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Article

Period and cohort-specific trends in life expectancy at different ages: Analysis of survival in high-income countries

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ABSTRACT

The number of older adults is increasing in high-income countries as survival chances continue to improve. We investigate changes in survival at older ages in high-income countries and show that although survival chances have improved, these improvements are concentrated at the top of the survival distribution where there is a small share of the population. Among females who survive to age 85 in the most recently birth cohort (1925), for example, about half die within 8 years while those in the top 25% of the survival distribution live at least 50% longer (12 years or more). Importantly, these results indicate that having some individuals reach exceptionally old age does not imply that the majority of the population is living longer. In addition, estimates of lifespan inequality at older ages suggests that years of life lost because of death have increased in recent times and among recently born cohorts leading to an increase uncertainty in the age at death at older ages. Thus, slow survival improvements at ages 65+ suggest that most of the population is unlikely to reach long life expectancies in the near future, which may lead to lower than expected fraction of adults reaching older ages.

Introduction

Life expectancy at birth in developed countries has more than doubled in the last two hundred years, from about 32 years in Sweden in 1800 –the record holder at the time– to about 87 years in Japan in 2017 –the current record holder (Human Mortality Database, 2019). This improvement in length of life has also been accompanied by an increasing number of older adults in high-income countries in the last decades. The optimism generated by these remarkable increases in survival has led some researchers to predict that future average length of life at birth will reach levels of at least 100 years of age (Christensen, Doblhammer, Rau, & Vaupel, 2009; Oeppen & Vaupel, 2002; Vaupel, 2010). Two antagonistic perspectives on future changes in life expectancy have prevailed in the literature. The less optimistic side suggests there is a biogenetic limit to the length of human life; thus, while projections of life expectancy are mathematically and demographically sound, such predictions ignore the underlying human biological mechanisms that might prevent survival, for most people, to age 100 (Carnes, Olshansky, & Hayflick, 2013; Miller, 2012; Olshansky, Carnes, & Désesquelles, 2001). The more optimistic side argues that if rates of decline in death rates at older ages were slowing, there would be an indication we are approaching a fixed limit on life expectancy; yet, empirical evidence does not seem to support this claim (Oeppen & Vaupel, 2002; Vaupel, 2010; Wilmoth, 1998; Wilmoth, Deegan, Hundstrom, & Horiuchi, 2000). Importantly, as with any other measure of central tendency, life expectancy at older ages (average length of life) is affected by extreme values. This appears to be the case in high-income countries given that under current mortality conditions in these countries, about 90% of newborns are expected to survive to age 65, thus life expectancy at older ages is slowly raising because of increasing survival prospects in a fraction of individuals reaching exceptionally old age (Rau, Soroko, Jasilionis, & Vaupel, 2008). In the last two decades there has been an increasing interest on studying variability in ages at death (e.g., Engelman, Canudas-Romo, & Agree, 2010; Engelman, Caswell, & Agree, 2014; Gillespie, Trotter, & Tuljapurkar, 2014; Tuljapurkar & Edwards, 2011) rather than just focusing on measures of central tendency such as life expectancy. In this paper we study life expectancy (at birth and at older ages) and also focus on a measure of variability in ages at death defined by percentiles of the distribution of ages at death and lifespan inequality at birth and conditional on surviving to older ages.

We examine trends in survival using the largest mortality repository of reliable data, the Human Mortality Database (Human Mortality Database, 2019) (supplementary methods). First, we compare and contrast increases in life expectancy at birth in the last 200 hundred years and also examine increases in life expectancy at ages 65 and above, reflecting progress made in survival at older ages in recent decades due to technological progress in medical care and

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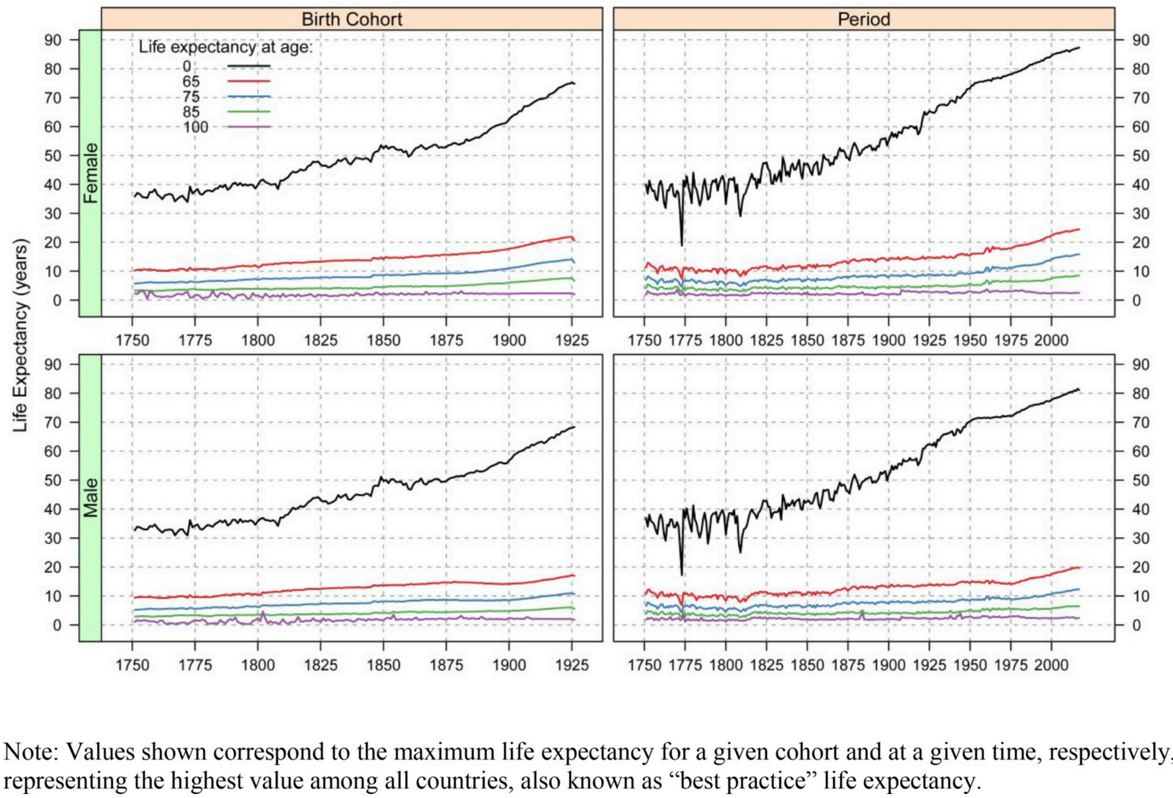


