Living to 100 in the Time of COVID-19: A Study of Late-Life Mortality Trajectories

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ABSTRACT

The shape of mortality trajectories at advanced ages is still a matter of controversy. We compare performance (goodnessoffit) of two competing mortality models—the Gompertz model and the "mortality deceleration" Kannisto model—at ages 80–105 years, using data for 1880–1902 single-year birth cohorts of men and women in nine countries. The mortality modeling approach suggests a transition from mortality deceleration in earlier birth cohorts to the Gompertzian mortality pattern in later birth cohorts in three countries for both men and women (the United States, U.K. and Belgium). Four countries demonstrated such a transition for male populations only, whereas for women in these countries neither model showed preference. In two countries (Japan and Spain) mortality deceleration was observed for almost all studied birth cohorts. The observed transition from mortality deceleration to the Gompertz-like mortality is consistent with the hypothesis about mortality deceleration fading away over time because of improvement in the accuracy of age reporting. Our results demonstrate that there is no single universal answer to the question about mortality pattern at extreme old ages because this answer depends on country and the historical period of mortality analysis. In old historical data the late-life mortality deceleration is always observed. In more recent data for some countries mortality continues to grow exponentially with age even at very old ages. This leads to more conservative estimates for future human longevity records and the proportion of older people (population aging). Study of period data compared mortality in 2020 during the COVID-19 epidemic with 2019 pre-epidemic year. All studied period mortality trajectories demonstrate mortality deceleration starting around age 90 years. During the COVID-19 epidemic mortality follows almost a parallel shift upward (in semilog scale) compared to the 2019 year. These mortality changes are observed for ages higher than 50 years. Thus, period mortality and cohort mortality of old historical periods show old-age mortality deceleration,whereas mortality of more recent birth cohorts often follows the Gompertz law.

INTRODUCTION

Population aging, which is going on now in the world, underscores the necessity of better knowledge of mortality patterns at advanced ages. Despite numerous studies in this area lack of certainty still surrounds the shape of late-life mortality trajectories. Earlier studies found that mortality after age 80 demonstrates slower growth with age compared to the exponential Gompertz law (Gavrilov and Gavrilova 1991; Horiuchi and Wilmoth 1998; Thatcher 1999). Mortality deceleration at advanced ages was shown for both cohort and period mortality and for several studied countries (Horiuchi and Wilmoth 1998). In later studies conclusions about mortality deceleration startingat age 80 became less certain. For the U.S. cohort data it was found that mortality follows the Gompertz law in the interval 80–106 years (Gavrilov and Gavrilova 2011; Gavrilova and Gavrilov 2015). Other researchers found that in some countries mortality deceleration is more expressed than in others (Bebbington et al. 2014; Feehan 2018). The main problem of these studies was an intention to make conclusions about the existence ofonly one possible shape of the mortality trajectory. Sometimes sweeping generalizations about the shape of mortality trajectory are made using only one or two examples (Barbi et al. 2018; Bohnstedt et al. 2021).

In 2017 we found a new trend of the U.S. old-age cohort mortality, which we called Gompertzialization of mortality trajectory, representing a transition from mortality deceleration to the Gompertzian mortality pattern over time for both men and women (Gavrilova and Gavrilov 2017; Gavrilov and Gavrilova 2019). We believe that there is a need to analyze existing changes in the shape of mortality trajectories at older ages using information for different countries and different historical periods. In this study we analyzed both cohort and period mortality trajectories before and during the COVID-19 epidemic. What is happening with the old age mortality trajectories over time, and how do these trends vary by region? This study attempts to answer these questions by analyzing the historical evolution of the old-age cohort mortality in nine countries having a relatively large population size. Then old-age mortality from the period life tables in the time of COVID-19 is compared to mortality in pre-COVID era.

We analyze historical evolution of mortality trajectories at advanced ages using age-specific death rates for 46 birth cohorts in nine countries. We study two competing models describing mortality trajectories (the Gompertz model and the Kannisto model) using the Akaike goodness-of-fit criterion to determine the best fit. We hypothesize that mortality deceleration vanishes in more recent birth cohorts because of age-reporting improvement over time.

1. STUDY OF HISTORICAL CHANGES IN COHORT MORTALITY

DATA AND METHODS

The Human Mortality Database (HMD) provides mortality and population data (www.mortality.org). Age-specific death rates are used as empirical estimates for the force of mortality. Datasets of age-specific cohort death rates (central mortality rates) of men and women are available in the HMD for ages up to 110 years or older. For all nine studied countries we analyze mortality of 1880–1902 single-year birth cohorts for men and women separately.

Datasets of age-specific cohort death rates (central mortality rates) of men and women are available in the database from ages 0 to 110 or older. We selected data available in one-year age and time increments denoted as M_x, where x indicates single year of age. Yearly central mortality rate for cohort c at age x is defined as number of deaths for cohort c between ages x and x+1 divided by the number of person-years lived by cohort c between ages x and x+1 (Chiang 1978). We analyze mortality for nine countries with

relatively large populations to have a sufficient number of survivors beyond age 100: Australia, Belgium, Canada, France, Italy, Japan, Spain, the U.K. and the U.S.

We fit mortality with two competing models used earlier in the study by Thatcher and coauthors (1998), the Gompertz model and the logistic model (a simplified two-parameter logistic model, also called the Kannisto model):

Gompertz: $$\mu(x) = a e^{bx} \quad (1)$$

Kannisto: $$\mu(x) = \frac{a e^{bx}}{1 + a e^{bx}} \quad (2)$$

where μ(*x*) is the force of mortality, *x* is age and *a*and *b* are parameters.

We test these two models for their performance of fitting the empirical data. We run a weighted nonlinear regression model in the age interval 80–105 years using the program *nlin* in Stata (StataCorp, version 14). Age-specific exposure values are used as weights in nonlinear regression analyses (Muller et al. 1997).

The Akaike information criterion (AIC) is used to evaluate goodness of fit for the Gompertz and the Kannisto models:

$$AIC = 2k - 2\ln(L) \quad (3)$$

where ln*L* is the maximized log-likelihood of the model and *k* is the number of parameters estimated.

The best model demonstrates the minimal value of the AIC (Burnham and Anderson 2002). It is not the absolute size of the AIC value, it is the difference of values for compared models (Δ_i) that is important in model selection. An AIC difference higher than 10 suggests strong support of the better model by the data (ibid.):

$$\Delta_i = AIC_i - AIC_{min} \quad (4)$$

where Δ_i is the AIC difference for the *i*th model, AIC_i is the AIC value for the *i*th model and AIC_{min} is the value of the criterion for the best model with minimal AIC.

Analyses were conducted using Stata (version14).

RESULTS

Figures 1–9 present the results of model fitting (AIC values) for the 1880–1902 birth cohorts in nine countries (a total of46 regression models per each country). Three countries (the U.S., U.K. and Belgium) demonstrate a clear transition from lower values of AIC for the Kannisto model in the case of earlier birth cohorts to lower values of AIC for the Gompertz model in the case of more recent birth cohorts (Figures 1, 3, and 4). This phenomenon (observed for both men and women) means that mortality deceleration, which is observed for both men and women, disappears for more recent birth cohorts. Four countries (Australia, Italy, Canada and France) demonstrate historical transition from mortality deceleration to the Gompertz model for men only. For women in these countries the situation is uncertain: neither model demonstrates

a clear advantage in terms of mortality fitting (Figures 2, 5, 7and 9). Only one country (Japan) continues to demonstrate mortality deceleration at advanced ages for both men and women and for almost all studied birth cohorts (Figure 6). A summary of results for these nine countries is presented in Table 1. Note that the majority of the studied populations demonstrate Gompertzialization of the mortality trajectory. This is particularly the case for male populations.

