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Author

Veerman, Lennert, Tarp, Jakob, Wijaya, Ruth, Wanjau, Mary Njeri, Möller, Holger, Haigh, Fiona, Lucas, Peta, Milat, Andrew

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1. TITLE PAGE

PHYSICAL ACTIVITY AND LIFE-EXPECTANCY: A LIFETABLE ANALYSIS

Author names, with highest academic degree and affiliations

J. Lennert Veerman, PhD, Public Health & Economics Modelling Group, School of Medicine and Dentistry, Griffith University, Gold Coast, Queensland, Australia.

Jakob Tarp, PhD, Department of Clinical Epidemiology, Aarhus University and Aarhus University Hospital, Aarhus, Denmark

Ruth Wijaya, MD, School of Medicine and Dentistry, Griffith University, Gold Coast, Queensland, Australia

Mary Njeri Wanjau, PhD, Public Health & Economics Modelling Group, School of Medicine and Dentistry, Griffith University, Gold Coast, Queensland, Australia

Holger Möller, PhD, School of Population Health, University of New South Wales, Sydney, Australia

Fiona Haigh, PhD, Health Equity Research and Development Unit (HERDU), University of New South Wales, Sydney, Australia

Peta Lucas, Bachelor of Human Movement Science, Centre for Population Health, NSW Ministry of Health, Sydney, Australia

Andrew Milat, PhD, School of Public Health, University of Sydney, Camperdown, New South Wales, Australia

Corresponding author

J. Lennert Veerman

Public Health & Economics Modelling Group, School of Medicine and Dentistry, Griffith University, Gold Coast, Queensland, Australia.

Gold Coast campus, Parklands Drive, Southport, QLD, 4222

l.veerman@griffith.edu.au

[redacted]

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Summary Box

What is already known on this topic

- Accelerometer assessed physical activity provides stronger associations with mortality, but estimates of the population health implications on life-expectancy are lacking.

What this study adds

- Our study provides estimates of the mortality burden attributable to low levels of physical activity in the United States.
- Americans over the age of 40 could live an extra 5.3 years if all were as active as the top 25% of the population.
- For the least active 25% of Americans, an extra hour's walk could add 6.3 hours of additional life-expectancy.

How this study might affect research, practice or policy

- Increased investment in physical activity promotion and creating living environments that foster physical activity can yield large gains in life-expectancy.

2. ABSTRACT

Objective

Low physical activity (PA) levels are associated with increased mortality. Improved measurement has resulted in stronger proven associations between PA and mortality, but this has not yet translated to improved estimates of the disease burden attributable to low PA. This study estimated by how much low physical activity reduces life expectancy, and by how much life expectancy could be improved by increasing physical activity levels for both populations and individuals.

Methods

We applied a predictive model based on device-measured physical activity risk estimates and a lifetable model analysis, using a lifetable of the 2019 United States population based on 2017 mortality data from the National Centre for Health Statistics. Included participants were aged 40+ years with PA levels based on data from the 2003-2006 National Health and Nutritional Examination Survey (NHANES). The main outcome was life expectancy based on PA levels.

Results

If all individuals were as active as the top 25% of the population, Americans over age 40 could live an extra 5.3 years (95% uncertainty interval 3.7 to 6.8 years) on average. The greatest gain in lifetime per hour of walking was seen for individuals in the lowest activity quartile where an additional hour's walk could add 376.3 minutes (~6.3 hours) of life expectancy (95% uncertainty interval 321.5 to 428.5 minutes).

Conclusion

Higher PA levels provide a substantial increase in population life expectancy. Increased investment in PA promotion and creating PA promoting living environments can promote healthy longevity.

3. INTRODUCTION

Low physical activity levels are associated with an increased incidence of non-communicable disease and premature mortality worldwide.[1,2] Higher levels of physical activity reduce the risk of death regardless of intensity and age. Benefits are greatest for those currently inactive, but continue to high levels of activity.[3] Increasing physical activity and decreasing sedentary behaviour is a policy priority in the United States (US) and many countries worldwide.[4-6] This is reflected in the US physical activity guidelines[7] as well as the World Health Organization's guidelines on physical activity and sedentary behaviour and their launch of the global action plan on physical activity.[6,8] Policies to promote physical activity can also help achieve many of the UN sustainable development goals, in particular SDG 3 'Improve health and well-being for all, at all ages'.[9] In the US, 46.9% of adults met the guidelines for aerobic activity and only 24.2% met the guidelines for both aerobic and muscle-strengthening activities in 2020. There are large differences between socioeconomic groups with 16.2% of men and 9.9% of women in the lowest income group (<100% of federal poverty income level) meeting aerobic and muscle strengthening guidelines compared with 32.4% and 25.9% in the highest income group (200% of federal poverty income level), respectively.[5] This highlights the large potential to increase health overall and decrease health inequalities for measures that increase physical activity.

Policy makers are interested in the potential health and cost benefits of interventions that improve physical activity. Such estimates rely on the evidence from epidemiological studies. A major limitation of these studies is that physical activity has commonly been assessed based on self-reporting which has been shown to have limited accuracy.[10] Imprecise measurement of exposure may lead to underestimation of the effect of physical activity on morbidity and mortality ('regression dilution bias').[11] Recently, estimates of the association of device-measured physical activity with health outcomes have become available. A 2019 meta-analysis of eight large cohort studies showed that the relationship of accelerometer-assessed physical activity with all-cause mortality is about twice as strong as previously estimated.[3] Benefits accrue at any level of activity, not just moderate or vigorous intensity activity.

This suggests that current estimates of the burden of disease attributable to low physical activity are far too low.[12] In this study, we use the new device-measured physical activity risk estimates and a lifetable model to estimate by how much low physical activity reduces life expectancy in the United States (US), and how much lifetime could be gained by increases in physical activity levels for both populations and individuals.