Fig. 1. Best practice Life expectancy among national populations by age, sex, cohort and period
Note: Values shown correspond to the maximum life expectancy for a given cohort and at a given time, respectively, representing the highest value among all countries, also known as "best practice" life expectancy.

improvements in life circumstances. Second, we look at the distribution of ages at death by year of birth (cohort) and calendar year (period), and link percentiles of this distribution with the typical indicator use to measure survival: life expectancy at older ages. Because the distribution of ages at death at older ages is not necessarily symmetric —indicating that only a fraction of people may reach old age— life expectancy (i.e., average length of life) may not accurately represent the survival chances for most people. Third, we also identify differences in the pace at which survival at older ages is increasing in these countries. Finally, we estimate lifespan inequality at birth and at ages 65, 75, and 85 and select the minimum among national populations (analogue to best practice life expectancy) to identify how much lifespans differ among individuals in the country with the lowest survival inequality by period and birth cohort.

Methods

We used cohort and period data from all countries for which data were available from the Human Mortality Database (HMD) (Human Mortality Database, 2019). Specifically, we use cohort life tables for single-year birth cohorts born between 1750 and 1925 in ten European countries (Denmark, Finland, France, Iceland, Italy, Netherlands, Norway, Sweden, Switzerland and England and Wales) and period life tables for single-years between 1750 and 2017 in 37 countries from Europe (Austria, Belarus, Belgium, Bulgaria, Czech Republic, Denmark, England &Wales, Estonia, Finland, France, Germany, Hungary, Iceland, Ireland, Italy, Latvia, Lithuania, Luxembourg, Netherlands, Norway, Poland, Portugal, Russia, Slovakia, Slovenia, Spain, Sweden, Switzerland, Ukraine), Americas (Canada, Chile, USA), Asia (Israel, Japan, Taiwan), and Oceania (Australia, New Zealand). It has been shown that mortality data for Norway from 1826-1866 and New Zealand from 1876-1930 have data quality issues (Vallin & Meslé, 2009), we thus eliminated these period mortality data from our analyses.

Percentiles in age at death

Let $\mu(x,t)$ be the force of mortality at age x and time t for some population and let $H_A(x,t)$ and $S_A(x,t)$ be the cumulative hazard and survival functions, respectively, from age A, at time t defined as: $H_A(x,t) = \int_A^x \mu(y,t)dy$, $S_A(x,t) = \exp(-H_A(x,t))$.

Let $x_p(t)$ be the p*th*-percentile of the distribution of ages at death at time t so that $x_p(t)$ equals an age x such that (Wilmoth & Horiuchi, 1999), $\frac{p}{100} = 1 - S_A(x,t) = 1 - \exp(-H_A(x,t))$. In our application, p = 25, 50, 75 and 90.

Lifespan inequality

It is defined as the average remaining life expectancy when death occurs above age x, or life years lost due to death (Vaupel, Zhang, & van Raalte, 2011; Vaupel & Romo, 2003). This indicator is represented by $e_y^{\dagger}$ and it is computed as

$$e_y^{\dagger} = \frac{\int_y^{\omega} \ell(x)\mu(x)e(x)dx}{\ell(y)} = \frac{\int_y^{\omega} d(x)e(x)dx}{\ell(y)}$$

Table 1
Slope from a yearly linear trend in life expectancy by age, birth cohort, time period and sex.
Source: Author's calculations from Human Mortality Database

Age	Birth Cohort				Time Period							
	Males		Females		Males				Females			
	1750-1885	1886-1925	1750-1885	1886-1925	1750–1790	1791–1885	1886–1960	1961–2005	1750–1790	1791–1885	1886–1960	1961–2017
0	0.168	0.417	0.165	0.513	-0.033	0.176	0.329	0.192	-0.027	0.175	0.333	0.222
65	0.046	0.070	0.047	0.154	-0.044	0.044	0.027	0.107	-0.043	0.051	0.037	0.142
75	0.028	0.068	0.028	0.118	-0.028	0.033	0.015	0.060	-0.026	0.037	0.021	0.100
85	0.013	0.036	0.013	0.059	-0.028	0.025	0.012	0.019	-0.026	0.025	0.013	0.041
100	0.011	-0.004	0.005	0.004	-0.014	0.024	0.004	-0.008	-0.014	0.021	0.006	-0.016

where $\ell(x)$, $\mu(x)$, $e(x)$, $d(x)$ and ω are the survival function, the force of mortality, life expectancy, the age at death distribution at age x, and the open-aged interval, respectively.