Table 1
SUMMARY OF RESULTS. THREE PATTERNS OF MORTALITY CHANGES IN OLD-AGE COHORT DATA.

Mortality Transition Pattern	Men	Women
From mortality deceleration to the Gompertz model	Australia, Belgium, Canada, France, Italy, U.K., U.S.	Belgium, U.K., U.S.
From mortality deceleration to uncertain pattern ($\|\Delta AIC\| < 5$)	Spain	Australia, Canada, France, Italy
Mortality deceleration for all studied birth cohorts	Japan	Japan, Spain

These results indicate that there is no single universal answer to the question about the shape of cohort mortality trajectories at advanced ages. The majority of male populations (seven out of nine) demonstrate Gompertzialization of the mortality curve (transition from mortality deceleration observed in the earlier birth cohorts to the Gompertz law). For women, such a clear transition is observed in only three countries, whereas in two countries no transition to the Gompertz model occurred. What we can say for certain is that mortality in the past indeed demonstrated deceleration, whereas later mortality changed to the Gompertz pattern in many countries. This transition was the most obvious in the U.S. (Figure 1).

2. LATE-LIFE MORTALITY TRAJECTORIES DURING THE TIME OF COVID-19

The second goal of this study was to analyze period mortality trajectories during the time of COVID-19 (2020 and partially 2021 years) and to find the effects of COVID-19 epidemic on mortality trajectories at older ages. The effect of COVID-19 infection on the age-specific mortality can be analyzed by comparing mortality in 2020 during the first year of the epidemic with mortality in 2019 (during the pre-epidemic period). Age-specific death rates were taken from the Human Mortality Database for countries presenting their data for 2020: Denmark (data available for both 2020 and 2021), Spain, Belgium, Finland, Croatia, Hungary, Japan, Latvia, Norway, Portugal, Sweden and the U.S.

We have found that for most studied countries mortality in 2020 had not noticeably changed compared to 2019. Only Spain, Belgium, Sweden and the U.S. showed a substantial increase of mortality in 2020 compared to 2019. Figures 10, 11, 12 and 13 demonstrate mortality in 2019 and 2020 for men and women in Spain, Belgium, Sweden and the U.S. in the age interval 80–105 years. In all cases mortality seems to shift upward in 2020 compared to 2019, with the U.S. demonstrating the largest increase of mortality in 2020. However, the mortality ratio $m_x(2020)$ to $m_x(2019)$ does not remain constant and shows very weak convergence to older ages. Thus, this apparently parallel shift of mortality upward is only approximate. It is interesting to note that, at younger ages (under 50), the COVID-19 epidemic had little or no effect on the total mortality rate (see Figure 14). Another observation from the period data is an obvious mortality deceleration at older ages observed for both male and female period mortality. Mortality deceleration starts around age 90 years and was observed for all studied populations. Thus, in the case of period data mortality deceleration is a widespread phenomenon.

Thus, our preliminary estimates demonstrate an upward parallel shift in mortality for both women and men (in semilog scale). Therefore, a model of proportional risks with a constant multiplier can be applied to mortality description during the COVID-19 epidemic. Our study of mortality at the peak of COVID-19 epidemic showed that the mortality rate was proportionally increased at older ages by a factor of two (Gavrilov and Gavrilova 2020). It is interesting to note that, at younger ages (under 50), the COVID-19 epidemic had little or no effect on the total mortality rate (see Figure 14). This kind of mortality change resembles a shock "aging" of the population during the COVID-19 epidemic. The multiplicative effect of the increase in mortality during the COVID-19 epidemic differs from the 1918 Spanish flu pandemic (Gavrilova and Gavrilov 2020). This mechanism also explains the predominant deaths of the older population in contrast to the Spanish flu in 1918. As in the case of the Spanish flu epidemic, the actuarial rate of aging (relative growth rate of mortality with age) does not change at older ages (65+ years). However, the so-called "compensation effect of mortality" (reduction of relative differences in mortality with age) is clearly observed when comparing mortality of men and women both before and during the epidemic (Gavrilov and Gavrilova 2020). Changes of mortality trajectories during the COVID-19 epidemic deserve more detailed consideration and analysis.

3. CONCLUSION

This study of 1880–1902 single-year birth cohorts found that mortality deceleration is more prevalent in historically earlier birth cohorts, whereas more recent birth cohorts tend to demonstrate the Gompertzian pattern of mortality, mostly among men. This transition from mortality deceleration to the Gompertzian trajectory is particularly evident for the U.S. birth cohorts, where it is observed for both men and women. These results support the hypothesis that mortality deceleration should vanish over time because of improvement in age reporting. These results agree with previous reports of the Gompertzian mortality in the U.S. cohorts born after 1889 (Gavrilov and Gavrilova 2011; Gavrilova and Gavrilov 2015).

Our results explain why earlier studies found mortality deceleration and mortality leveling off in cohort data (Gavrilov and Gavrilova 1991; Kannisto 1994; Horiuchi and Wilmoth 1998; Thatcher et al. 1998; Thatcher 1999), whereas more recent studies did not confirm these initial findings when U.S. data were analyzed (Gavrilov and Gavrilova 2011; Gavrilova and Gavrilov 2015).Age misreporting by older individuals is one of the most likely reasons for this phenomenon (Coale and Kisker 1986; Gavrilov and Gavrilova 2011; Newman 2018). Studies conducted more than 20 years ago used data for older birth cohorts when age reporting was not particularly accurate (Jdanov et al. 2008). A recent study found that old-age mortality in Australia, Canada and the U.S. is compatible with the Gompertzian model, confirming our findings (Bebbington 2014). These authors also found that mortality in European countries does show deceleration, but the onset of mortality deceleration is shifting over time to older ages (ibid.). Data cleaning of the U.S. records for persons with extremely old age (105+) demonstrated that improvement of data quality makes mortality after age 105 years closer to the Gompertz model (Gavrilova and Gavrilov 2018). This was particularly the case for male mortality, which shifted from mortality deceleration to the Gompertz law (Gavrilov and Gavrilova 2019).

In addition to age misreporting, other causes of old-age mortality deceleration may be involved. It was found that mortality of centenarians in the U.S. did not decrease noticeably in the past decades, despite a significant decline in mortality of younger age groups (Gavrilo et al. 2017). In some countries (Japan, France, Switzerland and Sweden) the historical decline of mortality among centenarians was interrupted about 10–20 years ago (Robine and Cubaynes 2017). Historical stagnation of mortality at ages 100 years and older may lead to steeper mortality curves for cohorts at extreme old ages, whereas historical mortality decline at old ages may produce apparent decelerating pattern of mortality with age. Feehan

(2018) studied cohort mortality after age 80 in different countries. He found that in some countries the Gompertz model performed poorly, whereas in other countries this model performed reasonably well. He suggested that period effects may have altered the shape of cohort mortality producing the strongest evidence of non-Gompertz death rates for cohorts that experienced continuous historical improvements in mortality at advanced ages (Feehan 2018). Our results do not completely exclude the possibility that the onset of mortality deceleration in the studied countries moved beyond 105 years of age because of delayed mortality. It is possible that both the improvement of age reporting and stagnation of mortality among centenarians contribute to the observed historical transition from mortality deceleration to the Gompertz law in cohort data. Overall, it appears that the onset of mortality deceleration occurs at much older ages than was reported earlier (Wilmoth 1995; Horiuchi and Wilmoth 1998; Thatcher et al. 1998; Thatcher 1999).

