Proceedings of the 2024 Winter Simulation Conference
H. Lam, E. Azar, D. Batur, S. Gao, W. Xie, S. R. Hunter, and M. D. Rossetti, eds.

MODELING THE LIFELONG IMPACT OF CHANGES IN PHYSICAL ACTIVITY BEHAVIOR ON NON-COMMUNICABLE DISEASE EVENTS AS A RESULT OF THE UK COVID-19 LOCKDOWN

Kate Mintram[1], Bhargavi Gottimukkala[1], and Anastasia Anagnostou[1]

[1]Modelling and Simulation Group, Dept. of Computer Science, Brunel University, London, UK

ABSTRACT

The risk of developing non-communicable diseases (NCDs) is inextricably linked to the level of physical activity undertaken by individuals. The Covid-19 lockdown caused a shift in physical activity behaviors among the UK population. This study used an agent-based simulation to predict the impact of the reduction in physical activity caused by the UK lockdown, quantified using data from smartphone tracked activity, on the number of annual NCD occurrences over the lifetime of a cohort. The model considers an individual's characteristics and health status to predict the risk of developing type 2 diabetes (T2D), cardiovascular disease (CVD), depression and musculoskeletal injuries (MSI). When physical activity was reduced as a result of the lockdown, the model showed an increase in the number of T2D, CVD and depression events and a decrease in the number of MSI events, over the short-term, but the number of incidences recovered over the lifetime of the cohort.

1 INTRODUCTION

Physical inactivity is a major risk factor for non-communicable diseases (NCDs) and mental health conditions (Santos et al. 2023). According to World Health Organization (WHO), seven of the 10 leading causes of deaths in 2019 were NCDs, with cardiovascular diseases (CVDs) such as ischemic heart disease and stroke being responsible for approximately 27% of the world's total deaths (WHO 2020). Around half of NCDs can be prevented by changes in lifestyle, including increased physical activity levels among others (NCD Alliance n.d.). The health and economic burden of physical inactivity is huge globally. WHO reported that almost 500 million new cases of preventable NCDs will occur between 2020 and 2030 with an annual cost of around US$ 27 billion (WHO 2022). In the same report, WHO considers recommendations on promoting physical activity as a means to save lives while responding to the impact of the Covid-19 pandemic on physical and mental health.

The Covid-19 pandemic brought unprecedented challenges to global public health, leading governments worldwide to implement strict measures, including lockdowns, to mitigate the spread of the virus. Whilst the transmission characteristics of the virus, as well as the risks associated with severe or fatal Covid-19 outcomes are now well established (e.g., Clift et al. 2020; Cuevas 2020; Kerr et al. 2021; Shamil et al. 2021), the longer-term effects of the implemented intervention strategies remain largely unknown. Lockdown measures significantly altered daily routines and behaviors, affecting various aspects of individuals' lives, including physical activity levels (Strain et al. 2022; Bailey et al. 2022; Rogers et al. 2020; McCarthy et al. 2021). Understanding the impact of the Covid-19 lockdown on physical activity is crucial for informing public health strategies to promote active lifestyles during such unprecedented times, and to inform future decision making on pandemic intervention strategies.

Here, we use the Physical Activity Lifelong Modelling and Simulation (PALMS) to assess the long-term effects of lockdown-induced changes to physical activity on the prevalence of NCDs, such as CVDs and type 2 diabetes (T2D), as well as depression and Muscular Skeletal Injuries (MSI). PALMS is an agent-based model that has previously been used to assess the impacts of various physical activity interventions in reducing instances of NCDs (Anagnostou et al. 2019), and has also been extended in a different context to the CoronAvirus Lifelong Modelling and Simulation (CALMS) model that assesses the health and economic impact of Covid-19 interventions on the UK population (Mintram et al. 2022).

The paper is structured as follows. Section 2 discusses studies reporting on changes of physical activity during the Covid-19 lockdowns. Section 3 gives an overview of the PALMS agent-based model and in Section 4 we discuss how we incorporated in the model the physical activity changes during lockdowns. We tested the short- and long-term impact of these changes by comparing the number of health events after one, two and 80 years of the UK lockdown with the baseline case, where no lockdown occurs. The results of our experiments are presented in Section 5. Section 6 concludes the paper and discusses the limitations and potential of this work.

2 STUDIES ON CHANGES OF PHYSICAL ACTIVITY IN THE COVID-19 LOCKDOWNS

During lockdowns, restrictions on movement, closure of recreational facilities, and work-from-home arrangements disrupted established physical activity patterns. People were required to adapt to new circumstances, leading to changes in how they engaged in physical activity, exercise, and sedentary behaviors. Across Europe, cross-sectional surveys have reported generally reduced physical activity as a result of the lockdown measures (Caputo and Reichert 2021). According to a survey undertaken in the UK by Strain et al (2022) of 726,257 individuals, the mean weekly duration of moderate-intensity activity was between 9.5% and 10.8% lower in April-May 2020, compared to the same months between 2015 and 2019. The proportion of people reporting any activity was lower in 2020, with 77.2% of respondents engaging in more than zero minutes per week of activity compared to 81.2% to 83.5% in the years 2016-2019. Another UK study using self-reported data found that nearly 29% of participants experienced reduced physical activity during the lockdown (Bu et al. 2021). Similar results have been reported in Greece (Bourdas and Zacharakis. 2020), Croatia (Đogaš et al. 2020), Spain (Balanzá-Martínez et al. 2021), France (Deschasaux-Tanguy et al. 2020) and Germany (Mutz and Gerk. 2020).