4. METHODS

Life-table model

We constructed a life table of the 2019 American population[13] based on 2017 mortality data from the National Centre for Health Statistics[14] (See Supplementary File Tables S1 and S2). We used potential impact fraction (PIF) calculations to vary mortality as a function of population physical activity levels. We then derived alternative life tables to estimate life expectancy at different levels of total physical activity.[15] PIF is a measure of effect that calculates the proportional change in risk (in this case, of death) after a change in the exposure of a risk factor (here, physical activity).[15]

Total physical activity data input

Population levels of total physical activity were based on estimates from the 2003-2006 National Health and Nutritional Examination Survey (NHANES).[13,16] The NHANES samples non-institutionalized U.S. civilians using a multistage probability sampling design that considers geographical area and minority representation.[17] Physical activity was measured by a hip-worn accelerometer (AM-7164; ActiGraph) for 7 days using a 1-minute epoch in the 2003/2004 and 2005/2006 cycles. We used data from the vertical axis. Individual level data from ≥10 hours for ≥4 days between 6 AM and midnight was required for inclusion in analysis, leading to the exclusion of 824 participants with insufficient wear-time (See Supplementary File p.4 and Table S3).[3] We defined non-wear according to the Choi algorithm and calculated total physical activity as total recorded counts/wear-time (counts per minute, cpm),[18] a metric explaining 20-30% of the variance in physical activity energy expenditure.[19] An ActiGraph 'count' is a dimensionless summary metric representing acceleration of the device following signal processing.[20] A higher 'count' reflects more movement.

For consistency, we applied the same exclusion criteria as in the meta-analysis by Ekelund and colleagues which we used for the dose response relationship in the modelling (i.e., equivalent to model C in their study).[3] Total physical activity was divided into quarters (Q1, Q2, Q3 and Q4) and tabulated in 10-year age strata with incorporation of sample weights to yield estimates representative of noninstitutionalized U.S. civilians above 40 years of age (Table 1).[17] In this paper Q1 is referred to as the least active (represents lower 25%) and Q4 as most active (upper 25%). In the model, we applied a normal distribution to reflect the uncertainty in average total physical activity levels. More recent data from NHANES [21,22] were explored but the 2003-2006 data[16] was used for consistency with the study by Ekelund and colleagues, and because the latest available accelerometer data from 2011-2014[22] were collected using a different accelerometer placement (wrist), which hindered conversion to estimates of walking equivalence (see below).

Table 1. Average total physical activity by quartile in counts per minute (cpm)

	Q1 (Least active)			**Q2**			**Q3**			**Q4 (Most active)**		
AGE	**Mean**	**SEM**	**n**	**Mean**	**SEM**	**n**	**Mean**	**SEM**	**n**	**Mean**	**SEM**	**n**
40-49.9	146.9	4.2	57	215.0	1.8	214	298.0	1.6	288	481.4	5.1	464
50-59.9	133.3	2.8	106	218.2	1.8	209	297.0	1.7	273	457.7	7.2	248
60-69.9	128.1	1.7	252	212.9	1.6	278	293.1	1.7	254	450.1	9.6	178
70-79.9	116.5	2.0	299	210.7	1.6	187	290.8	3.2	112	411.6	11.7	56

80+	107.7	3.3	240	207.0	3.7	65	294.7	7.2	28	464.6	66.1	9

Average total physical activity by quartile in counts per minute (cpm), based on NHANES 2003-2006 physical activity monitor data weighted to the noninstitutionalized U.S. civilian population aged 40+, in 10-year intervals. For the calculation of the SEMs, we used the svy command in Stata accounting for the complex survey design of the NHANES as described in the analytical guidelines published by the National Center for Health Statistics.[17]

N; number (estimates weighted to represent US civilian, non-institutionalized population >40), Q; quartile (total physical activity was divided into quarters from the least active [lower 25%] to most active [upper 25%]), SEM; Standard error of the mean

Physical activity and mortality

We used the dose response relationship between total accelerometer measured physical activity (regardless of intensity) and all-cause mortality from a recent meta-analysis of prospective cohort studies.[3] In their maximally adjusted model (model C), the authors found the following all-cause mortality hazard ratios (HR) per physical activity level quartile: Q1, least active (referent, HR= 1), Q2 (HR=0.54, 0.48 to 0.61), Q3 (HR=0.41, 0.32 to 0.51), and Q4, most active (HR=0.34, 0.29 to 0.41).[3]

From these HRs, with the counterfactual population set as the quartile of interest, PIF calculations were used to derive counterfactual mortality estimates for the four different physical activity levels. We used the relative risk shift method of calculating PIF, which is a method that changes the relative risks of the categories while keeping the proportion in each category constant (See Supplementary File p. 4).[15] The resulting life tables provide estimates of the life expectancy for four activity quartiles of the US population. We report on life expectancy at birth for each quartile.[14] (Up to the age of 40 years, mortality rates in the life tables remains stable; at higher ages, mortality rates vary as a function of physical activity.) In our main analysis, we compared health outcomes from scenarios with observed physical activity levels, to scenarios in which the whole population was in the least active quartile, and in the most active quartile.

Average physical activity levels by age (40-49.9, …, 80+ year) were applied to the U.S. Statistics Bureau's 2019 American population data to estimate the benefits of an hour of walking, a common and typical physical activity behaviour.[13,21]

In this study, we translate differences in mean counts per minute between physical activity quartiles into walking equivalents in order to better place the findings in an understandable context. To calculate minutes of walking equivalent, we first calculated the total counts per day by multiplying average cpm (as reported in the NHANES) with the mean wear-time in the NHANES sample (850 minutes/day). We then divided these total activity counts per day by the cpm of walking to get the minutes of walking equivalent. The cpm of walking was taken as the accelerometer output generated during 3mph (4.8km/h) walking in adults estimated as 2481 cpm.[24]

Based on the mean activity levels of each quartile, we computed the average extra daily minutes of walking (at 3 mph) required by less active individuals of the American population age ≥40 years to reach the next higher physical activity quartile, and the walking time needed to move all quartiles to the highest quartile.