Theoretical models (Beard 1959; Vaupel et al. 1979) and simulation studies (Wrigley-Field 2014) suggest that mortality deceleration at advanced ages may be a consequence of population heterogeneity. The heterogeneity hypothesis predicts that the age of onset for mortality deceleration should increase over time as frailer individuals reach advanced ages because of lower mortality at younger ages (Horiuchi and Wilmoth 1998; Lynch and Brown 2001). Studies of the U.S. period mortality (Lynch and Brown 2001) and cohort mortality in other countries (Horiuchi and Wilmoth 1998; Bebbington et al. 2014) provide some empirical support for this prediction. A study of the U.S. period mortality revealed an expansion of life span inequalities over time among survivors to older ages, suggesting that more heterogeneous populations are reaching older age now (Engelman et al. 2010).

Our results demonstrate that there is no definite answer to the question about mortality patterns at extreme old ages because this answer depends on the historical period of mortality analysis and on the particular country.

ACKNOWLEDGMENTS

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Appendix A: Supplemental Materials

Figure 1

CHANGES IN AKAIKE INFORMATION CRITERION (AIC) ACROSS BIRTH COHORTS FOR THE GOMPERTZ AND THE KANNISTO MODELS FITTING US OLD-AGE MORTALITY. LOWER AIC VALUES CORRESPOND TO A BETTER MODEL FIT.

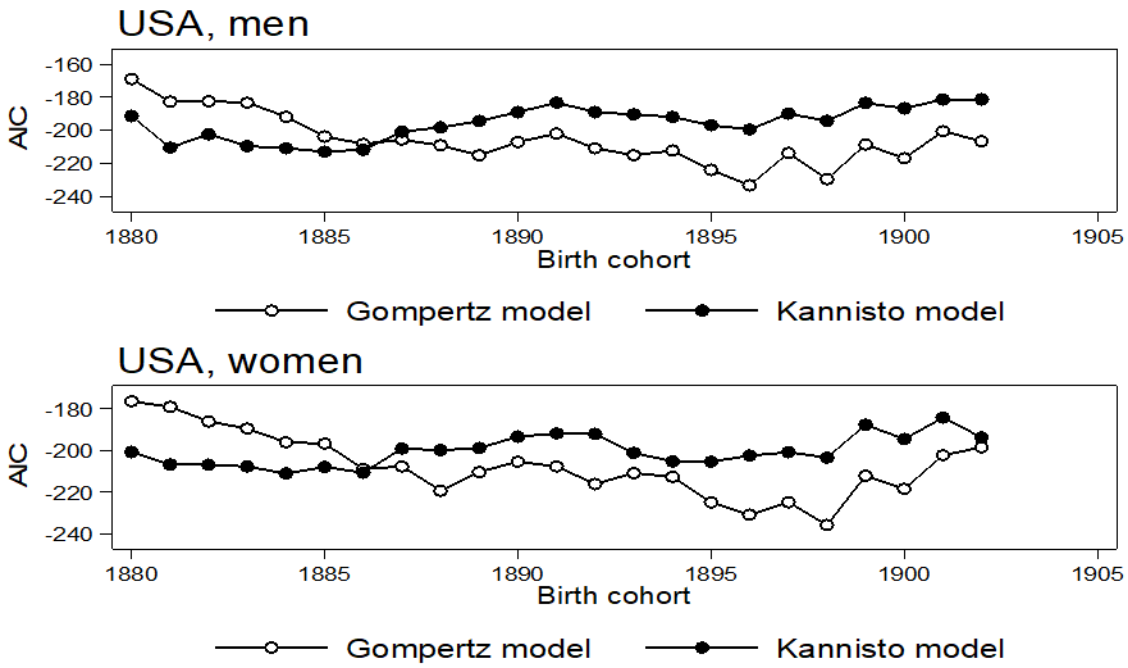


Figure 2

CHANGES IN AKAIKE INFORMATION CRITERION (AIC) ACROSS BIRTH COHORTS FOR THE GOMPERTZ AND THE KANNISTO MODELS FITTING AUSTRALIAN OLD-AGE MORTALITY. LOWER AIC VALUES CORRESPOND TO A BETTER MODEL FIT.

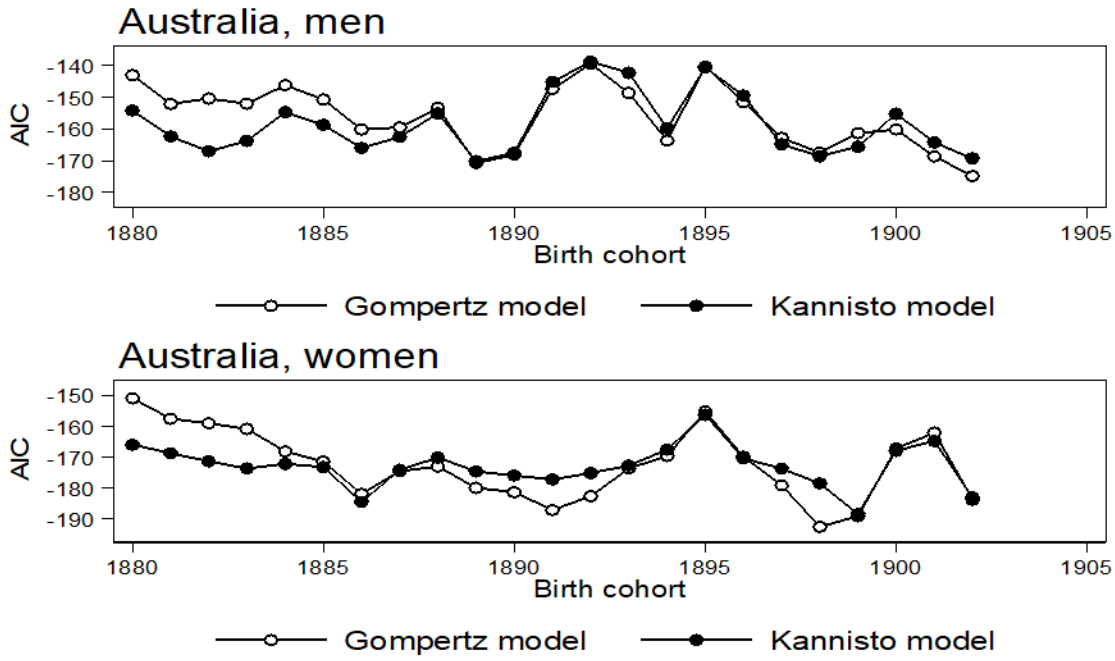


Figure 3

CHANGES IN AKAIKE INFORMATION CRITERION (AIC) ACROSS BIRTH COHORTS FOR THE GOMPERTZ AND THE KANNISTO MODELS FITTING BELGIAN OLD-AGE MORTALITY. LOWER AIC VALUES CORRESPOND TO A BETTER MODEL FIT.