Data

We used cohort life tables and cohort mortality rates for single-year birth cohorts born between 1760 and 1925 in ten European countries (607 birth cohorts) and period life tables for single-years between 1760 and 2017 in 37 countries from Europe, Americas, Asia and Oceania (see supplementary materials). To maintain comparability with previous work (Oeppen & Vaupel, 2002), we focus on trends in the maximum life expectancy observed among national populations at ages 0, 65, 75, and 85 (Fig. 1). The maximum life expectancy at a given time and for a given cohort corresponds to the highest value among all countries, also known as “best practice” life expectancy (Oeppen & Vaupel, 2002). We then estimate linear trends indicating average one-year cohort and one-year period increases in life expectancy at each age (Table 1). Previous studies using similar data have identified four periods of fluctuation in life expectancy values by year (1750–1790, 1791–1885, 1886–1960, after 1961), a result mainly due to the availability of country-data and data quality (Vallin & Meslé, 2009, Fig. 9), and a break point in cohort values at around 1865. We thus fitted 4 segments for period data (1750–1790, 1791–1885, 1886–1960, 1961–2005) and two segment lines for cohort data (born before and after 1865). We then estimate percentiles of the distribution of ages at death for cohorts and time periods, and assess the link between these estimates and life expectancy at older ages. Finally, we also selected the minimum value of lifespan inequality among all countries in each year and birth cohort as the analogue of “best practice” lifespan inequality. This value represents the lowest variability (lowest inequality) in ages at death across populations (Fig. 3).

Results

Period analysis of life expectancy

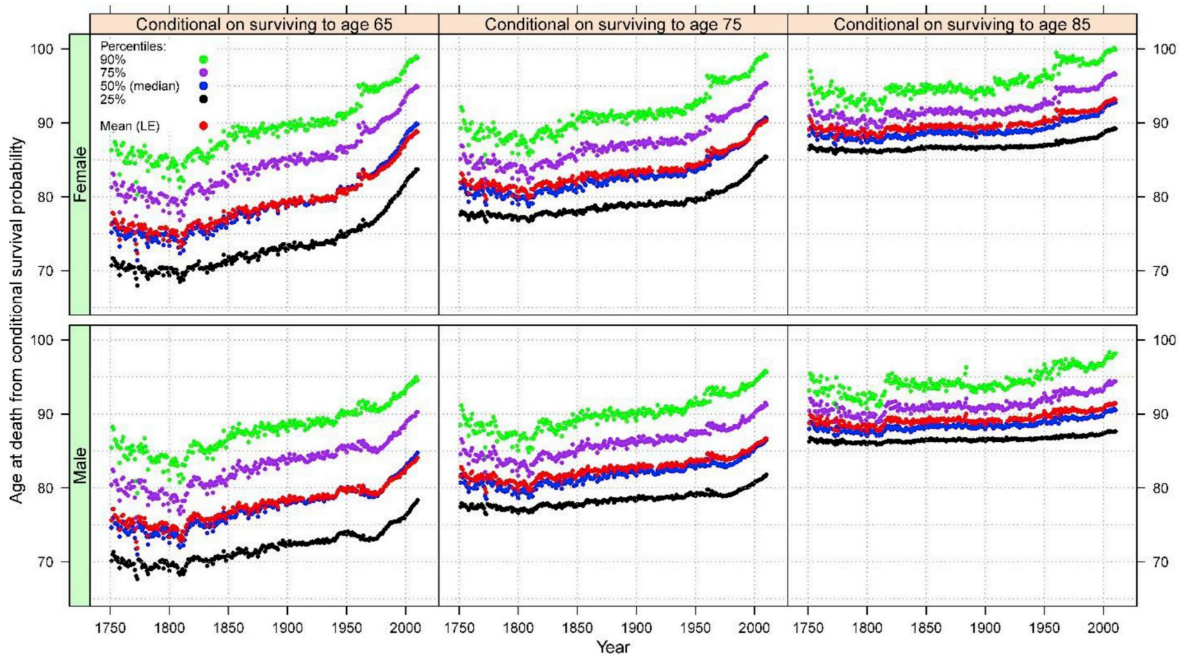
Consistent with previous findings (Oeppen & Vaupel, 2002; Vallin & Meslé, 2009) life expectancy at birth among these countries shows a remarkable increase for time periods since the late 1700s (Fig. 1). The increase is particularly accelerated during the first half of the twentieth century with females having a faster increase than males. The increase in life expectancy at birth has been associated with declines in early life mortality which predominated throughout the 1800s and the early part of the 1900s (Vallin & Meslé, 2009). At older ages, however, improvements in life expectancy have occurred at slower pace (Fig. 1): while period life expectancy has slightly increased at ages 65 and 75, there has been little progress at ages older than 75 as the pace of increase in life expectancy diminishes very rapidly with age. For example, the increase in period male life expectancy (LE) at age 65 in the last part of the 1800s (1886–1960) and the first half of the 20th Century is very modest — about 2 years of life over a 76 year period (Table 1). It is after 1960 that increases in LE(65) began to accelerate at a pace of 1.4 years per decade for females and 1.07 for males. Nonetheless, for ages older than 65 (e.g., 75, 85 and 100) there have been negligible increases in life expectancy with virtually no gains in average length of life after age 100. For example, the slope of a linear time trend of life expectancy at age 100 since 1961 indicates a downward trend, albeit of small magnitude, suggesting declines, rather than increases, in average years of life at age 100 for both females and males.