After translating differences in physical activity levels to the equivalent hours of walking, we also estimated how much lifetime can be gained by the average additional hour of walking for individuals above the age of 40 years, both at the population level and individual level. In the estimation of individual gains, we report the change in life expectancy at age 40 compared by activity level i.e., when less active individuals reached the next higher physical activity quartile. For these individual level gain estimates, we incorporated a lag period where increases in physical activity gradually translate to reduced mortality in the five following years.[25] Supplementary file Table S4 gives further detail.

Uncertainty in the activity levels of each quartile and the hazard ratios was incorporated using parametric bootstrapping (probabilistic sensitivity analysis), using normal and lognormal distributions, respectively.[23] We provide a step-by-step summary of our methods in Supplementary File p. 5.

The lifetable calculations were performed on MS Excel (Microsoft Corporation, Redmond, Washington, USA) with probabilistic sensitivity analysis performed using add-in Ersatz (Epigear.com, Brisbane, Australia; 10,000 iterations).

We used the Guidelines for Accurate and Transparent Health Estimates Reporting (GATHER) in our reporting.[26] We reviewed our statistical analysis and presentation for consistency with the CHecklist for statistical Assessment of Medical Papers (CHAMP) statement.[27] Ethics approval was not required for this study.

Equity, diversity, and inclusion statement

Our author team is gender balanced and includes junior, mid-career and senior researchers from different countries and a marginalised community. At the time of research, authors were working in different States in one country and one author was in a different country. Our lifetable analysis included the 2019 American population. In the study introduction, we describe the impact of socioeconomic disadvantage on the current health gap our research addresses and we discuss the potential to decrease health inequalities.

5. RESULTS

Life expectancy

Average life expectancy in the US was 78.6 years in 2017. Our estimates indicate that if all Americans in 2017 aged 40 years and above were as active as the least active 25% (Q1), there would be a loss in life expectancy of 5.8 years (95% Uncertainty Interval [UI]: 5.2 to 6.4). Life-expectancy at birth would be around 73.0 years (95% UI: 72.4 to 73.6; Figure 1). With subsequent increases in physical activity to the levels corresponding to Q2 and Q3, respective gains in life expectancy of 0.6 years (95% UI: -

0.5 to 1.7) and 3.5 years (95% UI: 1.6 to 5.5) would be expected. This corresponds to life expectancy at birth of 79.2 (95% UI: 78.1 to 80.2) and 82.0 (95% UI: 80.1 to 83.9; Figure 1). If all Americans over the age of 40 were as active as the top 25% (Q4), American life expectancy at birth would be 83.7 years (95% UI: 82.2 to 85.1; Figure 1), which is an increase of 5.3 years (95% UI: 3.7 to 6.8).

The gains for individuals

To receive the health benefits of the most active 25% (Q4, total physical activity level equivalent to 160 daily minutes of walking at 4.8 km/h), individuals in the lowest activity quartile (Q1) require the equivalent of an extra 111.2 min/d (95% UI: 106.7 to 115.9) of walking per person (Table 2). This daily dose of physical activity would increase life expectancy by up to 10.9 years (95% UI: 9.3 to 12.7). Each additional single hour of physical activity would prolong life by an average of 169.1 minutes (95% UI: 146.4 to 193.4).

Table 2 breaks down this potential gain for low active Americans in a stepwise manner. The non-linear risk curve, which is steep at low levels of physical activity, translates to benefits that show a 'diminishing returns' effect. To shift from the least active 1st quartile to the 2nd quartile, individuals require an extra 28.5 min/d of walking, with each hour adding about 6.3 hours to life. From the 2nd quartile to the 3rd quartile, an extra 27.8 min/d per person of walking would be required, with each hour walking adding almost 3 hours to life. Finally, from the 3rd quartile to most active 4th quartile, an extra 55.0 min/d of walking is needed, with an hour of walking prolonging life by just under an hour.

Similarly, for Americans at low to medium level of total physical activity (quartile 2) aiming to reach the highest activity quartile, an extra 82.8 min/d of walking would be needed, with every single hour of walking to increase life by 4.6 hours on average.

Table 2. Benefits achieved by lower active individuals when they move to higher physical activity levels

Change in PA (quartile)	Average extra 3mph walking equivalence (min/d)	Prolonged life (min) per hour of walking	Life-expectancy difference at age 40 (years)
1→ 2	28.5 (27.4-29.7)	376.3 (321.5-428.5)	**6.3 (5.1-7.5)**
2→ 3	27.8 (26.8-28.7)	160.1 (10.4-278.4)	**2.8 (0.1-5.5)**
2→ 4	82.8 (78.2-87.3)	96.1 (59.9-136.0)	**4.6 (2.7-6.8)**
3→ 4	55.0 (50.4-59.5)	57.1 (-37.0-136.9)	**1.9 (-1.0-4.6)**
1→ 4	111.2 (106.7-115.9)	169.1 (146.4-193.4)	**10.9 (9.3-12.7)**

Health benefits achieved by lower active individuals of the American population age ≥40 years when they move to higher physical activity levels, taking the difference between quartile means. Values reported as mean and 95% uncertainty intervals. The calculation of the minutes of walking equivalent, prolonged life (min) per hour of walking and the life-expectancy difference in years is detailed in the methods section. Mph; mile per hour, PA; physical activity, min/d; minutes per day.