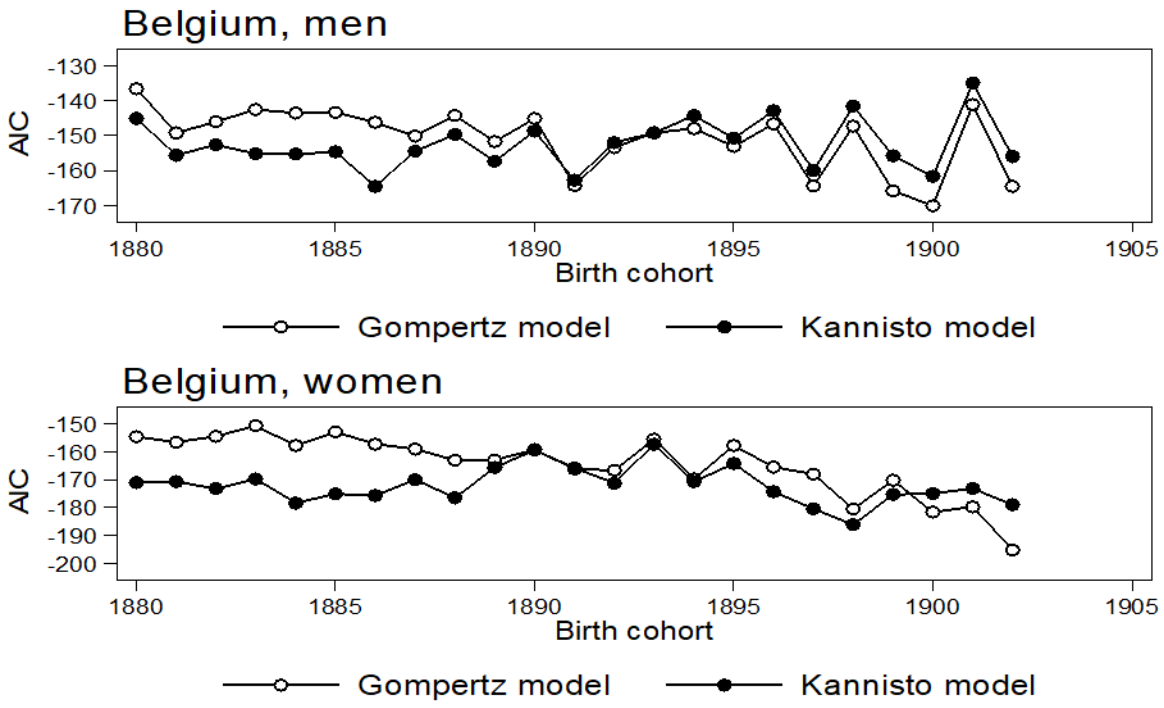


Figure 4

CHANGES IN AKAIKE INFORMATION CRITERION (AIC) ACROSS BIRTH COHORTS FOR THE GOMPERTZ AND THE KANNISTO MODELS FITTING U.K. OLD-AGE MORTALITY. LOWER AIC VALUES CORRESPOND TO A BETTER MODEL FIT.

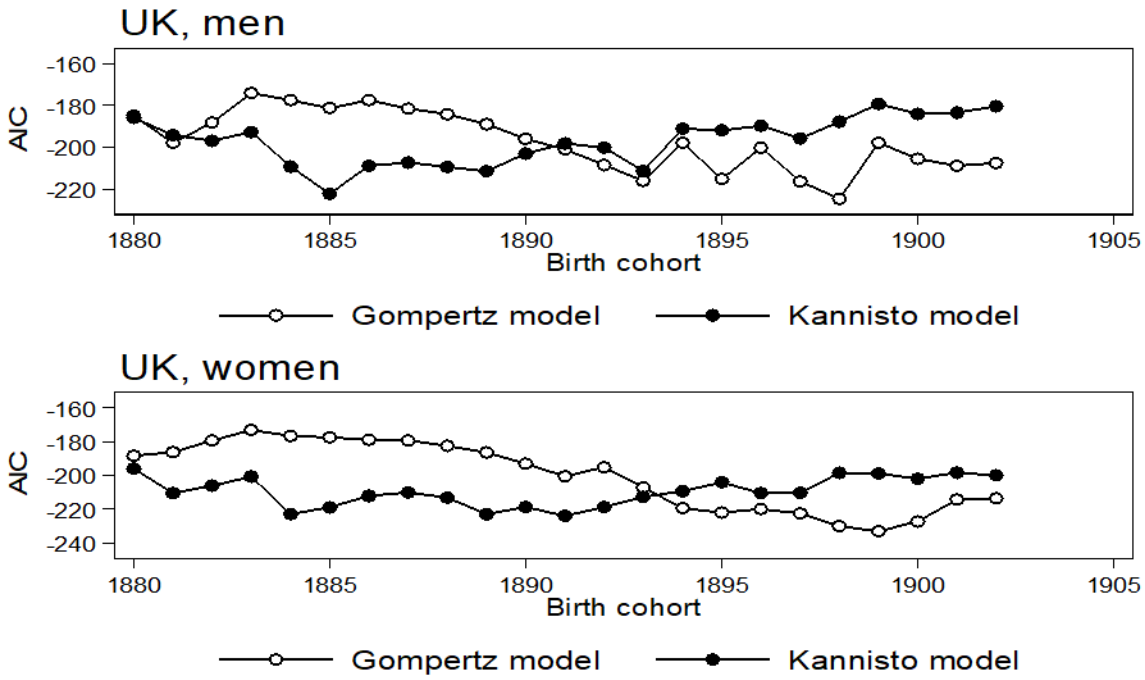


Figure 5

CHANGES IN AKAIKE INFORMATION CRITERION (AIC) ACROSS BIRTH COHORTS FOR THE GOMPERTZ AND THE KANNISTO MODELS FITTING ITALIAN OLD-AGE MORTALITY. LOWER AIC VALUES CORRESPOND TO A BETTER MODEL FIT.

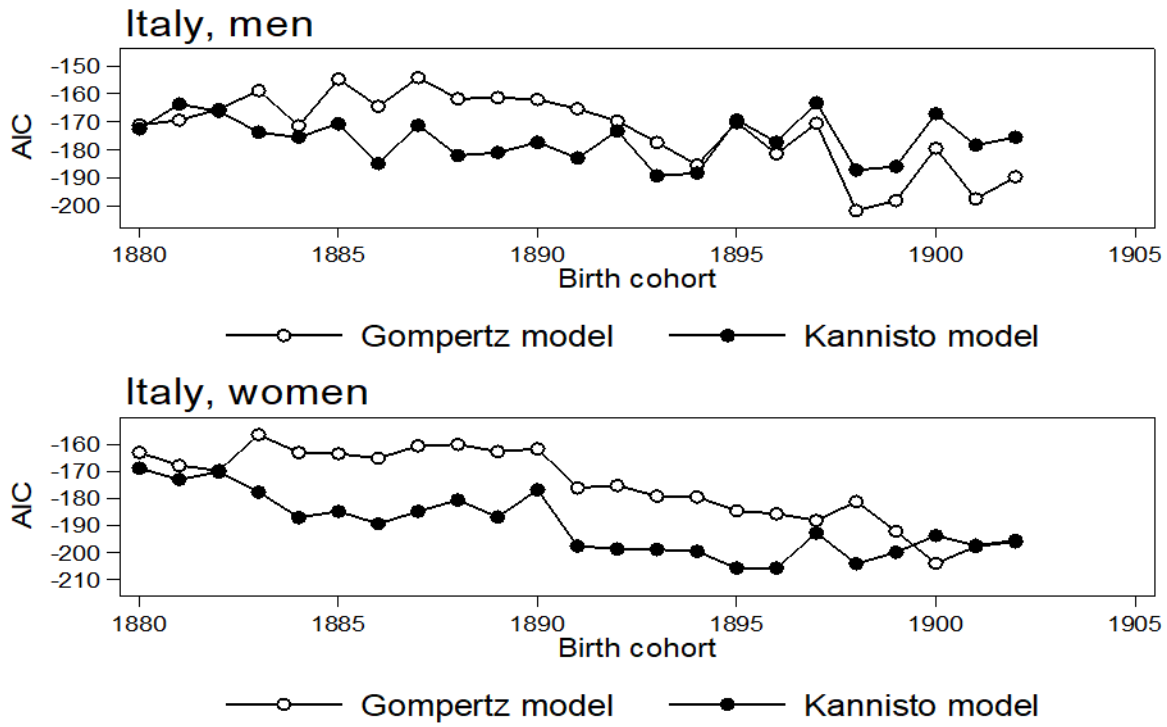


Figure 6

CHANGES IN AKAIKE INFORMATION CRITERION (AIC) ACROSS BIRTH COHORTS FOR THE GOMPERTZ AND THE KANNISTO MODELS FITTING JAPANESE OLD-AGE MORTALITY. LOWER AIC VALUES CORRESPOND TO A BETTER MODEL FIT.

