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Original Article

Learning From Leaders: Life-span Trends in Olympians and Supercentenarians

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Abstract

Life-span trends progression has worldwide practical implications as it may affect the sustainability of modern societies. We aimed to describe the secular life-span trends of populations with a propensity to live longer—Olympians and supercentenarians—under two hypotheses: an ongoing life-span extension versus a biologic "probabilistic barrier" limiting further progression. In a study of life-span densities (total number of life durations per birth date), we analyzed 19,012 Olympians and 1,205 supercentenarians deceased between 1900 and 2013. Among most Olympians, we observed a trend toward increased life duration. This trend, however, decelerates at advanced ages leveling off with the upper values with a perennial gap between Olympians and supercentenarians during the whole observation period. Similar tendencies are observed among supercentenarians, and over the last years, a plateau attests to a stable longevity pattern among the longest-lived humans. The common trends between Olympians and supercentenarians indicate similar mortality pressures over both populations that increase with age, scenario better explained by a biologic "barrier" forecast.

Key Words: Demography—Longevity—Life span—Limit

Is the continuous rise in world's life span still a plausible forecast? This topic is of great concern for public health and policymakers and has worldwide implications as it may affect the sustainability of modern societies and health care systems (1–3). Yet, the issue of longevity trends has divided researchers and remains a matter of controversy (4). The origin of this divergence is not only a philosophical matter, but it is also supported by differing methods of investigation. Based on past life table trends, the prolongevist side claims that life expectancy will continue to increase linearly (5,6). Best practices research has proposed dramatic increases in longevity outcomes, affirming that most children born in developed countries since 2000 will reach 100 years (7). Supported by biologic constraints and evolution based, the other side argues that such a forecast is fundamentally unreachable (8,9) because human life span is biologically determined and we are already approaching a "barrier" to life expectancy increase (1,10). Each side's conclusions point to opposite directions.

We propose an intermediate approach to investigate life-span trends with novel tools. The approach consists in analyzing life-span density trends of two highly selected populations with a propensity to live longer. Their current maximum life-span trends may figure the general population in the near future.

The analysis of longer lived cohorts' life-span trends may guide the debate towards the prolongevist or biologist direction based on one of the different hypotheses: accepting the scenario whereby the historic rise in life expectancy will continue, it is necessary to assume that people will more often live longer than 100, 110, and 120 years (2); precursor populations would then present signs of provable life extension. Conversely, a deceleration among longer lived cohorts could be seen as a sign of a close life-span limit (2).

The first population selected was made up of all worldwide Olympic athletes that had participated in the Olympic Games and were already deceased. Olympian medallists have demonstrated a 3-years' survival advantage in comparison with their compatriots in 13 developed nations (11). Other sources analyzing Olympians longevity, whether medallists or not, have demonstrated a similar advantage (12,13). To the best of our knowledge, Olympians constitute the sole worldwide well-defined population that has a proven survival advantage, including all ethnicities and dating back to the 19th century.

The registered longest-lived member of any species defines its maximum life span (10). Hence, the second population selected was made up of elite survivors (14): all deceased supercentenarians (individuals >110-years-old) worldwide (15).

We analyzed both populations' life span through density analysis. The density analysis (total number of life durations per birth date) reveals distinct life-span trends according to the number of subjects with time. Hence, it allows for a highly informative description of life-span upper limits and its relative relevance within the wide range of lifetime values.

Therefore, we aimed to describe life-span density trends of worldwide deceased Olympians and supercentenarians.

Methods

Study Population—Olympians

Day, month, and year of birth and death were collected for 19,012 (n = 17,815 men and n = 1,197 women) who had participated in at least one summer or winter Olympic Games competition since the first modern edition in 1896, up to 2012 and deceased up to 2013 (study's date point). Data came from the most authoritative source of Olympians biography (11). The Olympians' complete cohort (the cohort in which all subjects have entirely died out) ranges from 1828 to 1906. The Olympians population is mostly composed of adults from high-income countries in Western Europe and North America (Table 1).

Study Population—Supercentenarians

A verified and validated complete cohort of deceased supercentenarians born after 1800 was collected from the Gerontology Research Group (15). Overall, 1,205 supercentenarians (n = 125 men and n = 1,080 women) born up until 1897—the last year without any registered proof of a supercentenarian alive—were included. The majority of supercentenarians also come from high-income countries (Table 1).

Life-span Density Function

The life-span density of Olympians and supercentenarians was estimated over a two-dimensional mesh. X and Y were the date of birth and life span, respectively, such that the data of an individual are expressed as Xi and Yi with $i = 1, \ldots, N$ (see Supplementary Material).