Cohort analysis of life expectancy

On a cohort basis, life expectancy at birth among these countries shows an important increase which is particularly accelerated among those born after 1875. Again, females had a faster increase than males, a result that has been associated with excess male mortality from smoking attributable deaths and vascular conditions (Beltrán-Sánchez, Finch, & Crimmins, 2015). Similar to period data, there has been little progress in cohort life expectancy at older ages (e.g., at ages over 75). For instance, among cohorts born between 1886 and 1925, LE(65) increased by about 1.5 years and 0.7 years per decade of birth for females and males, respectively (Table 1); while the corresponding increase at age 85 is about 0.6 years and 0.4 years for females and males, respectively. These results suggest that life expectancy at birth is not an appropriate indicator of expanding length of life in aging populations because it does not clearly highlight mortality improvement at older ages. In aging populations most current and future increases in life expectancy depend on mortality improvements at older ages (Vaupel & Yashin, 1986). Additionally, negligible increases in LE over age 75 or 85 suggest that while it is true that more people could potentially achieve this age, a large portion of them are unlikely to reach 100 years of age given the slow improvement in average length of life after these ages. Results from Table 1 show very small gains in cohort life expectancy at age 100 for females, an annual improvement of about 0.004 for cohorts born between 1886-1925, and reductions of similar magnitude among males born in the same years.

Percentiles of the distribution of ages at death

We further estimated percentiles (25%, 50%, 75%, 90%) of the age at death distribution starting at ages 65, 75, and 85 for single-year birth cohorts and single time periods since 1750. Using a similar idea as for life expectancy, we selected the oldest age in each percentile for each



Note: Values shown correspond to the maximum percentile at a given time representing the highest value among all countries, this equivalent to the "best practice" life expectancy.

Fig. 2. Percentiles of the distribution of ages at death among national populations by age, sex, and period.
Note: Values shown correspond to the maximum percentile at a given time representing the highest value among all countries, this is analogue to the "best practice" life expectancy.

cohort-sex across all countries (best practice age at death in each percentile). These percentiles represent the age at which 25%, 50%, 75% and 90% of the population will die conditional on surviving up to the starting age (e.g., age 65). Results for period data show remarkable increases in survival at age 65 and 75 after 1950, with smaller improvements at age 85 (Fig. 2). For example, among females who survive to age 85, about half of them will die within 8 years and three-fourths will do so within 12 years. These results are similar when looking at cohort data (supplementary materials). Importantly, the age at death for people in the top 10% of the distribution has increased at a faster pace than those in the lower part of the distribution over time and across cohorts (Table 2). For females who survived to age 85, for example, the age at death in the bottom 25th percentile increased by an average of 0.39 years per decade between 1950-2017 while for those in the top 25% percent (75th percentile) it increased by half a year per decade (0.56). These results are more remarkable across birth cohorts: among females who survived to age 85, the age at death in the top 25% percent of the distribution increased twice as fast relative to those in the bottom 25% percent of the distribution for females born between 1880 and 1925. These results indicate that increases in survival in recent times, and among recently born cohorts, have also been accompanied by widening inequalities in ages at death with those in the top percentiles achieving longer survival at a faster pace.