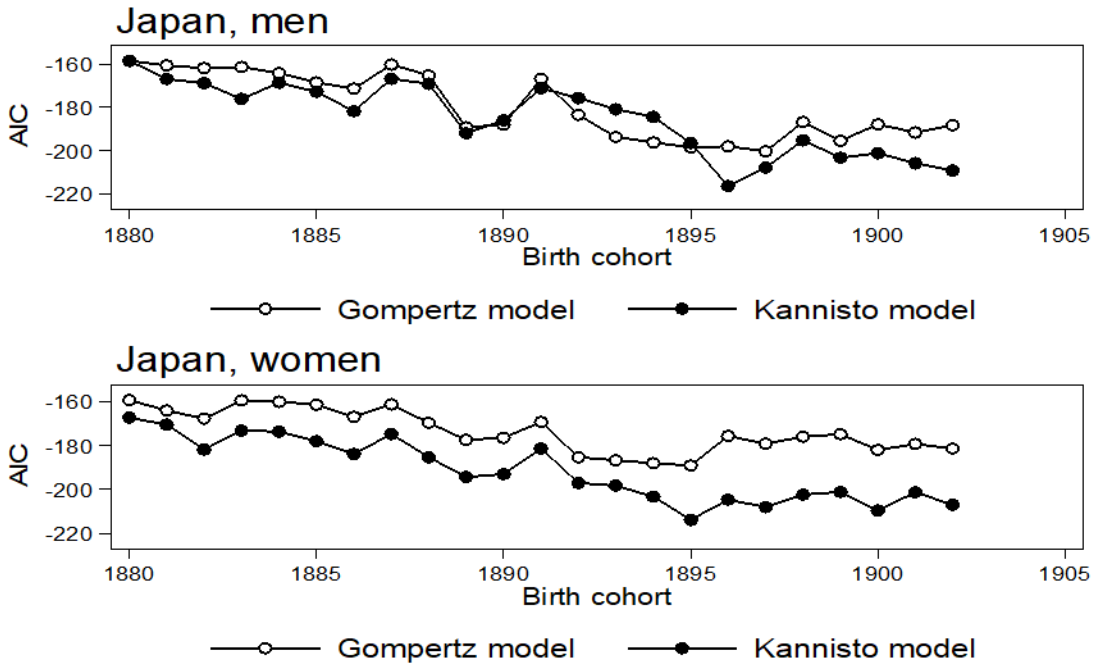


Figure 7

CHANGES IN AKAIKE INFORMATION CRITERION (AIC) ACROSS BIRTH COHORTS FOR THE GOMPERTZ AND THE KANNISTO MODELS FITTING CANADIAN OLD-AGE MORTALITY. LOWER AIC VALUES CORRESPOND TO A BETTER MODEL FIT.

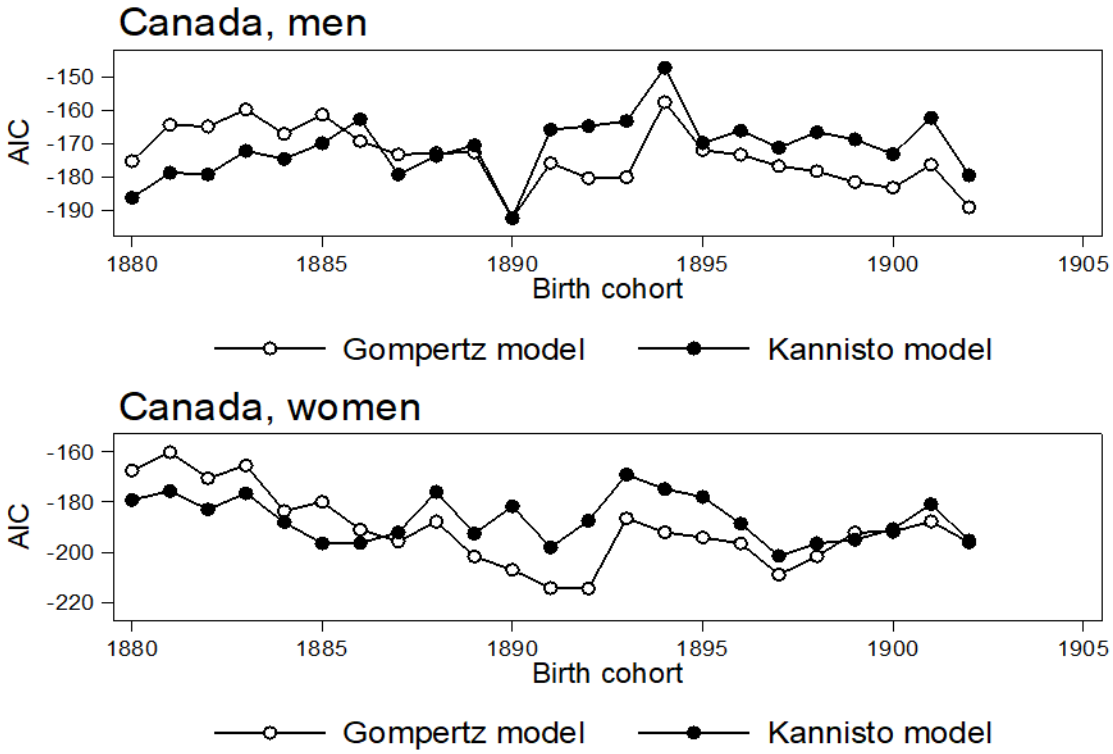


Figure 8

CHANGES IN AKAIKE INFORMATION CRITERION (AIC) ACROSS BIRTH COHORTS FOR THE GOMPERTZ AND THE KANNISTO MODELS FITTING SPANISH OLD-AGE MORTALITY. LOWER AIC VALUES CORRESPOND TO A BETTER MODEL FIT.