6. DISCUSSION

Our findings suggest that physical activity is associated with substantial gains in life expectancy for individual Americans and for the population. Moving the least active 25% of the population over age 40 to become as active as the top 25% could result in an average life-expectancy gain of about 11 years for this group. The greatest gain in lifetime per hour of walking was seen for individuals in the lowest activity quartile where an hour's walk could add an impressive 6 hours to life.

Strength and limitations

Our analysis builds upon hazard ratios from a published harmonized meta-analysis of large observational studies that spread across 8 cohorts, all of which included adults aged ≥40 years from the US and Western European countries.[3] This study assumes that these estimates are representative of the 2019 American population aged ≥40 years and that quartiles exist in each age group.[3] Ekelund et al did not make a formal comparison but the findings suggest that the 4 American cohorts may have been less active than the 4 European ones, adjusted for sex (when applicable), age, body mass index, socioeconomic position, and wear time.[3] Theoretically, since this would shift the US PA distribution to lower levels where the risk curve is steeper (more benefit for the same quantity of PA), this could bias our results toward underestimation. Using a conservative approach, we set gain of life-expectancy at age 40 to be equivalent to that at birth.

A strength is the use of total physical activity. Unlike exercise (moderate-to-vigorous PA) which represents a very small proportion of people's life, our measure encompasses the sum of all movement behaviours during waking hours.

Despite Ekelund et al.'s adjustments for sex, age, body mass index, economic status and additional covariates in their model C,[3] residual confounding may have affected their results, and by extension, ours. For example, while pre-existing illness (which could have led to inactivity) was adjusted for, this may not have removed all its effect, depending on how precisely it was measured.[3]

We assumed that physical activity levels measured in 2003-2006 relate to the 2017 mortality statistics. There is some evidence that adherence to physical activity guidelines in the US has improved over time.[28] Theoretically, since this would shift the US PA distribution to higher levels where the risk curve is shallower (less benefit for the same quantity of PA), this could bias our results toward overestimation.

Our estimates rely on crude estimation of averages and assume a uniform effect of physical activity within population quartiles. Compared to self-reported survey-based estimates, the use of accelerometer measured physical activity produced estimates that are less prone to measurement biases, which may reduce the 'regression dilution effect' of an imperfect exposure.[11] While the improved accuracy of physical activity assessment by accelerometry have doubled the magnitude of the association with all-cause mortality,[29] accelerometers explain approximately 20-30% of the variation in physical activity energy expenditure, as measured with the gold-standard doubly labelled water method,[19] meaning unexplained variance would still downward bias our life-expectancy estimates compared with true physical activity energy expenditure. Regression dilution bias would result to the extent that the unmeasured PA is random (not correlated with measured PA). However, hip-worn accelerometers systematically underestimate activity related energy expenditure of e.g., upper-body movement. If measured and unmeasured PA correlate, this would lead to overestimation of association of PA with outcomes (mortality).

Having a monitoring device for 1 week may lead to participation or response bias; people may be more active when wearing an accelerometer. In practice, measurements from the first day of device wear are mostly discarded due to reactivity concerns. After the first day, there is little evidence of reactivity when the device output is concealed (no feedback from device).[30] Furthermore, physical activity was measured during a single week at one point in time so does not account for seasonal variation or changes across the lifetime. Studies with repeated measurements of device-measured activity suggests a single week of measurements explains 40%-50% of the variance in 'usual' physical activity.[31,32] The likely effect of accounting for this within-person variability in activity levels is to increase the magnitude of associations with health outcomes.[3334,35]

Additional challenges include the processing, analysis and interpretation of device measured physical activity. We used Copeland's estimate that for older adults (mean age 70 years), 3mph walking would produce 2481 counts/min,[24] and apply that to all ages. However, there is uncertainty in the estimate; at the same speed, Freedson et al. arrived at a higher estimate of 3003 counts/minute for younger adults.[36] If we were to use this estimate in our analysis, fewer minutes of walking would be needed to change activity quartile and the benefit per hour of walking would be greater.

Comparison with other studies

Prior studies relied on self-reported data, rather than device-based measures. A systematic review of mostly multivariate life-table studies assessed 11 cohorts, and found a 0.43 to 4.21 years higher life-expectancy for self-reported physically active participants compared to inactive controls.[37] Our study exceeds the previously reported upper range of life gained by 6.7 years when comparing the most active group to the least active referent.

Our results suggest that the impact of low physical activity as a risk factor of all-cause mortality is comparable to that of smoking and potentially greater than that of hypertension. A UK based prospective study of one million women showed that smokers lose at least 10 years of lifespan.[38] Life-table modelling showed a loss of 220 minutes (3 hour 40 minutes) to life from smoking 1 pack of 20 cigarettes, though this is probably an underestimation.[39,40] According to our findings, this approximately equates to the minutes of life gained by walking just over half an hour for the most inactive 25% of Americans. With current declining prevalence of smoking in the US,[41] the population wide impact of low PA is expected to be larger in comparison. Based on the US Framingham Heart Study, hypertensive men and women had 5.1 and 4.9 years shortened life expectancy, which is less than half the loss associated with being in the lowest physical activity quartile we found in this study.[42] These results may seem surprising, but follow from an exposure to lower levels of physical activity affects 75% of the population (by definition), in combination with a strong mortality gradient - the finding that the mortality among the most active quartile of the population is lower than that among the least active quartile by two thirds.[3]

Implications and future research

Our findings suggest that physical activity provides substantially larger health benefits than previously thought, which is due to the use of more precise means of measuring physical activity. Our model demonstrates this large effect on life-expectancy by using more precise means of measuring physical activity. Adverse health outcomes due to low physical activity rival and may exceed the risk of death seen in hypertension and smoking; a single extra hour of walking above age 40 may increase life as much by 3 hours, on average.