Another cross-sectional online survey-based study in England, which collected data from 818 adults between 29th April and 13th May 2020, found contrasting results, with total physical activity increasing during the lockdown. They reported an increase in the proportion of participants engaging in high physical activity during the lockdown (from 32% to 36%), while the proportion of individuals with low physical activity decreased slightly (from 26% to 22%). The proportion of participants with moderate physical activity remained relatively stable at 42%. However, there was a shift in sitting behavior during the lockdown, with more participants spending longer hours sitting. The proportion of individuals engaging in high sitting increased from 29% before the lockdown to 41% during the lockdown (Bailey et al. 2022).

While the changes in physical activity and sedentary behaviour as a result of the lockdown are evident, some studies have additionally reported associations related to demographic and behavioral characteristics. Bailey et al. (2022) reported that lower education level and higher BMI were associated with increased odds of low physical activity during lockdown, compared to moderate or high physical activity, whereas non-White ethnicity was associated with reduced odds. For sitting behavior, younger individuals aged 18–39 years had significantly higher odds of engaging in high sitting during lockdown compared to those aged 60 years or older. Rogers et al. (2020) found that participants who engaged in less intensive physical activity during lockdown were found to have higher odds of having obesity, hypertension, lung disease, depression, and a disability. Being female, living alone, or lacking access to a garden were also associated with engaging in less intensive physical activity. Conversely, being in the highest income group or having school-age children were associated with a higher likelihood of engaging in more physical activity. Bu et al. (2021) similarly found that a range of factors were found to be associated with physical activity trajectories, such as age, gender, education, income, employment status, and health.

Self-reported questionnaires form the basis for many studies which quantify physical activity behaviors due to their inexpensive and convenient nature, and current physical activity guidelines are largely based on results from these surveys (Haskell et al. 2007; UK Department of Health and Social Care 2011). However, activity information derived from self-reported data is potentially subject to response biases such as imprecise recall and influence of social desirability (Althubaiti 2016)), and shows limited validity and reliability (Shephard. 2003). A study in the UK, which used longitudinal smartphone-tracking, reported more severe results compared to those described above (McCarthy et al. 2021). The authors report median reduction in physical activity between January and June 2020, and found that 63% of people decreased their physical activity over the lockdown period, where levels of physical activity among those classed as active at baseline showed a larger drop compared with those considered to be fairly active or inactive. In contrast to the self-reported data (Bailey et al. 2022), socioeconomic group and gender did not appear to be associated with changes in physical activity. Fitbit (Fitbit 2020) and Garmin (Garmin 2020) have also released some data, with both showing an increase in more vigorous physical activity and a reduction in step activity. Fitbit showed a 9% decline in step activity in the UK. This study, however, ended on 22nd March 2020 prior to the full lockdown restrictions and is therefore likely to underestimate the impact of the restrictions.

Despite differences across methodological approaches, there is generally a negative impact of lockdowns on physical activity behavior of individuals. Lower physical activity increases the risk of NCDs such as CVD (Muhammed and Abubakar 2021; Ahmed et al. 2012) and T2D (Hamasaki 2016), as well as depression (Pearce et al. 2022). Studies indicate that the occurrence of these NCDs have increased in the short-term as a result of the lockdown (Perrone et al. 2021; American Heart Association 2023; British Heart Foundation 2023; Izzo et al. 2023; Cecchini et al. 2021; Schuch et al.2020). Each of these conditions can cause substantial disability or death, and reduces the quality of life for patients living with the condition. Moreover, there is a significant cost to the NHS associated with the ongoing treatment of these chronic conditions (Scarborough et al. 2011). It is difficult, however, to interpret the long-term health, and associated economic, impacts of the effects of changes in physical activity on NCD occurrences. Deciphering this information is vital to understanding the full impacts of government intervention strategies on the overall health of a population, and informing on future pandemic management.

In this study, we attempt to shed some light on this impact by incorporating the lockdown effects in the PALMS agent-based model and reporting on the changes in NCD incidents, depressions and MSI events as a result of the physical activity changes due to the Covid-19 restrictive measures. We next present the model and our experimental results.

3 PHYSICAL ACTIVITY LIFELONG MODELLING AND SIMULATION MODEL (PALMS)

3.1 Model Overview and Description

PALMS is a micro-simulation that predicts the lifelong physical activity behavior of individuals of a population and its effect on their quality of life (Anagnostou et al. 2019). In Figure 1 we can see the main components of the model. The first component is the *seed population* where information about demographics, physiological and socioeconomic characteristics is included in the individual agents. The *Lifelong Modelling and Simulation (LMS)* component is the core module of the model where the life course modeling logic is implemented. In this component, all risk and output calculations occur. The *Physical Activity (PA)* component deals with updates on physical activity trajectories and relative risk adjustments. The final component is the *Life histories* component, where all output events are recorded for each individual agent in the model.

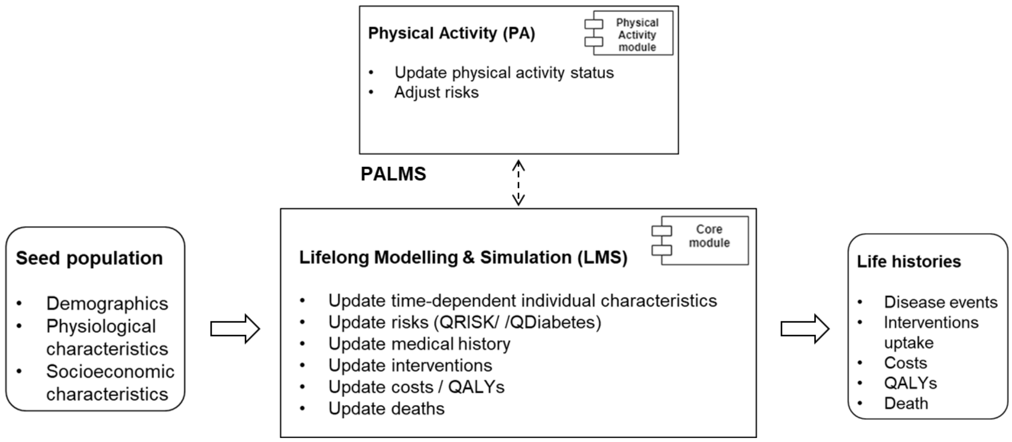

Figure 1: PALMS model components overview.