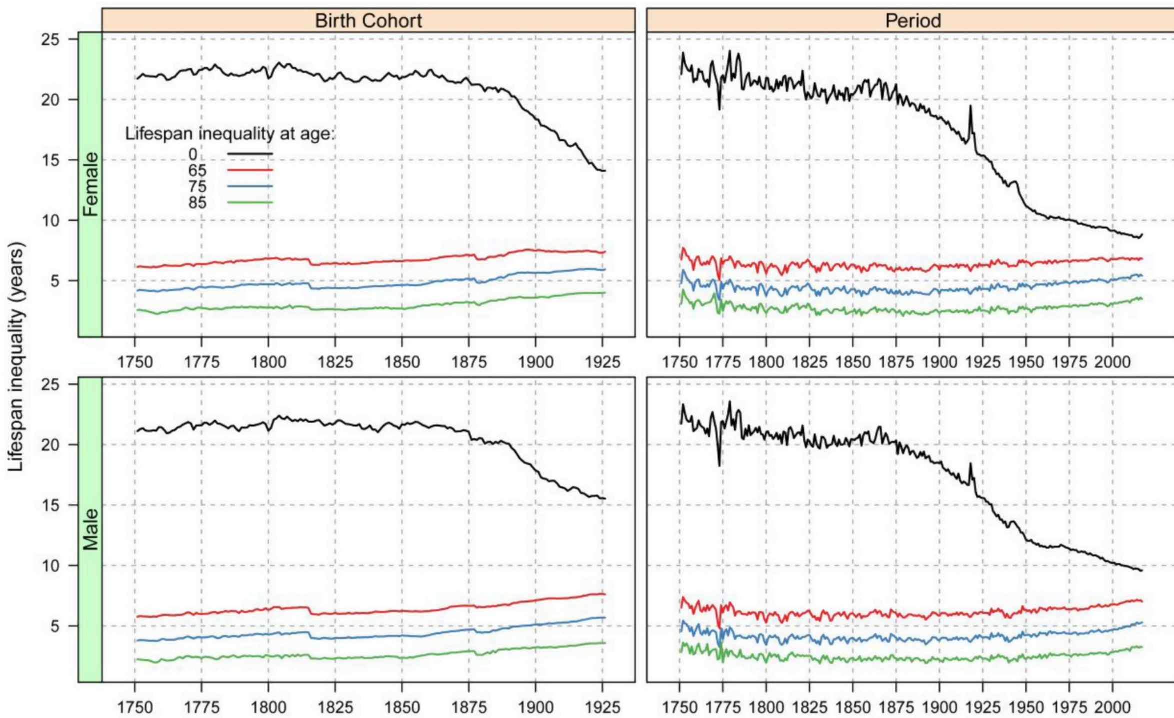
Lifespan inequality

We further estimated lifespan inequality at ages 0, 65, 75, and 85 for single-year birth cohorts and single time periods since 1750 and selected the lowest value among national populations (Fig. 3). Results for lifespan inequality at birth suggest large reduction over time and across birth cohorts, consistent with previous findings (Vaupel et al., 2011). In contrast, lifespan inequality at older ages clearly shows a continuous increase in both periods and birth cohorts even when we selected the minimum value across countries. Thus, there appears to be more life years lost because of death at older ages in recent times, and among recently born cohorts, which suggest a growing inequality in ages at death among older adults. In addition, the countries that achieved the highest life expectancy at older ages at a given time, and for a given birth cohort, are not the same ones that also attained the lowest lifespan inequality (see Appendix). Therefore, achieving higher overall survival at older ages is not being translated into lower uncertainty in ages at death for older adults.

Discussion

These results indicate that while life expectancy at ages 65 and older has shown increases among recently born cohorts and in recent years, the pace of increase is less than half the magnitude of that observed in historical increases in life expectancy at birth. In addition, estimates of lifespan inequality show a higher uncertainty in the age at death at older ages in recent times and among recently born cohorts. As current and future gains in life expectancy are being concentrated in improvements in old age mortality (Vaupel, 2010; Wilmoth, 1998), our results may indicate that future increases in life expectancy at older ages are unlikely to reach an increase similar in magnitude to the historically large improvements in life expectancy at birth, as previously suggested (Olshansky et al., 2001).

The unprecedented rise in life expectancy at birth in historical times has been associated with declines in early life mortality (Vallin & Meslé, 2009), which predominated throughout the 1800s and the early part of



Note: Values shown correspond to the minimum lifespan inequality for a given cohort and at a given time, respectively, representing the lowest value among all countries, it is analogue to "best practice" life expectancy.

Fig. 3. Best practice lifespan inequality among national populations by age, sex, cohort and period
Note: Values shown correspond to the minimum lifespan inequality for a given cohort and at a given time, respectively, representing the lowest value among all countries, it is analogue to "best practice" life expectancy.

Table 2
Slope from a yearly linear trend in percentiles of ages at death by age and sex.
Source: Author's calculations from Human Mortality Database

	Period 1950-2017		Cohorts born: 1880-1925	
Percentile	Males	Females	Males	Females
Age 65				
25th	0.081	0.150	0.011	0.136
50th	0.090	0.149	0.043	0.165
75th	0.083	0.132	0.073	0.165
90th	0.073	0.108	0.082	0.151
Age 75				
25th	0.043	0.097	0.031	0.098
50th	0.056	0.111	0.057	0.132
75th	0.061	0.107	0.075	0.139
90th	0.056	0.087	0.078	0.132
Age 85				
25th	0.014	0.035	0.017	0.039
50th	0.023	0.049	0.033	0.065
75th	0.028	0.051	0.044	0.079
90th	0.023	0.038	0.048	0.081

the 1900s. As early life mortality is reaching virtual minimum levels in most developed countries, it seems more desirable to use life expectancy at older ages—rather than at birth—as the main indicator of increases in population's overall survival. Moreover, given current trends in lifespan inequality at older ages (Fig. 3), monitoring indicators estimated at older ages will provide more useful for population-level survival prospects. This is particularly important as populations in most high-income countries continue to move into aging societies.

We also show that while average age at death has increased in recent times, this increase has also been accompanied by inequalities in survival (Fig. 3). This may be the result of the persistent disparities in health and longevity by socioeconomic status (Marmot, 2001; van Raalte, Sasson, & Martikainen, 2018), and its main surrogate income and wealth (Chetty et al., 2016), differential access to welfare programs such as social security and health care systems, as well as by health behaviors such as smoking that have had a large toll on survival in most high-income countries (Preston, Glei, & Wilmoth, 2010). Higher socioeconomic status has been shown to have beneficial effects on health resulting from several mechanisms such as the adoption of healthier lifestyles, better ability to cope with stress, and more quality medical care to effectively management chronic diseases (Hayward, Hummer, & Sasson, 2015). In the U.S., for example, there is ample evidence suggesting increasing survival inequalities by education (Hadden & Rockswold, 2008; Hayward et al., 2015; Montez, Hummer, & Hayward, 2012; Olshansky et al., 2012), and that these differences appear to be so systematic and permissive that they can be seen at the regional and county level (Kulkarni, Levin-Rector, Ezzati, & Murray, 2011; Murray, Kulkarni, & Ezzati, 2005; Sheehan, Montez, & Sasson, 2018). For example, a recent study linking educational attainment and adult mortality in the U.S. population shows that the growing mortality advantage of people with more education is a recent phenomenon that emerged at the end of the 20th Century and beginning of this century (Hayward et al., 2015). There is similar evidence from European countries in relation to educational differences in life expectancy at older ages (Majer, Nusselder, Mackenbach, & Kunst, 2011). Even in Japan –the current record holder of life expectancy at older ages—there is evidence that social inequalities in health are beginning to emerge in recent years (Kagamimori, Gaina, & Nasermoaddeli, 2009). This could indicate that future increases in survival may slow down for the overall Japanese population, although those with high socioeconomic position may well continue the upward trajectory towards longer life.