There is a strong need to communicate these new estimates to decision makers and clinicians. Our findings support national policies and global initiatives that aim to increase physical activity. Our study also highlights that the costs of physical inactivity are much larger than previously estimated. Our findings suggest that the Global Burden of Disease study currently greatly underestimates the burden attributable to physical inactivity.

Conclusion

The findings of this study highlight the impact of physical activity-promoting interventions in a quantifiable manner related to life expectancy. These include cost benefit analyses of measures that impact on physical activity, for example in urban planning and transport. Increasing physical activity at the population level is a complex task that requires a systems-based approach,[43] considering the wider social determinants that impact on physical activity, sedentary behaviour and their unequal distribution across population groups.[44] Infrastructure measures that encourage active transport, walkable neighbourhoods as well as green spaces might be promising approaches to increase physical activity and resultant healthy life expectancy at the population level.[43]

Author Contributions: J. Lennert Veerman developed the concept and design. Statistical analysis: Lennert Veerman, Jakob Tarp, Ruth Wijaya and Mary Njeri Wanjau ran the model analysis. J. Lennert Veerman, Jakob Tarp, Ruth Wijaya, Mary Njeri Wanjau and Holger Möller contributed to acquisition and interpretation of data. J. Lennert Veerman, Ruth Wijaya, Mary Njeri Wanjau contributed to drafting of the manuscript. All authors contributed to critical review of the manuscript and content. Lennert Veerman is guarantor.

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Competing interests: None declared

Data Availability Statement: All data relevant to the study are included in the article or uploaded as supplementary information.

Ethical approval: Ethics approval was not required for this study

Patient involvement: Patients were not involved in this study

7. REFERENCES

1. Evenson KR, Wen F, Herring AH. Associations of Accelerometry-Assessed and Self-Reported Physical Activity and Sedentary Behavior With All-Cause and Cardiovascular Mortality Among US Adults. *Am J Epidemiol* 2016; **184**(9): 621-32.
2. Lee IM, Shiroma EJ, Lobelo F, Puska P, Blair SN, Katzmarzyk PT. Effect of physical inactivity on major non-communicable diseases worldwide: an analysis of burden of disease and life expectancy. *Lancet* 2012; **380**(9838): 219-29.
3. Ekelund U, Tarp J, Steene-Johannessen J, et al. Dose-response associations between accelerometry measured physical activity and sedentary time and all cause mortality: systematic review and harmonised meta-analysis. *BMJ* 2019; **366**: l4570.
4. Klepac Pogrmilovic B, Ramirez Varela A, Pratt M, et al. National physical activity and sedentary behaviour policies in 76 countries: availability, comprehensiveness, implementation, and effectiveness. *The international journal of behavioral nutrition and physical activity* 2020; **17**(1): 116.
5. Elgaddal N, Kramarow EA, Reuben C. Physical Activity Among Adults Aged 18 and Over: United States, 2020. *NCHS Data Brief* 2022; (443): 1-8.
6. World Health Organization. Global action plan on physical activity 2018-2030: more active people for a healthier world. Geneva: World Health Organization; 2018.
7. U.S. Department of Health and Human Services. Physical Activity Guidelines for Americans. In: Department of Health and Human Services, editor. Washington, DC: U.S.; 2018.
8. Bull FC, Al-Ansari SS, Biddle S, et al. World Health Organization 2020 guidelines on physical activity and sedentary behaviour. *British journal of sports medicine* 2020; **54**(24): 1451-62.
9. United Nations. Sustainable Development Goals 2015. https://www.undp.org/sustainable-development-goals (accessed 07/03/2023 2023).
10. Dowd KP, Szeklicki R, Minetto MA, et al. A systematic literature review of reviews on techniques for physical activity measurement in adults: a DEDIPAC study. *International Journal of Behavioral Nutrition and Physical Activity* 2018; **15**(1): 15.
11. Clarke R, Shipley M, Lewington S, et al. Underestimation of risk associations due to regression dilution in long-term follow-up of prospective studies. *Am J Epidemiol* 1999; **150**(4): 341-53.
12. Emmanuel S, Ding D, Ulf E, Adrian EB. Sliding down the risk factor rankings: reasons for and consequences of the dramatic downgrading of physical activity in the Global Burden of Disease 2019. *British Journal of Sports Medicine* 2021; **55**(21): 1222.
13. United States Census Bureau. National Population by Characteristics: 2010-2019. Annual Estimates of the Resident Population by Single Year of Age and Sex: April 1, 2010 to July 1, 2019 https://www.census.gov/data/tables/time-series/demo/popest/2010s-national-detail.html.
14. Salkind N, Anderson RN. National Vital Statistics Reports. Encycl Hum Dev, 2013;68(7).
15. Barendregt JJ, Veerman JL. Categorical versus continuous risk factors and the calculation of potential impact fractions. *J Epidemiol Community Health* 2010; **64**(3): 209-12.
16. National Center for Health Statistics. National Health and Nutrition Examination Survey: Physical Activity Questionaire. In: Centers for Disease Control and Prevention: U.S. Department of Health & Human Services, editor. Available from: https://wwwn.cdc.gov/nchs/nhanes/Default.aspx; 2003-2006.
17. Johnson CL, Paulose-Ram R, Ogden CL, et al. National health and nutrition examination survey: analytic guidelines, 1999-2010. *Vital Health Stat 2* 2013; (161): 1-24.
18. Choi L, Liu Z, Matthews CE, Buchowski MS. Validation of accelerometer wear and nonwear time classification algorithm. *Med Sci Sports Exerc* 2011; **43**(2): 357-64.
19. Sardinha LB, Júdice PB. Usefulness of motion sensors to estimate energy expenditure in children and adults: a narrative review of studies using DLW. *European journal of clinical nutrition* 2017; **71**(3): 331-9.