3.1.1 Population Initialization

The model consists of a sub-population of individuals defined by their characteristics (e.g. age, sex) and health status (e.g. blood pressure, CVD, diabetes). The initial population data was obtained from the Health Survey for England (HSE 2012) representing 9,594 individuals. Table 1 describes the seed population characteristics included in the model at initialization. Bootstrapping methods are implemented at initialization using sampling with replacement if we wish to run experiments with larger than the seed population size. We provide an overview of the model here, but a detailed description of the model can be found in Anagnostou et al. (2019).

Table 1: A summary of selected baseline characteristics of the initial population (adapted from Anagnostou et al. 2019).

Selected baseline characteristics of the initial population (n = 9,594)	
Female, n (%)	5,268 (54.9)
Age, (years) median (25th, 75th percentile)	45 (27, 63)
Ethnicity, n (%)	
– **White**	8,470 (88.3)
– **Black**	247 (2.5)
– **Asian**	642 (6.6)
– **Other**	235 (2.4)
Physical activity status, (min per week) median (25th, 75th percentile)	225 (30, 570)
BMI, median (25th, 75th percentile)	25.95 (22.21, 29.72)
CVD history, n (%)	1,033 (10.8)
Type 2 Diabetes, n (%)	527 (5.5)

3.1.2 Model Conceptualization

Figure 2 summarizes the processes undertaken be each agent in the simulation over time. The model is initialized for n agents by reading population data (see Table 1) from an input CSV file, and the simulation characteristics (simulation time (years) and n runs) are set.

Over each time step (3 months), individuals may develop CVD, T2D, depression and MSI according to established and validated risk algorithms (QRisk2 (Hippisley-Cox et al. 2008) and QDiabetes (Hippisley-Cox et al. 2017) for CVD and diabetes, respectively) or estimated probabilities established from the literature (depression and MSI (Rait et al. 2009; Wijlaars et al. 2012)). The relative risk of developing these NCDs is dependent on the individual's physical activity level. In addition, the physical activity level itself is dependent on an individual's characteristics and health status, and the change in physical activity over time is a function of previous activity levels. The formulae for calculating physical activity level can be found in Anagnostou et al. (2019). Several time and/or condition dependent variants are then updated. These include aging, physical activity changes, costs, quality of life and medical history.

Physical activity levels are classified into three categories using minutes of vigorous physical activity (MVPA) per week as a measure: Inactive (0 < physical activity status < 85 min per week); Moderately active (86 < physical activity status < 425 min per week); and Very active (physical activity status > 426).