We also found that conditional on reaching at least 85 years of age, there is a fraction of individuals at the top 10% of the distribution whose survival prospects have increased at a faster pace than that of their counterparts in the lower half of the survival distribution. This is in line with empirical evidence from the U.S. suggesting that individuals at the bottom of the education distribution are experiencing a slower rate of increase in life expectancy relative to those at the top (Hayward et al., 2015; Olshansky et al., 2012) while those in the top quartile of the income distribution have enjoyed a longer life expectancy (Bosworth, Burtless, & Zhang, 2016; Chetty et al., 2016). In Europe, some evidence suggests that recent changes in life expectancy have been associated with economic growth (Mackenbach & Looman, 2013) and that people in the upper income distribution have longer survival (Kalwij, Alessie, & Knoef, 2013; Tarkiainen, Martikainen, Laaksonen, & Valkonen, 2012).

Our results also highlight the heterogeneity and randomness in survival at older ages (Carnes et al., 2013; Finch & Kirkwood, 2000). This implies that having some individuals reach exceptionally old age does not indicate that the survival distribution for the overall population is similarly moving upward. As we look into future prospects of survival, it seems unlikely that socioeconomic and health inequalities would be reduced in the near future so that the survival gap could be narrowed. Thus, the tug exerted by social and behavioral factors may indeed create an additional barrier to the human biological mechanisms (Carnes et al., 2013; Miller, 2012; Olshansky et al., 2001) that might prevent survival to old age for the majority of the population.

Ethics approval

This Human Subjects Research falls under Exemption, without exception, all data sources that are used in the study are in the public domain (on-line), have been de-identified, and contain information that cannot be used in any manner to identify subjects who participated in the original data collection.

Financial statement

Beltrán-Sánchez acknowledges support from grants by the National Institute on Aging (R01AG052030) and the National Institute of Child Health and Human Development (P2C-HD041022) to the California Center for Population Research at UCLA.

Appendix A

Materials and Methods

We used cohort and period data from all countries for which data were available from the Human Mortality Database (HMD) (Human Mortality Database, 2019). Specifically, we use cohort life tables for single-year birth cohorts born between 1750 and 1900 in ten European countries (Denmark, Finland, France, Iceland, Italy, Netherlands, Norway, Sweden, Switzerland and England and Wales) and period life tables for single-years between 1750 and 2010 in 37 countries from Europe (Austria, Belarus, Belgium, Bulgaria, Czech Republic, Denmark, England &Wales, Estonia, Finland, France, Germany, Hungary, Iceland, Ireland, Italy, Latvia, Lithuania, Luxembourg, Netherlands, Norway, Poland, Portugal, Russia, Slovakia, Slovenia, Spain, Sweden, Switzerland, Ukraine), Americas (Canada, Chile, USA), Asia (Israel, Japan, Taiwan), and Oceania (Australia, New Zealand). It has been shown that mortality data for Norway from 1826-1866 and New Zealand from 1876-1930 have data quality issues (Vallin and Meslé 2009), we thus eliminated these period mortality data from our analyses.

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$$\mathrm{H_A(x,t)} = \int_A^x \mu(y, t)dy \,, \mathrm{SA(x,t)} = \exp(-H_A(x, t)\Big)$$