20. Brønd JC, Møller NC, Grøntved A. The Intrinsic Properties of ActiGraph Counts and Alternatives. *Journal for the Measurement of Physical Behaviour* 2024; **7**(1): jmpb.2023-0049.

21. National Center for Health Statistics. National Health and Nutrition Examination Survey: Physical Activity Questionaire. In: Centers for Disease Control and Prevention: U.S. Department of Health & Human Services, editor. Available from: https://wwwn.cdc.gov/nchs/nhanes/search/datapage.aspx?Component=Questionnaire&CycleBeginYear=2017; 2020.

22. National Center for Health Statistics. National Health and Nutrition Examination Survey. In: Centers for Disease Control and Prevention, editor. Available from: https://wwwn.cdc.gov/nchs/nhanes/search/datapage.aspx?Component=Examination&CycleBeginYear=2011; 2011.

23. Rothman KJ, Greenland S, Lash TL. Modern Epidemiology, 3e (pb): Lippincott; 2008.

24. Copeland JL, Esliger DW. Accelerometer assessment of physical activity in active, healthy older adults. *Journal of aging and physical activity* 2009; **17**(1): 17-30.

25. Götschi T, Kahlmeier S, Castro A, et al. Integrated Impact Assessment of Active Travel: Expanding the Scope of the Health Economic Assessment Tool (HEAT) for Walking and Cycling. *International Journal of Environmental Research and Public Health* 2020; **17**(20): 7361.

26. Stevens GA, Alkema L, Black RE, et al. Guidelines for Accurate and Transparent Health Estimates Reporting: the GATHER statement. *The Lancet* 2016; **388**(10062): e19-e23.

27. Mohammad Ali M, Gary SC, Rasmus Oestergaard N, et al. CHecklist for statistical Assessment of Medical Papers: the CHAMP statement. *British Journal of Sports Medicine* 2021; **55**(18): 1002.

28. Centers for Disease Control and Prevention: Physical activity. 2008 Physical Activity Guidelines for Americans: Trends in Meeting the 2008 Physical Activity Guidelines, 2008—2018. In: U.S. Department of Health & Human Services, editor. Available from: https://www.cdc.gov/physicalactivity/downloads/trends-in-the-prevalence-of-physical-activity-508.pdf.

29. Ekelund U, Dalene KE, Tarp J, Lee IM. Physical activity and mortality: what is the dose response and how big is the effect? *Br J Sports Med* 2020; **54**(19): 1125-6.

30. Ullrich A, Baumann S, Voigt L, John U, Ulbricht S. Measurement Reactivity of Accelerometer-Based Sedentary Behavior and Physical Activity in 2 Assessment Periods. *Journal of Physical Activity and Health* 2021; **18**(2): 185-91.

31. Chomistek AK, Yuan C, Matthews CE, et al. Physical Activity Assessment with the ActiGraph GT3X and Doubly Labeled Water. *Med Sci Sports Exerc* 2017; **49**(9): 1935-44.

32. Saint-Maurice PF, Sampson JN, Keadle SK, Willis EA, Troiano RP, Matthews CE. Reproducibility of Accelerometer and Posture-derived Measures of Physical Activity. *Med Sci Sports Exerc* 2020; **52**(4): 876-83.

33. Boe LA, Shaw PA, Midthune D, et al. Issues in Implementing Regression Calibration Analyses. *Am J Epidemiol* 2023; **192**(8): 1406-14.

34. Martinez-Gomez D, Cabanas-Sanchez V, Yu T, et al. Long-term leisure-time physical activity and risk of all-cause and cardiovascular mortality: dose-response associations in a prospective cohort study of 210 327 Taiwanese adults. *Br J Sports Med* 2022; **56**(16): 919-26.

35. Lee DH, Rezende LFM, Ferrari G, et al. Physical activity and all-cause and cause-specific mortality: assessing the impact of reverse causation and measurement error in two large prospective cohorts. *Eur J Epidemiol* 2021; **36**(3): 275-85.

36. Freedson PS, Melanson E, Sirard J. Calibration of the Computer Science and Applications, Inc. accelerometer. *Medicine and science in sports and exercise* 1998; **30**(5): 777-81.

37. Reimers CD, Knapp G, Reimers AK. Does physical activity increase life expectancy? A review of the literature. *J Aging Res* 2012; **2012**: 243958.

38. Pirie K, Peto R, Reeves GK, Green J, Beral V. The 21st century hazards of smoking and benefits of stopping: a prospective study of one million women in the UK. *Lancet* 2013; **381**(9861): 133-41.

39. Doll R, Peto R, Boreham J, Sutherland I. Mortality in relation to smoking: 50 years' observations on male British doctors. *Bmj* 2004; **328**(7455): 1519.
40. Shaw M, Mitchell R, Dorling D. Time for a smoke? One cigarette reduces your life by 11 minutes. *Bmj* 2000; **320**(7226): 53.
41. Cornelius ME, Loretan CG, Wang TW, Jamal A, DM H. Tobacco Product Use Among Adults — United States, 2020. *MMWR Morb Mortal Wkly Rep* 2022; **71:397–405**.
42. Franco OH, Peeters A, Bonneux L, de Laet C. Blood pressure in adulthood and life expectancy with cardiovascular disease in men and women: life course analysis. *Hypertension* 2005; **46**(2): 280-6.
43. World Health Organization. Global action plan on physical activity 2018–2030: more active people for a healthier world. Geneva: World Health Organization, 2018.
44. Australian Institute of Health and Welfare. Physical activity across the life stages. 2018. https://www.aihw.gov.au/getmedia/c249ef97-e219-44df-a8bd-f5e50d04064c/aihw-phe-225.pdf.aspx?inline=true2020).