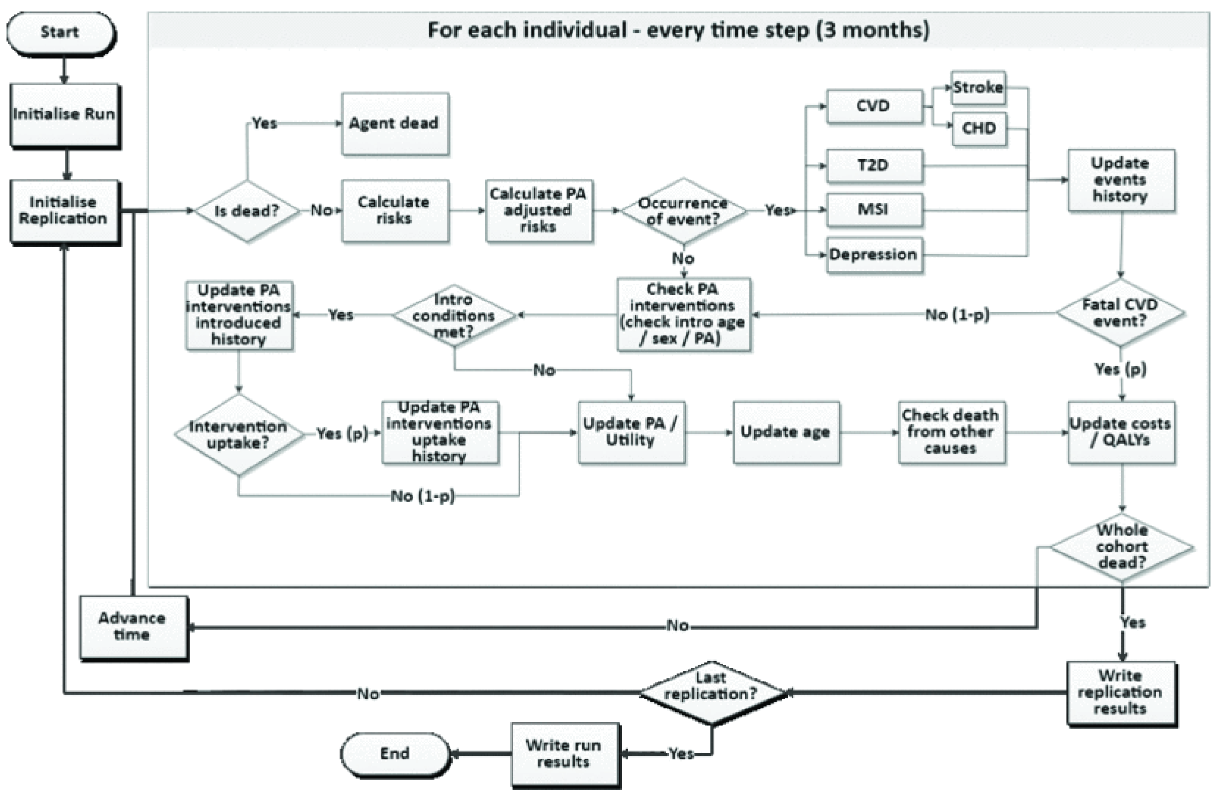

Figure 2: A summary of the PALMS simulation and agent logic (Anagnostou et al. 2019).

3.1.3 Model Outputs

The model tracks the health status of individuals in the population over time, including BMI, cholesterol, blood pressure, number of NCD events, physical activity status, utility, and QALYs as well as the economic costs associated with NCD events and interventions. Individual and aggregated outputs are recorded in CVS files and key parameters can be visualised on a desktop GUI in real-time.

4 MODELLING THE EFFECTS OF THE UK COVID-19 LOCKDOWN ON PHYSICAL ACTIVITY

McCarthy et al. (2021) explored patterns of smartphone-tracked activity before, during, and immediately after lockdown in the UK. This study was chosen as the primary data source for our simulations because other studies of physical activity in the UK during the pandemic have primarily used self-reported data (e.g., Strain et al. 2022; Bailey et al. 2022).

The study reported physical activity between the week before the first case of Covid-19 was reported (22nd January 2020) and the day the shops re-opened (17th June 2020). The authors found that socioeconomic group and gender did not appear to be associated with changes in physical activity. There appeared to be an effect of age, whereby younger people engaged in more physical activity before lockdown and the least amount of physical activity after lockdown resulting in the greatest difference among age categories. In contrast, those aged ≥65 years appeared to remain more active throughout and increased their activity levels as soon as the lockdown was eased. Reductions in physical activity remained fairly static throughout most of the lockdown, until the study ended on June 17th.

To obtain the data reported in the published time-series graphs, an online graph digitizer was used (https://plotdigitizer.com/) and the percentage decrease was calculated from 22nd January 2020 (baseline) to the first full week of lockdown (25th March 2020) as shown in Table 2

In a longitudinal study undertaken by Solomon-Moore et al. (2022), an online survey comparing physical activity during the UK lockdown to the same time period 12 months later showed no differences between baseline and follow-up physical activity. This indicates no recovery from the reported reductions in physical activity between March 2020 and March 2021. This is supported by Sport England who reported recovery in physical activity starting in mid-March 2021 (Sport England 2022).

A survey undertaken between November 2021 and November 2022 reported that physical activity levels had returned to pre-pandemic levels (Sport England 2023). To model this, we implemented a linear incremental increase for each 3-month time step between March 2021 and March 2022 to reach pre-pandemic physical activity levels.

The simulation timeline is therefore as follows (the timestep in the model in 3 months):

- Initialization in December 2019 with baseline parameters.
- Reductions in physical activity begin March 2020 and remain until March 2021.
- Physical activity increases linearly between March 2021 and March 2022.
- March 2022 physical activity has fully recovered.

Table 2: Physical activity change.

Age	Percentage reduction in Physical Activity
14-24	87
25-34	92
35-44	83
45-54	70
55-64	66
≥ 65	38

4.1 Simulation Conditions and Output Analysis

Outputs of total (cumulative) CVD, T2D, depression and MSI events were recorded, and the baseline scenario (no lockdown effects on physical activity) was compared to the scenario where the UK Covid-19 lockdown affected physical activity as described above after one, two and 80 years. These timesteps were chosen for analysis to represent the year following the reductions in physical activity, the year following the recovery of physical activity, and the lifespan of the cohort. Model outputs represent the average (±SD) of 100 runs on a cohort of 10,000 agents.

5 SIMULATION RESULTS

Following the reduction in physical activity as a result of the UK lockdown at the end of year one, the total number of CVD, diabetes and depression events increased by 2.3, 0.6, and 3.92 events per 10,000 individuals, respectively, compared to the baseline scenario where no lockdown occurred (equivalent to a 2.2%, 1%, and 2.8% increase). Similarly, at the end of year two, the total cumulative number of events increased by 3.67, 1.63, and 8.05 events per 10,000 individuals, respectively, compared to the baseline scenario (amounting to a 1.7%, 1.4%, and 3.0% increase). Comparatively, by year 80, there were no differences (<0.01%) in the total cumulative number of CVD, diabetes and depression events between the two scenarios, indicating that the effects of reduced physical activity effects on the cohort as a result of the lockdown were able to recover over time (see Figure 4)