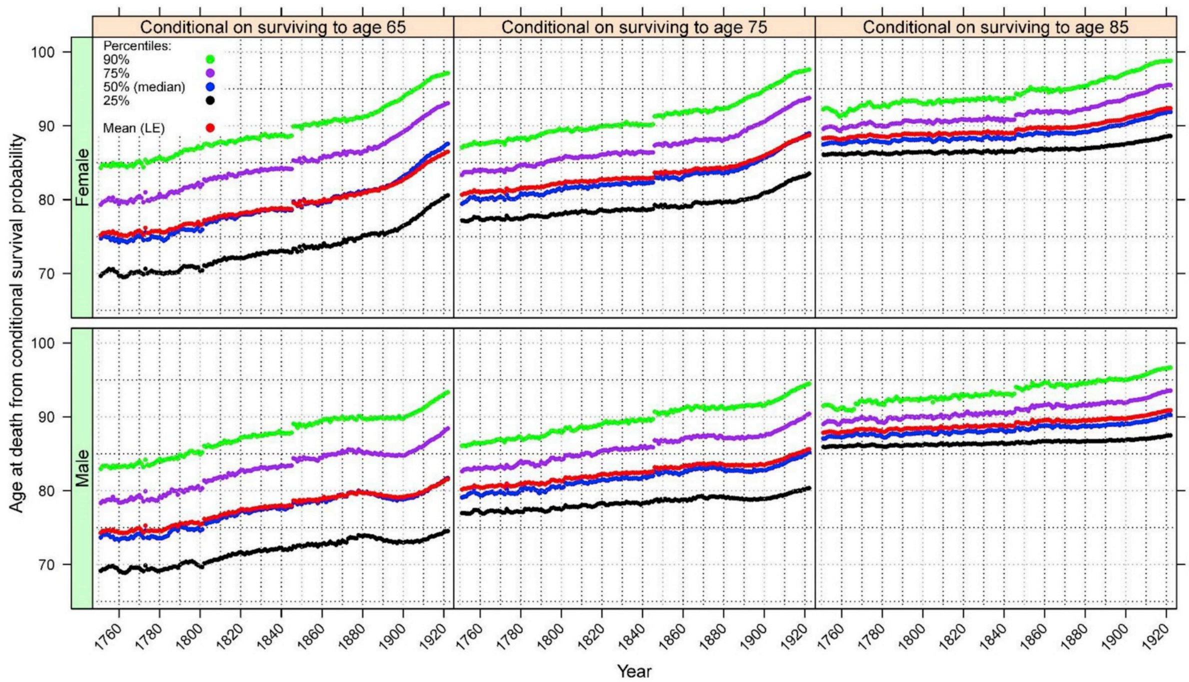
Let $x_p(t)$ be the p*th*-percentile of the distribution of ages at death at time t so that $x_p(t)$ equals an age x such that (Wilmoth and Horiuchi, 1999) $\frac{p}{100} = 1 - S_A(x, t) = 1 - \exp(-H_A(x, t))$In our application, $p =$ 25, 50, 75 and 90.

Lifespan inequality

It is defined as the average remaining life expectancy when death occurs above age x, or life years lost due to death (Vaupel et al., 2011; Vaupel & Romo, 2003). This indicator is represented by $e_y^\dagger$ and it is computed as

$$e_y^\dagger = \frac{\int_y^\omega \ell(x)\mu(x)e(x)dx}{\ell(y)} = \frac{\int_y^\omega d(x)e(x)dx}{\ell(y)}$$

where $\ell(x)$, $\mu(x)$, $e(x)$, $d(x)$ and ω are the survival function, the force of mortality, life expectancy, the age at death distribution at age x, and the open-aged interval, respectively.



Note: Values shown correspond to the maximum percentile at a given time representing the highest value among all countries, this equivalent to the "best practice" life expectancy

Figure. Percentiles of the distribution of ages at death among national populations by age, sex, and cohort..
Note: Values shown correspond to the maximum percentile at a given time representing the highest value among all countries, this equivalent to the "best practice" life expectancy.
Source: Author's calculations from Human Mortality Database