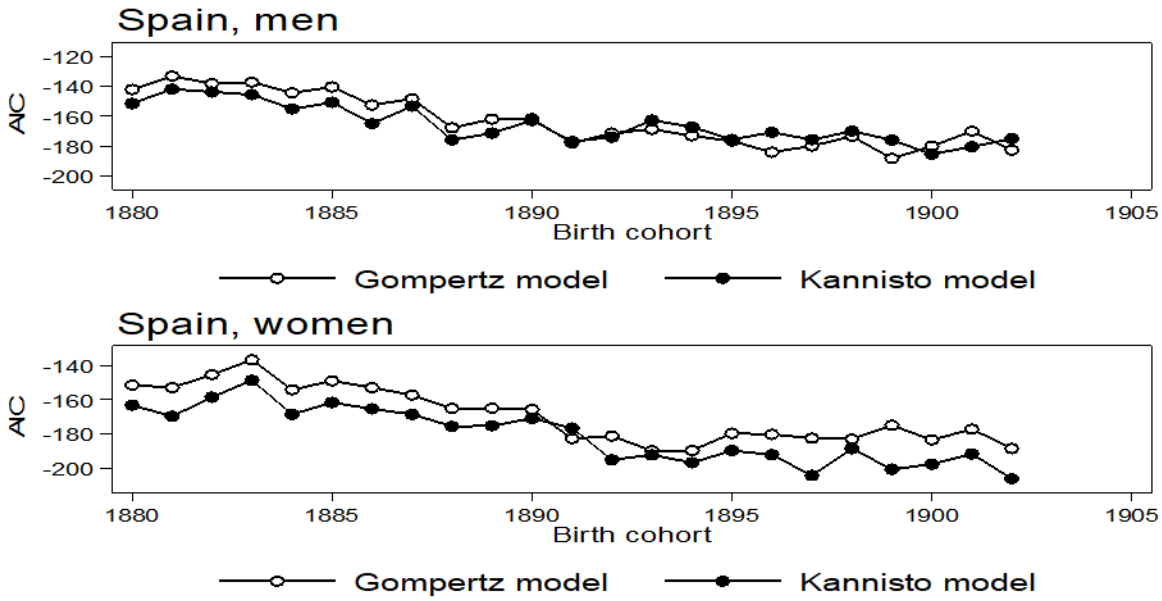


Figure 9

CHANGES IN AKAIKE INFORMATION CRITERION (AIC) ACROSS BIRTH COHORTS FOR THE GOMPERTZ AND THE KANNISTO MODELS FITTING FRENCH OLD-AGE MORTALITY. LOWER AIC VALUES CORRESPOND TO A BETTER MODEL FIT.

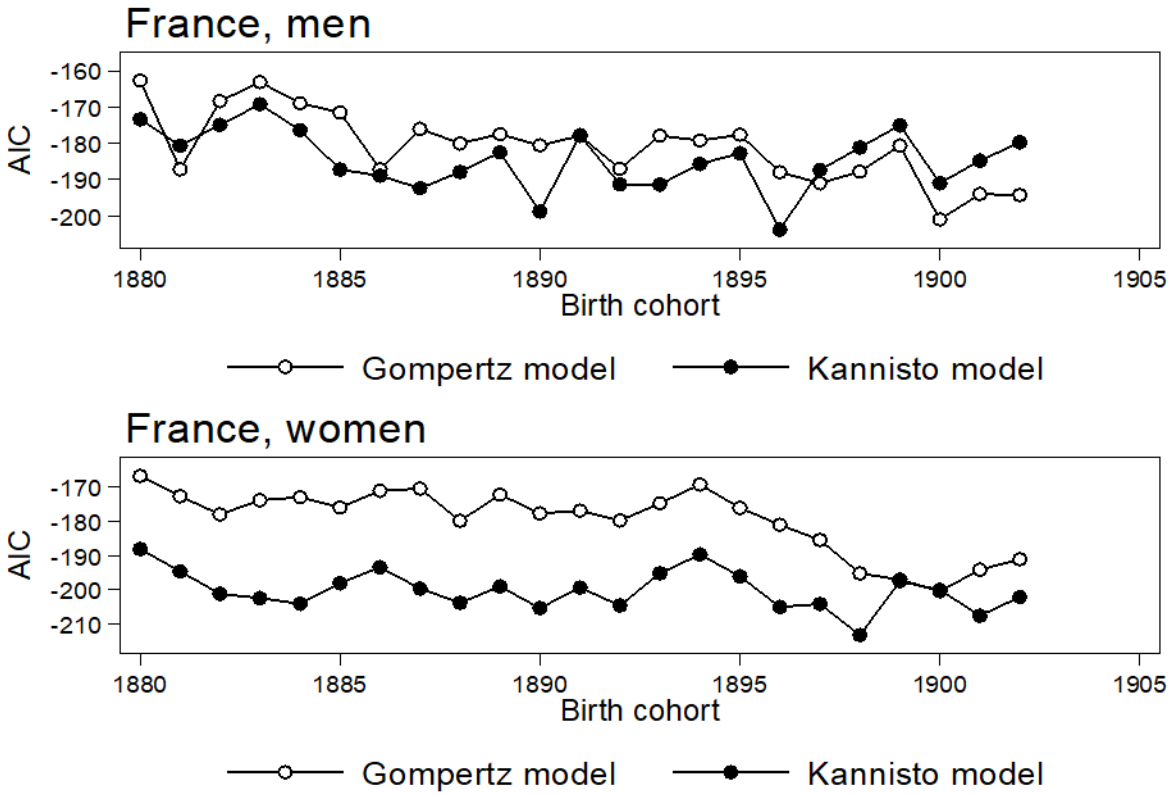


Figure 10

MORTALITY AFTER AGE 80 (COMMON LOG SCALE WITH BASE 10) OF MEN AND WOMEN IN SPAIN BEFORE AND DURING THE COVID-19 EPIDEMIC.