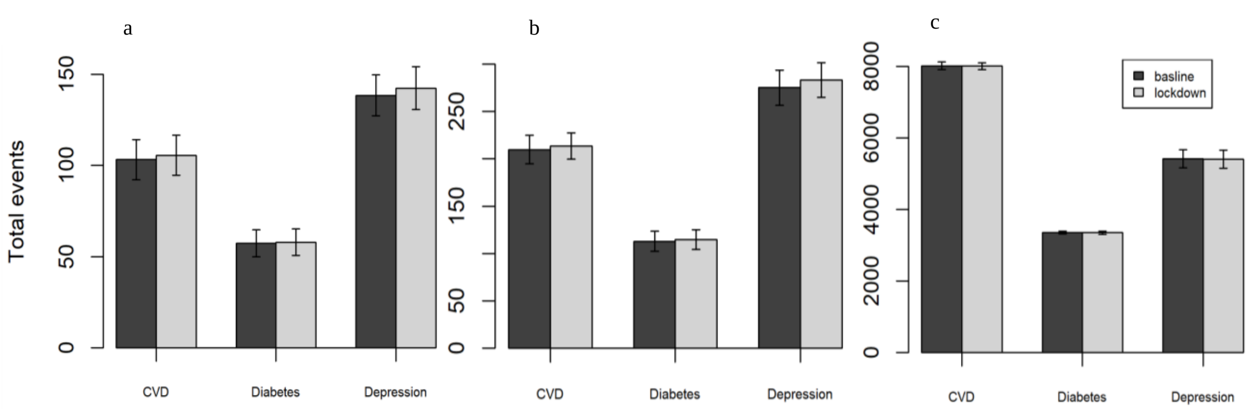

Figure 3: Total number of CVD, diabetes and depression events following reductions in physical activity as a result of the UK Covid-19 lockdown (grey bars) compared to the baseline scenario (no lockdown - black bars) after 1 (a) ,2 (b) and 80 (c) years. Outputs represent the mean (±SD) of 100 runs for a cohort of 10,000 agents.

MSI showed contrasting patterns, where the reduced physical activity during year one and year two caused a decrease of 269.24 and 457.76 events per 10,000 individuals, respectively (equivalent to a 16.7% and 14.4% decrease). This is expected since MSI is an adverse event of physical activity. After 80 years, however, the number of events had recovered to a change of <0.01% between the two scenarios (see Figure 4).

6 CONCLUDING DISCUSSIONS

We simulated the effects of reduced physical activity as a result of the UK Covid-19 between March 2020 and March 2021, followed by a linear recovery back to pre-pandemic levels between March 2021 and March 2022. We assessed the effects on NVDs, such as CVD and T2D, as well as depression and MSI, and compared the results to a baseline scenario where no lockdown (or changes in physical activity) occurred.

The simulations showed that compared to the baseline scenario, the lockdown resulted in a higher number of CVD, T2D and depression events, but a lower number of MSI events by the end of years one and two. This emerges from the relationship in the model which quantifies an individual's NCD risk as a

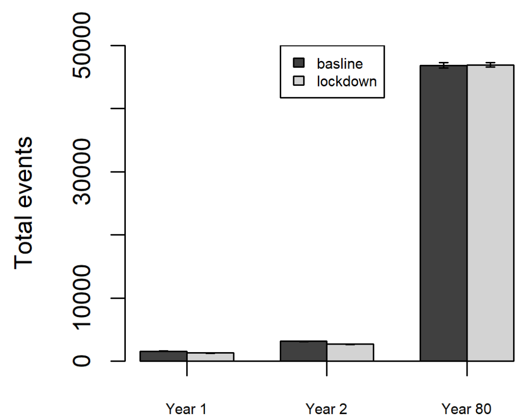

Figure 4: Cumulative number of MSI events following reductions in physical activity as a result of the UK Covid-19 lockdown (grey bars) compared to the baseline scenario (no lockdown - black bars) after 1, 2 and 80 years. Outputs represent the mean (±SD) of 100 runs for a cohort of 10,000 agents.

function of their physical activity level, where a lower physical activity increases the risks of CVD, T2D and depression, but decreases the risk of MSI. It should be noted that the model does not account for physical activity effects on other characteristics, such as BMI or blood pressure, which may in reality affect the risk of developing an NCD; thus, these results may be under-representative.

The cumulative number of events did, however, recover over the lifetime of the cohort (80 years), where cumulative changes in the number of CVD, T2D, depression and MSI events were <0.01%. This recovery emerged due to the physical activity levels recovering after two years of lockdowns, resulting in the relative risk converging with the baseline scenario. In addition, there are more fatalities due to NCDs during the period with lower levels of physical activity. Nonetheless, further investigation is needed in order to understand fully the impacts. The long-term recovery may again be under-represented in the model, as it does not account for the increased fatalities from Covid-19 of older individuals at higher risk of undergoing an NCD event, resulting in a marginally younger cohort with fewer comorbidities. The results from this simulation study are therefore likely to be conservative.

Our results are supported by empirical studies in the literature which show that in patients with the simulated NCDs, the risk of an event occurring in the short-term increased during the lockdown as a result of changes in physical activity. Perrone et al. (2021) found that patients with high cardiovascular risk showed increased LDL and cholesterol levels during the lockdown in Italy, increasing the ischemic heart disease risk. In the US, the number of deaths from heart disease increased by 4.1%, representing about five years of lost progress in reducing heart disease death rates among adults (American Heart Association 2023). Similarly, in the UK, nearly 100,000 more people with cardiovascular disease than expected have died since the start of the pandemic in England (British Heart Foundation 2023).

For depression, Cecchini et al. (2021) found a significant rise during the lockdown in Spain, and observed a negative relationship between the increase in depressive symptoms and moderate-to-vigorous physical activity (MVPA) levels. Schuch et al. (2020) found the same pattern in self-isolating individuals in Brazil. A similar trend is shown for T2D, for example, Izzo et al. (2023) undertook a 6-year study on more than 200,000 adult participants in Italy, and found that the incidence of T2D was significantly higher during the pandemic compared to the pre-COVID-19 phase. These studies give a good indication that our simulations are accurate, but they cannot assess how the diseases may progress in the long-term nor have they attempted to quantify the cost of these diseases to the health system.