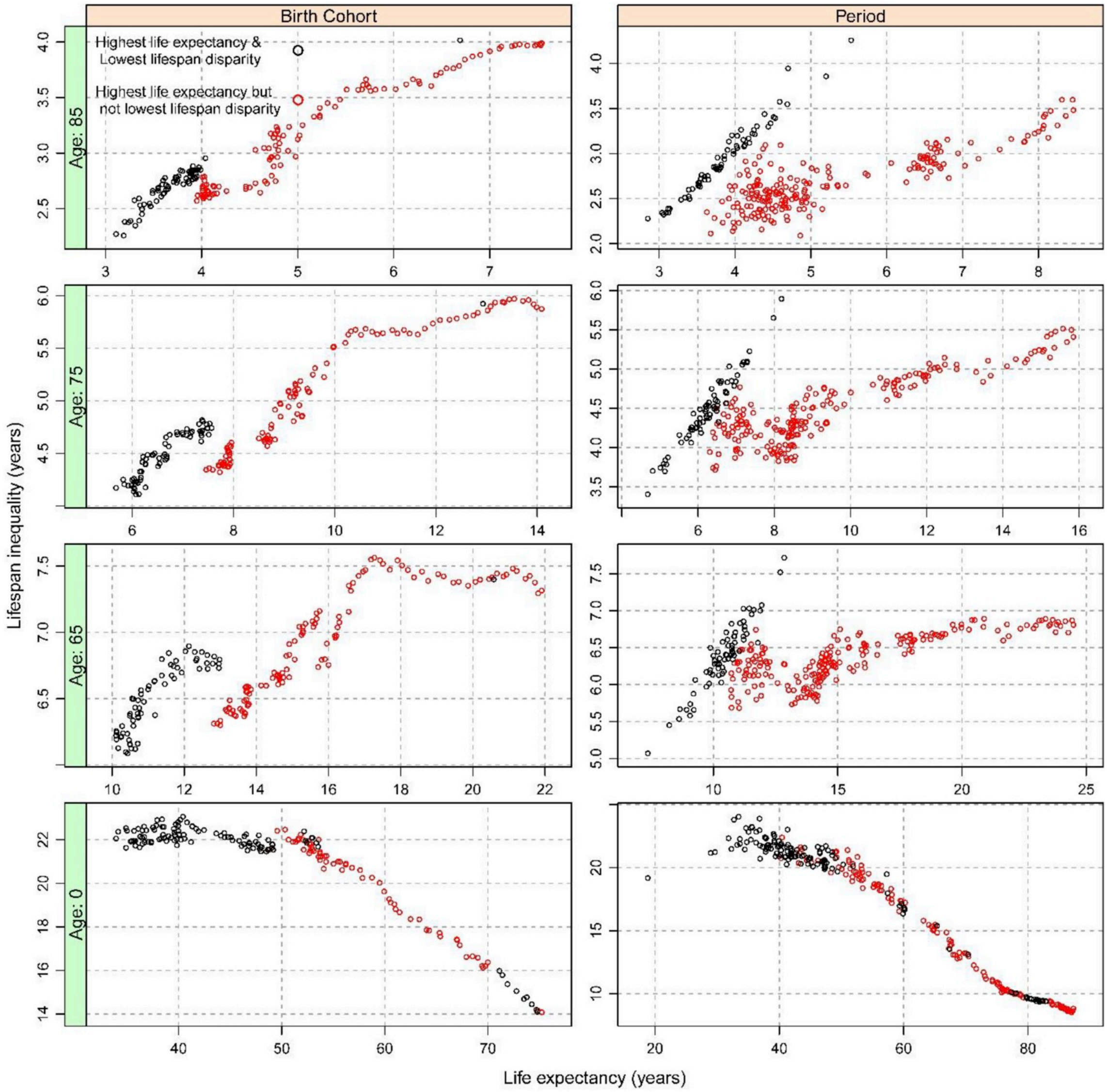


Figure. Scatterplot of best practice life expectancy vs. best practice lifespan inequality among national populations by age, period and cohort for Females..

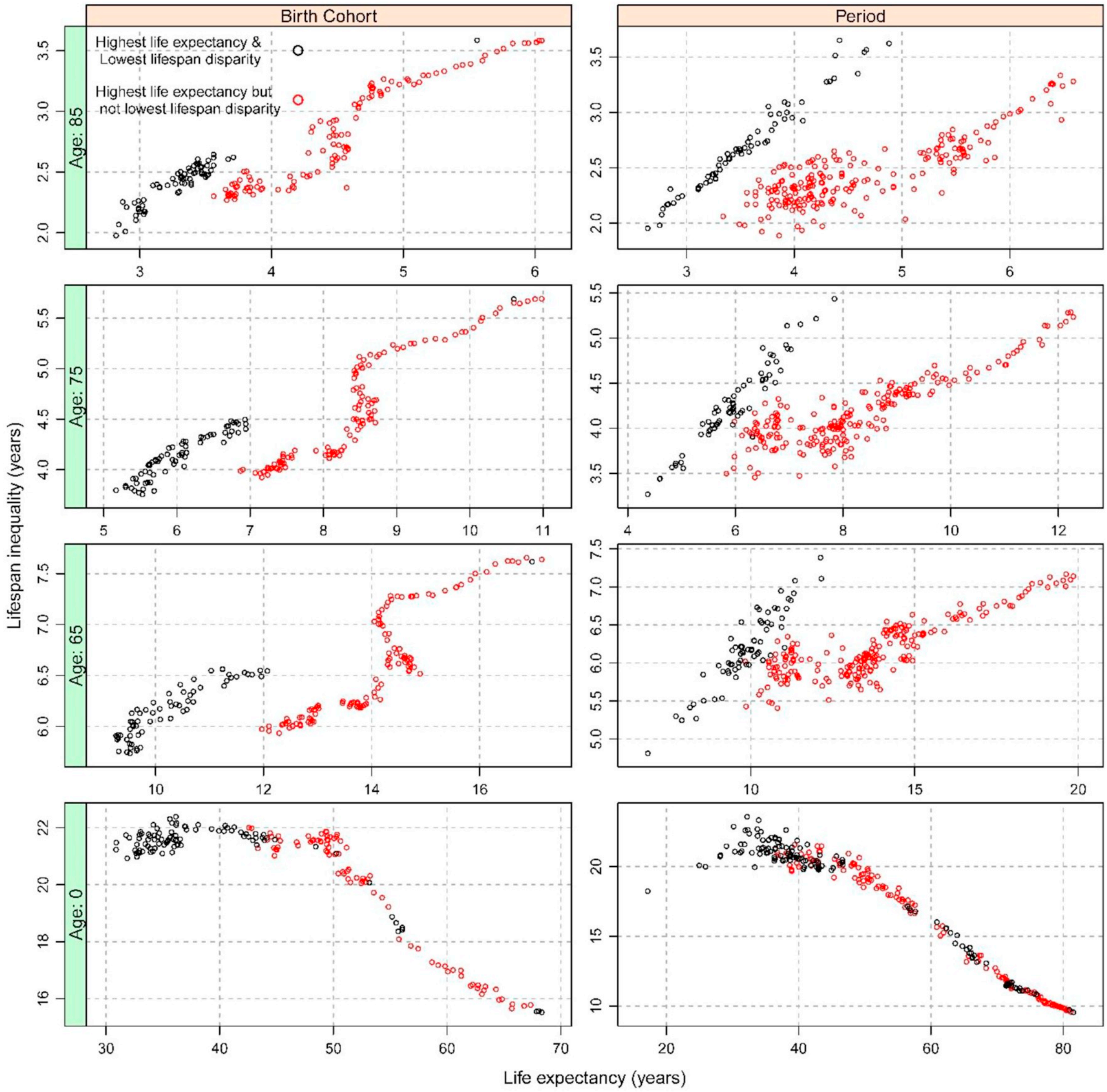


Figure. Scatterplot of best practice life expectancy vs. best practice lifespan inequality among national populations by age, period and cohort for Males..

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ssmph.2019.100422.

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