. Another strength of this study was the algorithm we used to classify stepping based on the longest period of continuous stepping within an upright bout. Using this algorithm short durations of stepping that were functionally associated with longer periods of stepping could be identified. This allowed more accurate quantification of the volume of stepping associated with indoor activity by disregarding short periods of stepping associated with outdoor physical activity, such as exercise or active transport.

Limitations

A limitation within our study was that we used free-living physical activity captured during a non-lockdown population where the days spent solely indoors were not independently identified. While we used a heuristic approach to identify days with an activity profile that was potentially characteristic of remaining in the home, there is likely to be some degree of misclassification of days using 60 seconds of continuous stepping as the cut-off point for identifying indoor activity. We made a decision not to include an upper limit for allowable periods of stepping in days classified as indoor and exercise as we believe there was not sufficient information concerning real-world lockdown behaviour to set an appropriate level.

A further limitation arising from our use of physical activity data obtained during non-lockdown conditions is the difference in the circumstances leading to an individual remaining indoors, as this was more likely to be a voluntary choice in our sample. During lockdown individuals may have undertaken a range of compensatory behaviour [36, 37], such as web-based exercise classes [37], leading to increased levels of physical activity. Thus, our study may overestimate the reductions in stepping behaviour seen during lockdown. While this may the case for some indvidiuals, a substantial number of individuals do not undertake additional physical activity during lockdowns [36, 37], either through choice or due to external factors (poor internet access, no free space to undertake exercise, other personal circumstances, etc). These individuals may be likely to have a similar daily step count to the levels simulated in our study. If our assumption is correct, our results reinforce the need for a more focused public messaging on the importance of undertaking additional periods of physical activity during lockdown conditions.

In our analysis we assumed that each day was independent when characterising the difference between days spent indoors and days with outdoor activity. However as our analysis considers multiple days of physical activity for each individual, it is likely that these days will not be truly independent as individuals may potentially modify their behaviour based on activities undertaken on a different day, such as spending a day indoors to recover following a day of strenuous activity. This type of behaviour may account for some of the reduction in step count we observe in days classified being spent indoor. Given the large reduction in step count compared to days with outdoor activity we suggest this behaviour does not solely account for the reduction in step count observed in days classified as being indoor only.

We were also unable to know the reason individuals chose to limit their physical activity on these days, such as illness or other physical limitations. That may have led to an overestimation of the decrease in physical activity seen during lockdown. However, most individuals we categorised as having spent at least one day indoors had one of more instances of prolonged stepping during the observation period. This may suggest that relatively few individuals had low daily step volumes that were solely due to limiting physical conditions. Given that the study sample was roughly representative of people aged 46-48 in the general population, we assume that the influence of prevalent illness to the observed low step count is similar to real world lockdown conditions.

Perspectives

This study demonstrated large differences in the number of steps and sedentary time between days that had only indoor activity and those days in which there was outdoor activity in a population of 46 – 47 year-olds. Our analysis of short stepping bouts supports these findings demonstrating that there seems to be a ceiling of indoor activity, approximately 3,500 steps, irrespective of the overall activity level. There is a very strong relationship between both a reduction in the number of steps and an increased sitting time with a range of poor health outcomes. These findings, therefore, have significant implications for the formulation of public health policy and the delivery of public health messaging during a pandemics.

Conflict 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 https://www.ukdataservice.ac.uk/. Restrictions apply to the availability of these data, which were used under license for this study.

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