Given this important knowledge gap, future work will assess the long-term economic effects of the simulated changes in NCD occurrences as a result of the lockdown with the aim to provide a cost-benefit analysis of increased NCD cases vs. Covid-19 infections prevented.

REFERENCES

Ahmed, H.M., M.J. Blaha, K. Nasir, J.J. Rivera, and R.S. Blumenthal. 2012. "Effects of Physical Activity on Cardiovascular Disease". *The American Journal of Cardiology* 109(2):288-295 https://doi.org/10.1016/j.amjcard.2011.08.042.

Althubaiti, A. 2016. "Information bias in health research: definition, pitfalls, and adjustment methods". *Journal of multidisciplinary healthcare* 211-217 https://doi.org/10.2147/JMDH.S104807.

American Heart Association 2023. *Heart Disease Death Rates Spiked During the COVID-19 Pandemic, Erasing Years of Progress*. American Heart Association Scientific Sessions 2022, Abstract VP161. https://newsroom.heart.org/news/heart-disease-death-rates-spiked-during-the-covid-19-pandemic-erasing-years-of-progress, accessed 28th March 2024.

Anagnostou, A., S.J.E. Taylor, D. Groen, D. Suleimenova, N. Anokye, R. Bruno et al. 2019. "Building Global Research Capacity in Public Health: The Case of a Science Gateway for Physical Activity Lifelong Modelling and Simulation". In *2019 Winter Simulation Conference (WSC)*, 1067-1078 https://doi.org/10.1109/WSC40007.2019.9004845.

Bailey, D.P., A.V. Wells, T. Desai, K. Sullivan, and L. Kass. 2022. "Physical Activity and Sitting Time Changes in Response to the COVID-19 Lockdown in England". *PLOS One* 17(7):e0271482 https://doi.org/10.1371/journal.pone.0271482.

Balanzá-Martínez, V., F. Kapczinski, T. de Azevedo Cardoso, B. Atienza-Carbonell, A.R. Rosa, J.C. Mota et al. 2021. "The assessment of lifestyle changes during the COVID-19 pandemic using a multidimensional scale". *Revista de Psiquiatria y Salud Mental* 14(1):16-26 https://doi.org/10.1016/j.rpsm.2020.07.003.

British Heart Foundation 2023. *Excess Deaths Involving Cardiovascular Disease: An Analysis*. https://www.bhf.org.uk/what-we-do/policy-and-public-affairs/excess-deaths-involving-cardiovascular-disease-an-analysis, accessed 29th March 2024.

Bourdas, D.I. and E.D. Zacharakis. 2020. "Evolution of changes in physical activity over lockdown time: Physical activity datasets of four independent adult sample groups corresponding to each of the last four of the six COVID-19 lockdown weeks in Greece". *Data in Brief 32*:106301 https://doi.org/10.1016/j.dib.2020.106301.

Bu, F., J.K. Bone, J.J. Mitchell, A. Steptoe, and D. Fancourt. 2021. "Longitudinal changes in physical activity during and after the first national lockdown due to the COVID-19 pandemic in England". *Scientific Reports* 11:17723 https://doi.org/10.1038/s41598-021-97065-1.

Caputo, E.L, and F.F Reichert. 2020. "Studies of physical activity and COVID-19 during the pandemic: A scoping review". *Journal of Physical Activity and Health* 17:1275–1284 https://doi.org/10.1123/jpah.2020-0406.

Cecchini, J.A., A. Carriedo, J. Fernández-Río, A. Méndez-Giménez, C. González, B. Sánchez-Martínez et al. 2021. "A Longitudinal Study on Depressive Symptoms and Physical Activity During the Spanish Lockdown". *International Journal of Clinical and Health Psychology* 21(1):100200 https://doi.org/10.1016/j.ijchp.2020.09.001.

Clift, A.K., C.A. Coupland, R.H. Keogh, K. Diaz-Ordaz, E. Williamson, E.M. Harrison et al. 2020. "Living Risk Prediction Algorithm (QCOVID) for Risk of Hospital Admission and Mortality from Coronavirus 19 in Adults: National Derivation and Validation Cohort Study". *BMJ*, 371 https://doi.org/10.1136/bmj.m3731.

Cuevas, E. 2020. "An Agent-Based Model to Evaluate the COVID-19 Transmission Risks in Facilities". *Computers in Biology and Medicine* 121:103827 https://doi.org/10.1016/j.compbiomed.2020.103827.

Deschasaux-Tanguy, M., N. Druesne-Pecollo, Y. Esseddik, F.S. de Edelenyi, B. Alles, V.A. Andreeva et al. 2020. "Diet and physical activity during the COVID-19 lockdown period (March-May 2020): results from the French NutriNet-Sante cohort study". *The American Journal of Clinical Nutrition* 113(4):924-938 https://doi.org/10.1093/ajcn/nqaa336.

Đogaš, Z., L. Lušić Kalcina, I. Pavlinac Dodig, S. Demirović, K. Madirazza, M. Valić et al. 2020. "The effect of COVID-19 lockdown on lifestyle and mood in Croatian general population: a cross-sectional study". *Croatian Medical Journal* 61(4):309-318 https://hrcak.srce.hr/255101.

Fennell, C., T. Eremus, M.G. Puyana, and B. Sañud. 2022. "The Importance of Physical Activity to Augment Mood During COVID-19 Lockdown". *International Journal of Environmental Research and Public Health* 19(3):1270 https://doi.org/10.3390/ijerph19031270.

Fitbit 2020. *The Impact of Coronavirus on Global Activity*. Fitbit, March 23. https://blog.fitbit.com/covid-19-global-activity, accessed 29th March 2024.

