Physical activity and life expectancy: a life-table analysis

Lennert Veerman [1], Jakob Tarp [2], Ruth Wijaya,[3] Mary Njeri Wanjau [1], Holger Möller,[4] Fiona Haigh,[5] Peta Lucas,[6] Andrew Milat[7]

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[1]Public Health & Economics Modelling Group, Griffith University School of Medicine and Dentistry, Gold Coast, Queensland, Australia
[2]Department of Clinical Epidemiology, Aarhus University and Aarhus University Hospital, Aarhus, Denmark
[3]Griffith University School of Medicine and Dentistry, Gold Coast, Queensland, Australia
[4]School of Population Health, University of New South Wales, Sydney, New South Wales, Australia
[5]Health Equity Research and Development Unit (HERDU), University of New South Wales, Sydney, New South Wales, Australia
[6]Centre for Population Health, New South Wales Ministry of Health, Sydney, New South Wales, Australia
[7]The University of Sydney School of Public Health, Sydney, New South Wales, Australia

Correspondence to
Professor Lennert Veerman; l.veerman@griffith.edu.au

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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 how much low PA reduces life expectancy, and how much life expectancy could be improved by increasing PA levels for both populations and individuals.

Methods We applied a predictive model based on device-measured PA risk estimates and a life-table model analysis, using a life-table of the 2019 US population based on 2017 mortality data from the National Centre for Health Statistics. The participants included were 40+ years with PA levels based on data from the 2003–2006 National Health and Nutritional Examination Survey. 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 the age of 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 min (~6.3 hours) of life expectancy (95% uncertainty interval 321.5 to 428.5 min).

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.

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 USA.
⇒ 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.

INTRODUCTION

Low physical activity (PA) levels are associated with an increased incidence of non-communicable disease and premature mortality worldwide.[1 2] Higher levels of PA 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 PA and decreasing sedentary behaviour is a policy priority in the USA and many countries worldwide.[4–6] This is reflected in the US PA guidelines[7] as well as the WHO's guidelines on PA and sedentary behaviour and their launch of the global action plan on PA.[6 8] Policies to promote PA 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 USA, 46.9% of adults met the guidelines for aerobic activity and only 24.2% met the guidelines for 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 PA.

Policy-makers are interested in the potential health and cost benefits of interventions that improve PA. Such estimates rely on the evidence from epidemiological studies. A major limitation of these studies is that PA 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 PA on morbidity and mortality ('regression dilution bias').[11] Recently, estimates of the association of device-measured PA with health outcomes have become available. A 2019 meta-analysis of eight large cohort studies showed that the relationship of accelerometer-assessed PA 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 PA are far too low.[12] In this study, we use the new device-measured PA risk estimates and a life-table model to estimate how much low PA reduces life expectancy in the

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USA, and how much lifetime could be gained by increases in PA levels for both populations and individuals.

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 online supplemental tables S1 and S2). We used potential impact fraction (PIF) calculations to vary mortality as a function of population PA levels. We then derived alternative life tables to estimate life expectancy at different levels of total PA.[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 to a risk factor (here, PA).[15]

Total PA data input

Population levels of total PA were based on estimates from the 2003–2006 National Health and Nutritional Examination Survey (NHANES).[13 16] The NHANES samples non-institutionalised US civilians using a multistage probability sampling design that considers geographical area and minority representation.[17] PA was measured by a hip-worn accelerometer (AM-7164; ActiGraph) for 7 days using a 1-min 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 6:00 and midnight was required for inclusion in the analysis, leading to the exclusion of 824 participants with insufficient wear-time (see online supplemental file p.4 and online supplemental table S3).[3] We defined non-wear according to the Choi algorithm and calculated total PA as total recorded counts/wear-time (counts per minute, cpm),[18] a metric explaining 20%–30% of the variance in PA energy expenditure.[19] An ActiGraph 'count' is a dimensionless summary metric representing the 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 *et al* which we used for the dose–response relationship in the modelling (ie, equivalent to model C in their study).[3] Total PA 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 non-institutionalised US civilians above 40 years of age (table 1).[17] In this paper, Q1 is referred to as the least active quarter (represents lower 25%) and Q4 as the most active (upper 25%). In the model, we applied a normal distribution to reflect the uncertainty in average total PA levels. More recent data from NHANES[21 22] were explored but the 2003–2006 data[16] were used for consistency with the study by Ekelund *et al*, and because the latest available accelerometer data from 2011 to 2014[22] were collected using a different accelerometer placement (wrist), which hindered conversion to estimates of walking equivalence (see *PA and mortality*).

PA and mortality

We used the dose–response relationship between total accelerometer-measured PA (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 PA level quartile: Q1, least active (referent, HR=1), Q2 (HR=0.54, 95% UI 0.48 to 0.61), Q3 (HR=0.41, 95% UI 0.32 to 0.51), and Q4, most active (HR=0.34, 95% UI 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 PA 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 online supplemental 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 remain stable; at higher ages, mortality rates vary as a function of PA.) In our main analysis, we compared health outcomes from scenarios with observed PA levels, to scenarios in which the whole population was in the least active quartile and the most active quartile.

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

In this study, we translate differences in mean counts per minute between PA 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 the average cpm (as reported in the NHANES) with the mean wear-time in the NHANES sample (850 min/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 (4.8 km/hour) walking in adults estimated as 2481 cpm.[23]

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

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 non-institutionalised US 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 Centre for Health Statistics.[17]
n, number; NHANES, National Health and Nutritional Examination Survey; Q, quartile - total physical activity was divided into quarters from the least active 25% to most active 25%; SEM, standard error of the mean.