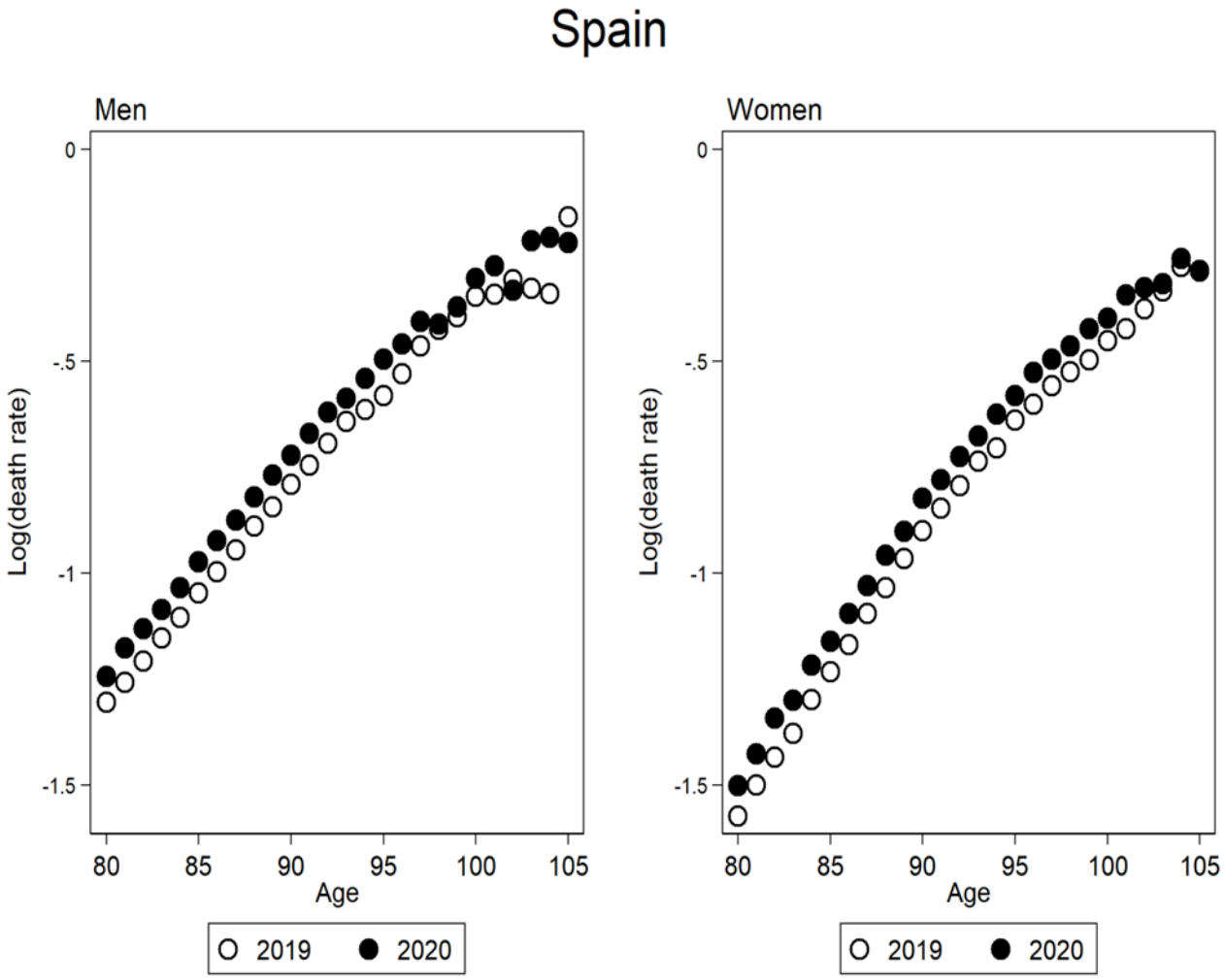


Figure 11

MORTALITY AFTER AGE 80 (COMMON LOG SCALE WITH BASE 10) OF MEN AND WOMEN IN BELGIUM BEFORE AND DURING THE COVID-19 EPIDEMIC.

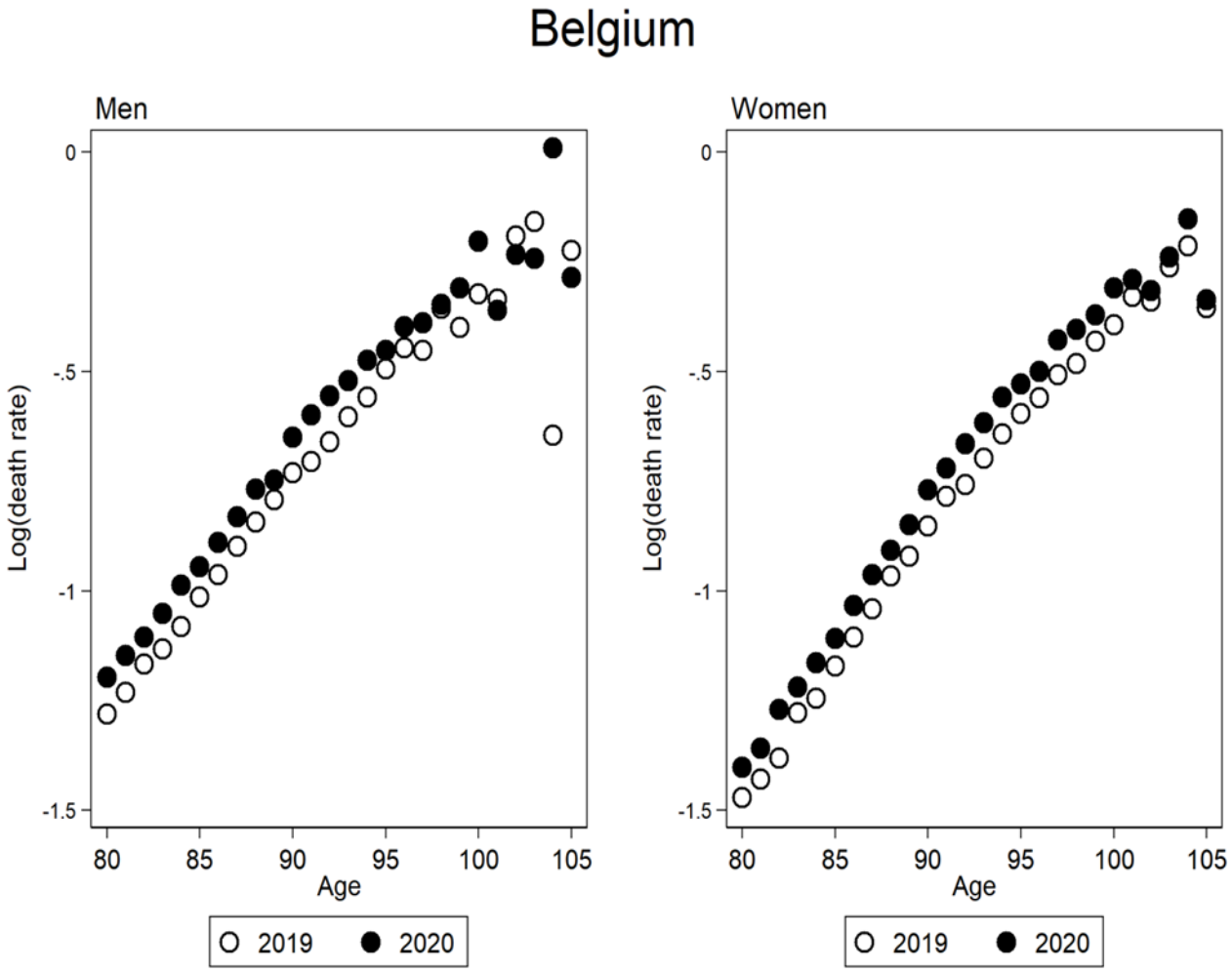


Figure 12

MORTALITY AFTER AGE 80 (COMMON LOG SCALE WITH BASE 10) OF MEN AND WOMEN IN SWEDEN BEFORE AND DURING THE COVID-19 EPIDEMIC.