Figure 1*.* Average U.S. life expectancy by age, comparing observed to results by adult physical activity quartile.

PHYSICAL ACTIVITY AND LIFE-EXPECTANCY

Supplementary File

Contents

Annual estimates of the resident population by single year of age for the United States: July 1, 2019

Table S1: Total population for male and female: 328,239,523

Age	Population number	Age	Population number	Age	Population number
0	3,783,052	**36**	4,372,444	**71**	3,083,083
1	3,829,599	**37**	4,361,286	**72**	3,191,048
2	3,922,044	**38**	4,305,576	**73**	2,334,433
3	3,998,665	**39**	4,382,349	**74**	2,283,164
4	4,043,323	**40**	4,105,313	**75**	2,198,286
5	4,028,281	**41**	4,020,254	**76**	2,222,392
6	4,017,227	**42**	3,974,741	**77**	1,911,261
7	4,022,319	**43**	3,854,040	**78**	1,720,817
8	4,066,194	**44**	3,967,275	**79**	1,599,909
9	4,061,874	**45**	3,837,909	**80**	1,475,278
10	4,060,940	**46**	3,889,372	**81**	1,381,641
11	4,189,261	**47**	4,058,038	**82**	1,241,341
12	4,208,387	**48**	4,282,657	**83**	1,151,190
13	4,175,221	**49**	4,329,775	**84**	1,067,757
14	4,164,459	**50**	4,096,572	**85**	922,467
15	4,175,459	**51**	4,004,343	**86**	856,646
16	4,150,420	**52**	4,001,782	**87**	778,923
17	4,142,425	**53**	4,068,851	**88**	703,078
18	4,255,827	**54**	4,305,603	**89**	635,982
19	4,330,439	**55**	4,374,565	**90**	536,447
20	4,269,683	**56**	4,361,016	**91**	467,172
21	4,278,323	**57**	4,342,385	**92**	394,067
22	4,298,772	**58**	4,385,570	**93**	320,785
23	4,341,644	**59**	4,413,855	**94**	264,277
24	4,444,518	**60**	4,252,663	**95**	207,086
25	4,539,058	**61**	4,215,172	**96**	157,463
26	4,611,220	**62**	4,156,645	**97**	116,969
27	4,733,869	**63**	3,996,088	**98**	86,150
28	4,818,725	**64**	3,950,578	**99**	57,124
29	4,806,144	**65**	3,774,597	**100+**	100,322
30	4,614,384	**66**	3,618,069		
31	4,502,311	**67**	3,464,437		
32	4,421,505	**68**	3,345,475		
33	4,432,973	**69**	3,252,423		
34	4,460,132	**70**	3,136,704		
35	4,315,866				

Source: Annual Estimates of the Resident Population by Single Year of Age and Sex for the United States: April 1, 2010 to July 1, 2019 (NC-EST2019-SYASEXN), U.S. Census Bureau, Population Division[1]
Release Date: June 2020

Mortality rates by single year of age based on 2017 mortality data from the National Centre for Health Statistics

Table S2: Mortality rates by single year of age

Age (years)	mortality rates	Age (years)	mortality rates	Age (years)	mortality rates
0	0.005777	36	0.001679	71	0.020317
1	0.000382	37	0.001740	72	0.022102
2	0.000248	38	0.001798	73	0.024194
3	0.000193	39	0.001860	74	0.026342
4	0.000149	40	0.001936	75	0.029042
5	0.000141	41	0.002036	76	0.032001
6	0.000126	42	0.002160	77	0.035443
7	0.000114	43	0.002306	78	0.039257
8	0.000104	44	0.002470	79	0.043393
9	0.000095	45	0.002647	80	0.048163
10	0.000093	46	0.002846	81	0.053216
11	0.000103	47	0.003079	82	0.059240
12	0.000133	48	0.003357	83	0.066564
13	0.000186	49	0.003682	84	0.074045
14	0.000258	50	0.004030	85	0.081954
15	0.000338	51	0.004401	86	0.090879
16	0.000421	52	0.004820	87	0.101938
17	0.000510	53	0.005285	88	0.114075
18	0.000603	54	0.005778	89	0.127331
19	0.000698	55	0.006284	90	0.141733
20	0.000795	56	0.006794	91	0.157289
21	0.000889	57	0.007319	92	0.173986
22	0.000970	58	0.007869	93	0.191788
23	0.001032	59	0.008456	94	0.210633
24	0.001080	60	0.009093	95	0.230432
25	0.001123	61	0.009768	96	0.251066
26	0.001165	62	0.010467	97	0.272395
27	0.001207	63	0.011181	98	0.294253
28	0.001252	64	0.011922	99	0.316456
29	0.001300	65	0.012710	100	1.000000
30	0.001351	66	0.013621		
31	0.001402	67	0.014620		
32	0.001454	68	0.015770		
33	0.001506	69	0.017100		
34	0.001556	70	0.018428		
35	0.001615				

Source: Salkind N, Anderson RN. National Vital Statistics Reports. Encycl Hum Dev, 2013;68(7).[2]

Estimation of lifetime gains from the average additional hour of walking for individuals above the age of 40 years

For the individual level gain estimates, we incorporated a lag period where increases in physical activity gradually translate to reduced mortality in the five following years.[3] This 5 year build-up time is based on expert consensus from a meeting by the WHO Regional Office for Europe.[3] In our model, the physical activity effect on all-cause mortality is interpolated linearly over the 5-year build-up time.

For each activity quartile, we calculated the difference in hours walked per year and life years (gained) when less active individuals reached the next higher physical activity quartile or moved to the highest quartile. The gains in hours walked and life years are each summed up for all ages ≥40 years. We then divided the total life years gained by the total hours walked per year and multiplied the result by 365.25 days, 24 hours and 60 minutes to derive the minutes gained (prolonged life) per hour of walking (See Table S3). In this estimation of prolonged life (min) per hour of walking, we varied the calculation in two ways where we used the lifetable cohort/population numbers (results in Table 2 of main manuscript) and in another way used the 2019 estimates of the American population numbers by single year. The differences in the calculations are summarised in Table S4.