Garmin. 2020. *Are We Still Moving? The Effect of the Global Pandemic on Active Lifestyles*. https://www.garmin.com/en-US/blog/general/the-effect-of-the-global-pandemic-on-active-lifestyles, accessed 29th March 2024.

Hamasaki, H. 2016. "Daily Physical Activity and Type 2 Diabetes: A Review". *World Journal of Diabetes* 7(12):243-251 https://doi.org/10.4239%2Fwjd.v7.i12.243.

Haskell W.L., I.M. Lee, R.R. Pate, K.E. Powell, S.N. Blair, B.A. Franklin et al. 2007. "Physical Activity and Public Health: Updated Recommendation for Adults from the American College of Sports Medicine and the American Heart Association". *Medicine and Science in Sports and Exercise* 39(8):1423-1434 https://doi.org/10.1249/mss.0b013e3180616b27.

Hippisley-Cox, J., C. Coupland, Y. Vinogradova, J. Robson, R. Minhas, A. Sheikh et al. 2008. "Predicting cardiovascular risk in England and Wales: prospective derivation and validation of QRISK2". *BMJ* 336(7659):1475-1482 https://doi.org/10.1136/bmj.39609.449676.25

Hippisley-Cox, J., and C. Coupland. 2017. "Development and Validation of QDiabetes-2018 Risk Prediction Algorithm to Estimate Future Risk of Type 2 Diabetes: Cohort Study", *BMJ* 359:j5019 https://doi.org/10.1136/bmj.j5019.

Health Survey for England. 2012. *Health Survey for England – 2012*. https://digital.nhs.uk/data-and-information/publications/statistical/health-survey-for-england/health-survey-for-england-2012. Accessed 6th June 2024.

Izzo, R., D. Pacella, V. Trimarco, M.V. Manzi, A. Lombardi, R. Piccinocchi et al. 2023. "Incidence of Type 2 Diabetes Before and During the COVID-19 Pandemic in Naples, Italy: A Longitudinal Cohort Study". *EClinicalMedicine* 66 https://doi.org/10.1016/j.eclinm.2023.102345.

Kerr, C.C., R.M. Stuart, D. Mistry, R.G. Abeysuriya, K. Rosenfeld, G.R. Hart et al. 2021. "Covasim: An Agent-Based Model of COVID-19 Dynamics and Interventions". *PLOS Computational Biology* 17(7):e1009149 https://doi.org/10.1371/journal.pcbi.1009149.

McCarthy, H., H.W. Potts, and A. Fisher. 2021. "Physical Activity Behavior Before, During, and After COVID-19 Restrictions: Longitudinal Smartphone-Tracking Study of Adults in the United Kingdom". *Journal of Medical Internet Research* 23(2):e23701 https://doi.org/10.2196/23701.

Mintram, K., A. Anagnostou, N. Anokye, E. Okine, D. Groen, A. Saha et al. 2022. "CALMS: Modelling the Long-Term Health and Economic Impact of Covid-19 Using Agent-Based Simulation". *PLOS One* 17(8):e0272664 https://doi.org/10.1371/journal.pone.0272664.

Muhammad, D.G. and I.A. Abubakar. 2021." COVID-19 Lockdown May Increase Cardiovascular Disease Risk Factors". *The Egyptian Heart Journal* 73:1-3 https://doi.org/10.1186/s43044-020-00127-4.

Mutz, M. and M. Gerke. 2021. "Sport and exercise in times of self-quarantine: How Germans changed their behaviour at the beginning of the Covid-19 pandemic". *International Review for the Sociology of Sport*, 56(3):305-316 https://doi.org/10.1177/101269022093433

NCD Alliance. n.d. A Global NCD Agenda for Resilience and Recovery from Covid-19. https://ncdalliance.org/sites/default/files/3889%20NCDA%20Resilience%20and%20Recovery_WEB.pdf, accessed 1st April 2024.

Pearce, M., L. Garcia, A. Abbas, T. Strain, F.B. Schuch, R. Golubic et al. 2022. "Association Between Physical Activity and Risk of Depression: A Systematic Review and Meta-Analysis". *JAMA Psychiatry* 79(6):550-559 https://doi.org/10.1001/jamapsychiatry.2022.0609.

Perrone, M.A., A. Feola, M. Pieri, B. Donatucci, C. Salimei, M. Lombardo et al. "The Effects of Reduced Physical Activity on the Lipid Profile in Patients with High Cardiovascular Risk During COVID-19 Lockdown". *International Journal of Environmental Research and Public Health* 18(16):8858 https://doi.org/10.3390/ijerph18168858.

Rait, G., K. Walters, M. Griffin, M. Buszewicz, I. Petersen, and I. Nazareth. 2009. "Recent Trends in the Incidence of Recorded Depression in Primary Care". *The British Journal of Psychiatry* 195(6):520-524 https://doi.org/10.1192/bjp.bp.108.058636.

Rogers, N.T., N.R. Waterlow, and H. Brindle. 2020. "Behavioral Change Towards Reduced Intensity Physical Activity is Disproportionately Prevalent among Adults with Serious Health Issues or Self-Perception of High Risk During the UK COVID-19 Lockdown". *Frontiers in Public Health* 8:575091 https://doi.org/10.3389/fpubh.2020.575091.

Santos, A.C., J. Willumsen, F. Meheus, A. Ilbawi, and F.C. Bull. 2023. "The Cost of Inaction on Physical Inactivity to Public Health-Care Systems: A Population-Attributable Fraction Analysis". *The Lancet Global Health* 11(1):e32-e39 https://doi.org/10.1016/S2214-109X(22)00464-8.