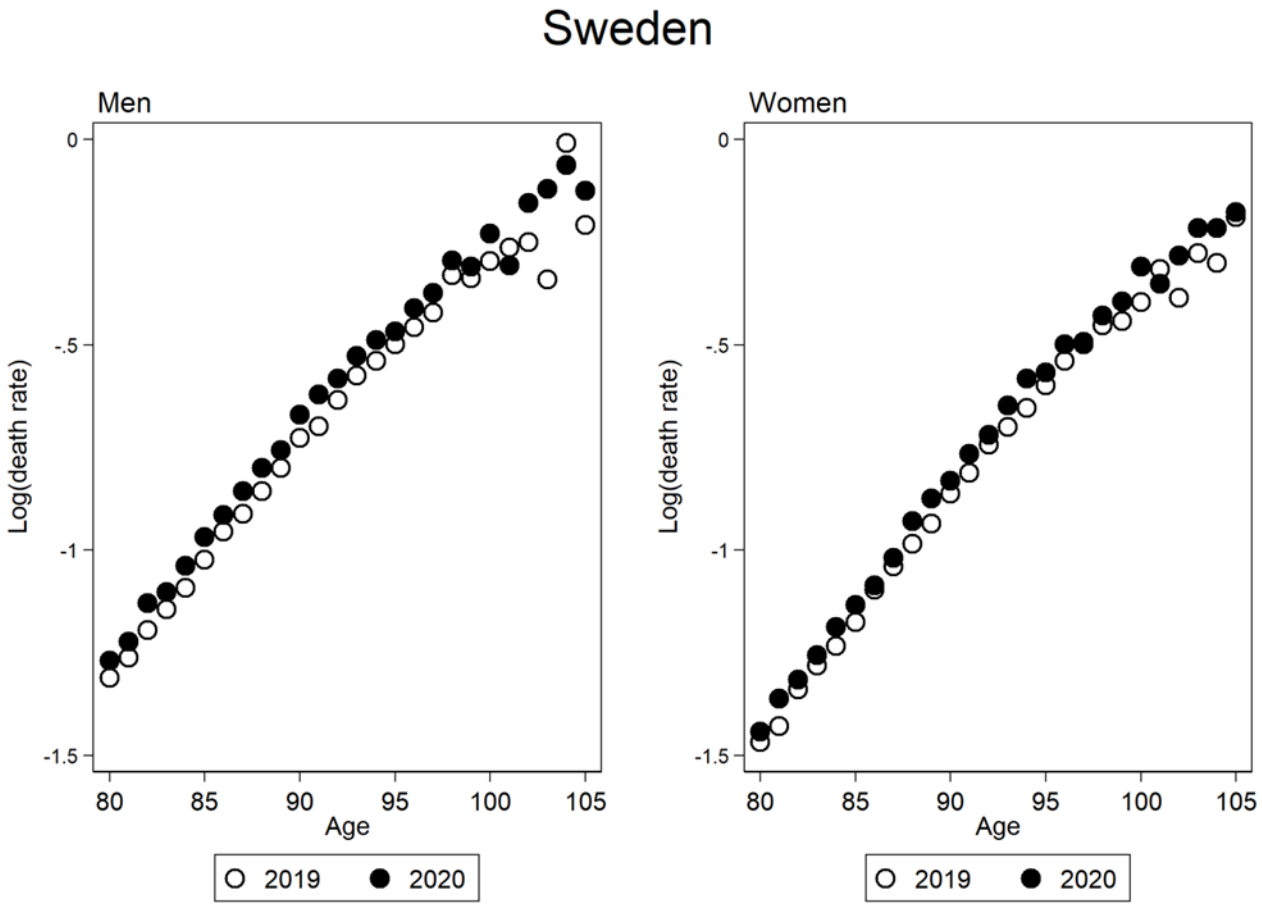


Figure 13

MORTALITY AFTER AGE 80 (COMMON LOG SCALE WITH BASE 10) OF MEN AND WOMEN IN THE U.S. BEFORE AND DURING THE COVID-19 EPIDEMIC.

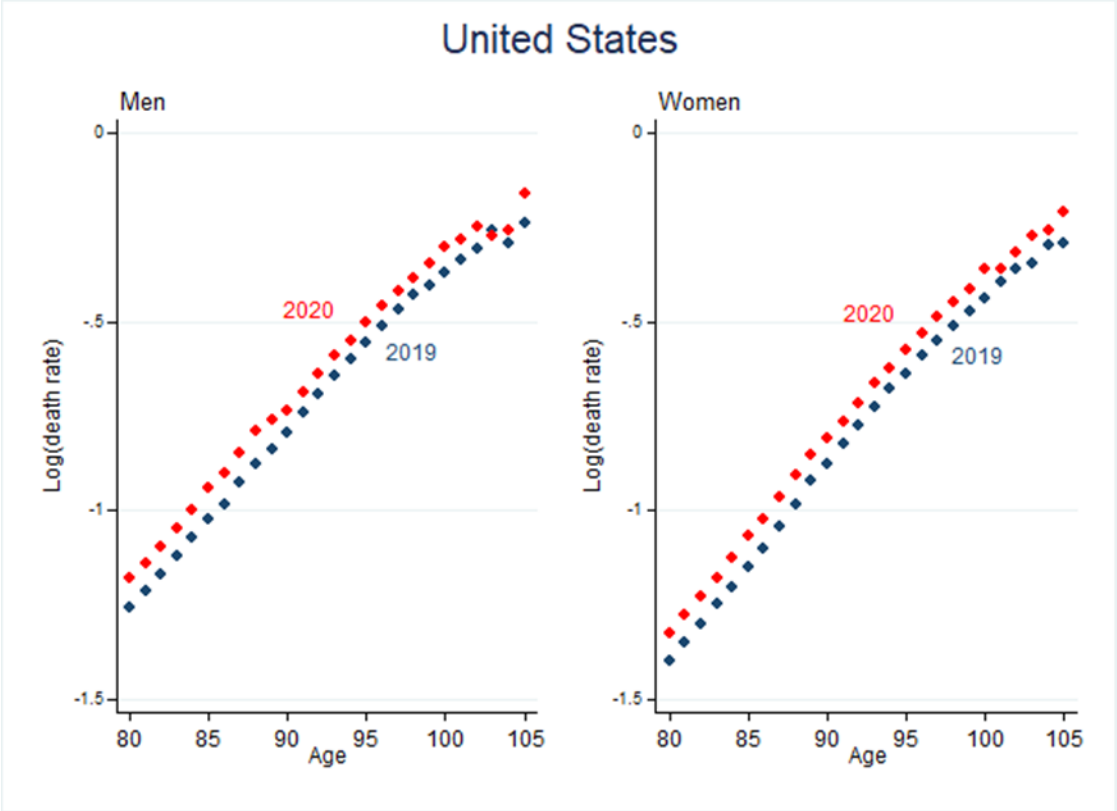
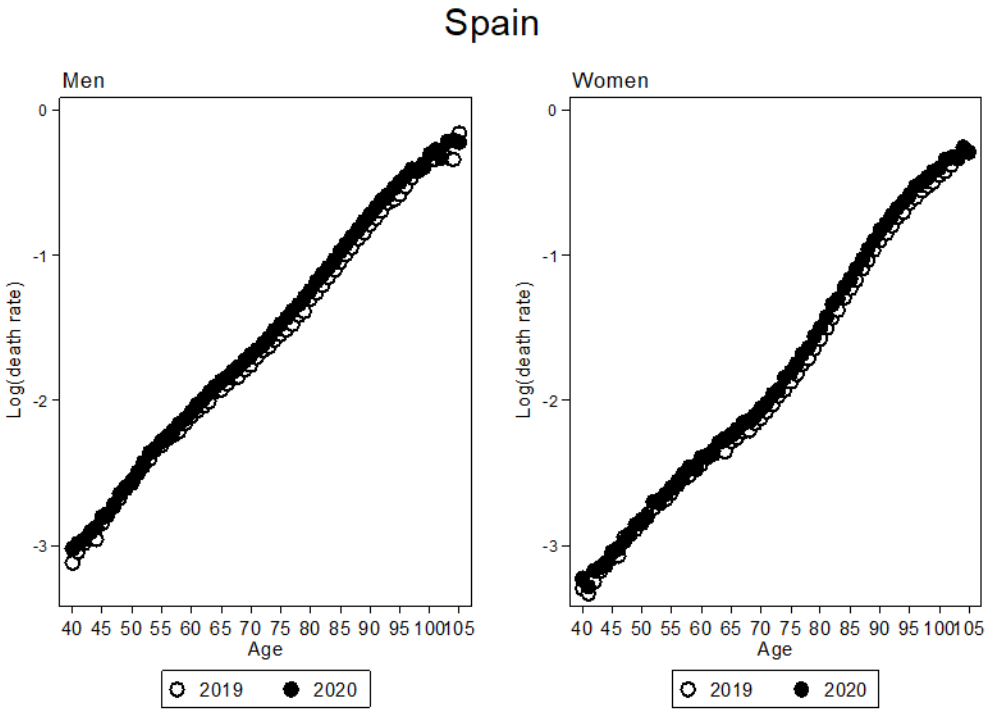


Figure 14
MORTALITY AFTER AGE 40 (COMMON LOG SCALE WITH BASE 10) OF MEN AND WOMEN IN SPAIN BEFORE AND DURING THE COVID-19 EPIDEMIC.



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