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years to reach the mean of the next higher PA quartile, and the walking time needed to move all quartiles to the highest quartile.

After translating differences in PA 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, that is, when less active individuals reached the next higher PA quartile. For these individual-level gain estimates, we incorporated a lag period where increases in PA gradually translate to reduced mortality in the five following years.[24] Online supplemental table S4 gives further detail.

Uncertainty in the activity levels of each quartile and HRs was incorporated using parametric bootstrapping (probabilistic sensitivity analysis), using normal and lognormal distributions, respectively.[25] We provide a step-by-step summary of our methods in online supplemental file p.5.

The life-table calculations were performed on MS Excel (Microsoft, 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 in our reporting.[26] We reviewed our statistical analysis and presentation for consistency with the CHeck-list for statistical Assessment of Medical Papers statement.[27]

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 life-table 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.

RESULTS

Life expectancy

Average life expectancy in the USA 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% 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 PA 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 PA level equivalent to 160 daily min of walking at 4.8 km/hour), individuals in the lowest activity quartile (Q1) require the equivalent of an extra 111.2 min/day (95% UI 106.7 to 115.9) of walking per person (table 2). This daily dose of PA would increase life expectancy by up to 10.9 years (95% UI 9.3 to 12.7). Each additional single hour of PA would prolong life by an average of 169.1 min (95% UI 146.4 to 193.4).

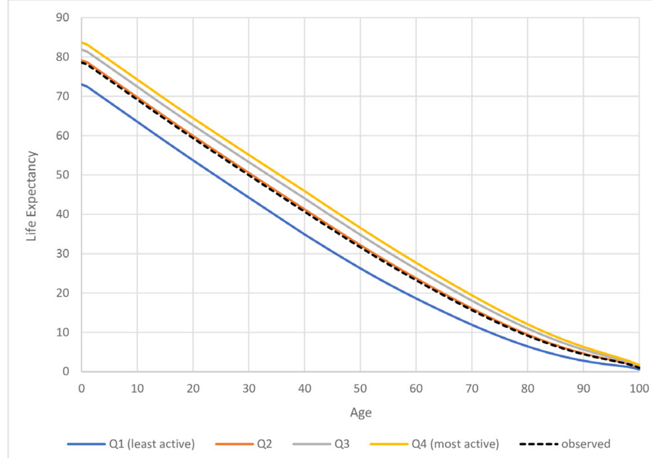

Figure 1 Average US life expectancy by age, comparing observed to results by adult physical activity quartile.

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 PA, translates to benefits that show a ‘diminishing returns’ effect. To shift from the least active first quartile to the second quartile, individuals require an extra 28.5 min/day of walking, with each hour adding about 6.3 hours to life. From the second quartile to the third quartile, an extra 27.8 min/day per person of walking would be required, with each hour of walking adding almost 3 hours to life. Finally, from the third quartile to the most active fourth quartile, an extra 55.0 min/day 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 PA (quartile 2) aiming to reach the highest activity quartile, an extra 82.8 min/day of walking would be needed, with every single hour of walking to increase life by 4.6 hours on average.

DISCUSSION

Our findings suggest that PA 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 on HRs from a published harmonised meta-analysis of large observational studies that spread across eight cohorts, all of which included adults aged ≥40 years from the USA 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 four American cohorts may have been less active than the four 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

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

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

underestimation. Using a conservative approach, we set the gain of life expectancy at age 40 to be equivalent to that at birth.

A strength is the use of total PA. 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 PA levels measured in 2003–2006 relate to the 2017 mortality statistics. There is some evidence that adherence to PA guidelines in the USA 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 towards overestimation.

Our estimates rely on crude estimation of averages and assume a uniform effect of PA within population quartiles. Compared with self-reported survey-based estimates, the use of accelerometer-measured PA 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 PA assessment by accelerometry has doubled the magnitude of the association with all-cause mortality,[29] accelerometers explain approximately 20%–30% of the variation in PA 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 PA 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 for example, upper-body movement. If measured and unmeasured PA correlate, this would lead to an overestimation of the 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, PA 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 suggest a single week of measurements explains 40%–50% of the variance in 'usual' PA.[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.[33–35]

Additional challenges include the processing, analysis and interpretation of device-measured PA. We used Copeland's estimate that for older adults (mean age 70 years), 3 mph walking would produce 2481 counts/min[23] 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/min 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 0.43–4.21 years higher life expectancy for self-reported physically active participants compared with 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 PA as a risk factor for 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 min (3 hours 40 min) 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 the current declining prevalence of smoking in the USA,[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 PA quartile we found in this study.[42] These results may seem surprising but follow from an exposure to lower levels of PA 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 PA provides substantially larger health benefits than previously thought, which is due to the use of more precise means of measuring PA. Our model demonstrates this

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large effect on life expectancy by using more precise means of measuring PA. Adverse health outcomes due to low PA 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 PA. 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 PA-promoting interventions in a quantifiable manner related to life expectancy. These include cost–benefit analyses of measures that impact on PA, for example, in urban planning and transport. Increasing PA at the population level is a complex task that requires a systems-based approach,[43] considering the wider social determinants that impact on PA, sedentary behaviour and their unequal distribution across population groups.[44] Infrastructure measures that encourage active transport, walkable neighbourhoods as well and green spaces might be promising approaches to increase PA and resultant healthy life expectancy at the population level.[43]

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ORCID iDs
Lennert Veerman http://orcid.org/0000-0002-3206-8232
Jakob Tarp http://orcid.org/0000-0002-9186-7077
Mary Njeri Wanjau http://orcid.org/0000-0002-4588-7528

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