Scarborough, P., P. Bhatnagar, K.K. Wickramasinghe, S. Allender, C. Foster, and M. Rayner. 2011. "The Economic Burden of Ill Health Due to Diet, Physical Inactivity, Smoking, Alcohol and Obesity in the UK: An Update to 2006–07 NHS Costs". *Journal of Public Health* 33(4):527-535 https://doi.org/10.1093/pubmed/fdr033.

Schuch, F.B., R.A. Bulzing, J. Meyer, D. Vancampfort, J. Firth, B. Stubbs *et al*. 2020. "Associations of Moderate to Vigorous Physical Activity and Sedentary Behavior with Depressive and Anxiety Symptoms in Self-Isolating People During the COVID-19 Pandemic: A Cross-Sectional Survey in Brazil". *Psychiatry Research* 292:113339 https://doi.org/10.1016/j.psychres.2020.113339.

Shamil, M.S., F. Farheen, N. Ibtehaz, I.M. Khan, and M.S. Rahman. 2021. "An Agent-Based Modeling of COVID-19: Validation, Analysis, and Recommendations". *Cognitive Computation* 1-12 https://doi.org/10.1007/s12559-020-09801-w.

Shephard, R.J. 2003. "Limits to the Measurement of Habitual Physical Activity by Questionnaires". *British Journal of Sports Medicine* 37(3):197-206 https://doi.org/10.1136/bjsm.37.3.197.

Solomon-Moore, E., J. Lambert, E. Grey, F. Gillison, N. Townsend, B. Busam et al. 2022. "Life in Lockdown: A Longitudinal Study Investigating the Impact of the UK COVID-19 Lockdown Measures on Lifestyle Behaviours and Mental Health". *BMC Public Health* 22(1):1495 https://doi.org/10.1186/s12889-022-13888-1.

Sport England. 2022. *Active Lives Survey 2020-2021 Year 6 Technical Note*. https://sportengland-production-files.s3.eu-west-2.amazonaws.com/s3fs-public/2022-04/Active%20Lives%20Survey%202020-21%20Year%206%20%28full%29%20-%20technical%20note.pdf?VersionId=gNMO3A95Zf.g5f3Shj05Sc7u73VTY3zo, accessed 29th March 2024.

Sport England. 2023. *Active Lives Adult Survey November 2021-22 Report*. https://sportengland-production-files.s3.eu-west-2.amazonaws.com/s3fs-public/2023-04/Active%20Lives%20Adult%20Survey%20November%202021-22%20Report.pdf?VersionId=ln4PN2X02DZ1LF18btgaj5KFHx0Mio9o, accessed 29th March 2024.

Strain, T., S.J. Sharp, A. Spiers, H. Price, C Williams, C. Fraser et al. 2022. "Population Level Physical Activity Before and During the First National COVID-19 Lockdown: A Nationally Representative Repeat Cross-Sectional Study of 5 Years of Active Lives Data in England". *The Lancet Regional Health–Europe* 12 https://doi.org/10.1016/j.lanepe.2021.100265.

UK Department of Health and Social Care. 2011. *Start Active, Stay Active: A Report on Physical Activity from the Four Home Countries' Chief Medical Officers*. https://www.gov.uk/government/publications/start-active-stay-active-a-report-on-physical-activity-from-the-four-home-countries-chief-medical-officers, accessed 29th March 2024.

WHO. 2020. The Top 10 Causes of Death. https://www.who.int/news-room/fact-sheets/detail/the-top-10-causes-of-death, accessed 1st April 2024.

WHO. 2022. Global Status Report on Physical Activity 2022. https://www.who.int/publications/i/item/9789240059153, accessed 1st April 2024.

Wijlaars, L.P., I. Nazareth, and I. Petersen. 2012. "Trends in Depression and Antidepressant Prescribing in Children and Adolescents: A Cohort Study in The Health Improvement Network (THIN)". *PLOS One* 7(3):e33181 https://doi.org/10.1371/journal.pone.0033181.

AUTHOR BIOGRAPHIES

KATE MINTRAM is an Associate Lecturer in the Department of Computer Science at Brunel University London and is a member of the Modelling & Simulation Group. Her main research interest is using simulation modelling to address complex biological problems. She has developed population dynamics models for chemical risk assessments, climate change, understanding genetic viral resistance, and more recently has focussed on agent-based modelling for pandemic crisis management. Her email address is kate.mintram@brunel.ac.uk and her ORCID iD is https://orcid.org/0000-0001-7180-9200.

BHARGAVI GOTTIMUKKALA is a recent graduate of Brunel University London, currently working at Queen's Park Community School as a Computer Science teaching assistant. She contributed to the literature review in the current paper as part of an internship at the end of her degree. Her email address is gottimukkalabhargavi@gmail.com.

ANASTASIA ANAGNOSTOU is a Senior Lecturer in the Department of Computer Science at Brunel University London and the co-lead of the Modelling Simulation Group. Her main research interests lie in the areas of Advanced Computing Infrastructures for M&S, Open Science and M&S for Global Challenges primarily in Industry and the Healthcare sector.. She was Conference Co-Chair for the 10th OR Society Simulation Workshop (SW21). At the Winter Simulation Conference (WSC), she served as Chair of the PhD Colloquium Committee in 2018 and was Track Co-Chair for the Healthcare, Introductory Tutorials and Hybrid Simulation Tracks. She is also Program Chair for WSC 2025. She ACM SIGSIM Vice Chair and Assosiate Editor of the Journal of Simulation. Her email address is anastasia.anagnostou@brunel.ac.uk and her ORCID iD is https://orcid.org/0000-0003-3397-8307.