Table S3 presents the results for the US population numbers.

Supplementary File Table 3. Estimation of average lifetime gains per additional hour of walking above the age of 40 years

Change in PA (quartile)	**Hours walked per year**	**Life years gained**	**Prolonged life (minutes gained) per hour of walking aged ≥40**
1→ 2	27,245,372,997 (26,142,310,566-28,289,493,100)	22,130,806 (17,930,090-26,331,664)	427.4 (343.6-514.4)
2→ 3	26,623,824,392 (25,717,983,860-27,481,517,997)	9,873,310 (852,362-18,856,817)	195.2 (16.8-370.7)
2→ 4	106,394,293,239 (102,072,863,399-111,159,279,885)	38,037,992 (32,152,526-43,889,758)	188.1 (157.7-216.7)
3→ 4	79,148,920,242 (75,019,526,565-83,824,504,533)	15,907,186 (8,445,046-22,801,538)	105.8 (56.3-150.4)
1→ 4	52,525,095,850 (48,414,922,838-56,951,203,678)	6,033,876 (-3,305,153-15,533,084)	60.5 (-33.0-156.5)

Values reported as mean and 95% uncertainty intervals. The calculation of the minutes of walking equivalent, prolonged life (min) per hour of walking and the life-expectancy difference in years is detailed in the methods section.

Table S4. Model variations for population-level vs individual-level outcomes

	Population-level	**Individual-level**
Life year difference	Life years difference calculated using the period perspective: For each age, we used the difference in change in mortality	Life years difference calculated for the cohort: For each age, we calculated the difference between the number of

	between observed and expected populations and multiplied that by the life expectancy and population numbers for each age.	person years lived by the cohorts before (observed) and after shift in physical activity quartile (expected).
Total extra hours walking (For each quartile and age category, this is estimated by multiplying the population number with the minutes of walking equivalent derived from the average counts per minute as reported in NHANES).	The American population numbers used.	We used the lifetable (cohort) numbers for the expected population after 'intervention' change to activity counts for the selected quartile.
5-year lagged effect of physical activity on mortality.[3]	No	Yes

NHANES: National Health and Nutritional Examination Survey[4]

Model testing and validation

In testing the validity of the model, we assessed the formal validity of the model (mathematically correct implementation, all links correct, etc.), and the plausibility (face validity) of the output, in view of the input. Our findings support the formal validity and plausibility of the model.

Formal validity

Multiple team members assessed parts of the model as they were working on it, and newly implemented changes being assessed by a second team member. Changes were recorded in a 'log' tab. No errors were observed in the final version of the model.

Model output was scrutinised for any unexpected patterns. To this end, the model has 548 output parameters, which cover 505 single year life expectancy outputs and 43 aggregate outcomes like hours walked per year, minutes walked per day, minutes gained per hour walked, potential impact fraction (PIF) values for each of the four activity quartiles, life expectancy and life years gained.

For each aggregate output parameter, Ersatz reports the median, mean, standard deviation, highest and lowest value, and 95% uncertainty boundaries. We entered the output into a template spreadsheet so that it populated pre-prepared graphs and tables. We used these in the reporting. The outputs were also used to check for unexpected results such as values that were higher or lower than expected, patterns across the activity quartiles that were not expected based on model input, and any other observations not readily understood. Such unexpected results were investigated and explained to satisfaction, or the model was amended and re-tested until all outputs were explained to satisfaction.

Plausibility tests

We conducted two tests confirmed that 1) when no change in exposure to physical activity was modelled (PA levels remained the same), all related outputs were zero and 2) when the hazard ratio values were set to 1 (no variation in mortality as a function of population physical activity levels), outputs were also zero.

Patterns were examined, with the following findings:

- Changes in mean minutes walking between quartiles gains were greater when people moved from quartiles apart (e.g., Q1 to Q4 or Q2 to Q4) as opposed to next quartile (e.g., Q1 to Q2 or Q2 to Q3).
- Minutes gained per hour walk above age 40 were highest for the movement from Q1 to Q2, next highest was Q2 to Q3, and Q3 to Q4 was smallest, in line with the evidence on the highest gain being for those who are least active (diminishing returns).
- Life expectancy gains were higher when people moved from lowest activity quartile (Q1) to other quartiles (Q2, Q3, Q4) with highest gain seen in movement from Q1 to Q4. This is in line with evidence on the dose-response relationship between total accelerometer measured physical activity and all-cause mortality. A similar pattern was observed in life years gained.

In sum, our review did not detect any unexpected patterns in model output.

References

1. United States Census Bureau. National Population by Characteristics: 2010-2019. Annual Estimates of the Resident Population by Single Year of Age and Sex: April 1, 2010 to July 1, 2019 https://www.census.gov/data/tables/time-series/demo/popest/2010s-national-detail.html.

2. Salkind N, Anderson RN. National Vital Statistics Reports. Encycl Hum Dev, 2013;68(7).

3. Götschi T, Kahlmeier S, Castro A, et al. Integrated Impact Assessment of Active Travel: Expanding the Scope of the Health Economic Assessment Tool (HEAT) for Walking and Cycling. *International Journal of Environmental Research and Public Health* 2020; **17**(20): 7361.

4. National Center for Health Statistics. National Health and Nutrition Examination Survey: Physical Activity Questionaire. In: Centers for Disease Control and Prevention: U.S. Department of Health & Human Services, editor. Available from: https://wwwn.cdc.gov/nchs/nhanes/Default.aspx; 2003-2006.