Analysis of the Dynamics of Life-span Trends in a Specific Time Frame

To assess the trends among the life-span upper values, the superior contour of each density layers was smoothed through a two-dimensional convolution kernel. The frame was defined within the intervals: $X_{\text{(Olympians)}}$ in [1865; 1906]; $Y_{\text{(Olympians)}}$ in [80; 123]; and $X_{\text{(supercentenarians)}}$ in [1865; 1897]; $Y_{\text{(supercentenarians)}}$ in [110; 123]. The frame selected in X corresponded to the first year forming a density layer up to the last year of a complete cohort. The selected frame in Y corresponded to a life span superior to 80 years up to its maximum values.

The life-span trends dynamics, for each birth date in the selected frame, was calculated by the sum of differences between adjacent densities in the Y (life span) direction (see Supplementary Material). All analyses were performed using Matlab 7.13 (MathWorks Inc.) software.

Results

Olympians and Supercentenarians Life-span Density

The life-span density of worldwide Olympians and supercentenarians is presented in Figure 1.

Table 1. Olympians and Supercentenarians Cohort Description

	Olympians (N = 19,012)	Supercentenarians (N = 1,205)
Range in years		
Birth	1828–1991	1807–1897
Death	1900–2013	1917–2013
World distribution by region (%)		
Africa	1.7	0.4
The Americas	19.8	50.8
Asia	2.6	11.8
Europe	73.7	35.4
Oceania	2.1	1.4
Age at cohort's entry, mean (SD)	26.5 (6.6)	110
Range of life span in years (y) and days (d)	15 y and 120 d–105 y and 305 d	110 y and 0 d–122 y and 164 d

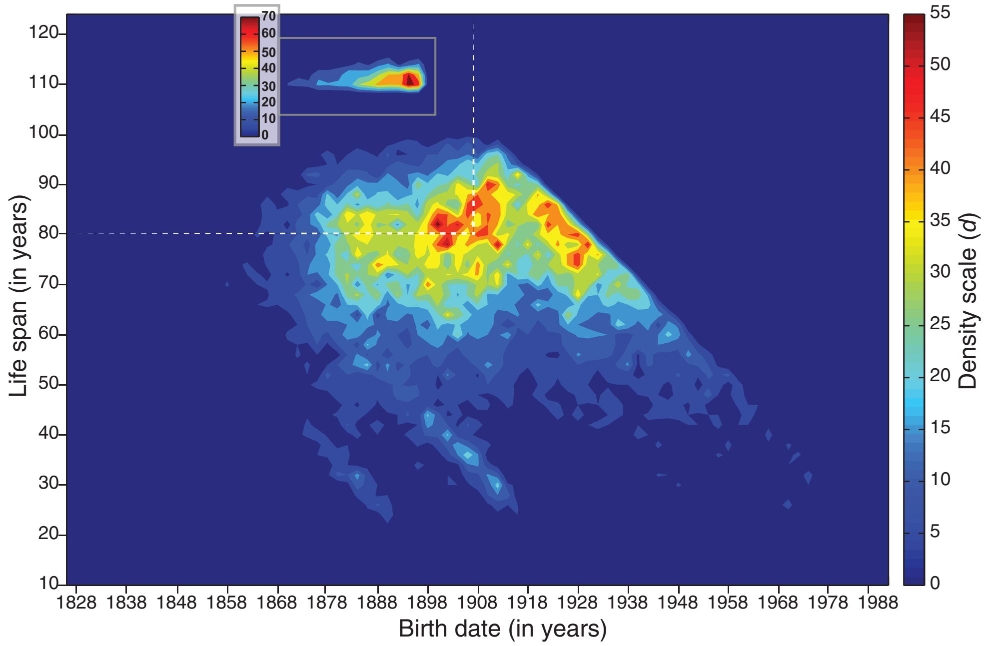

Figure 1. Life-span (collected in days and represented in years) density of all deceased Olympians (N = 19,012) and all validated supercentenarians (N = 1,205) born since 1800 in function of their birth date (represented in years). Window: $X_{(Olympians)}$ in (1828;1991); $Y_{(Olympians)}$ in [10;123]; $X_{(supercentenarians)}$ in [1828;1897]; and $Y_{(supercentenarians)}$ in [110;123]. The resolution was defined as a = 2 years (see Supplementary Material). The density scale ranges from dark blue illustrating the lowest density values with fewer subjects' life span to dark red corresponding to the highest density values. The vertical dashed line delimitates the complete cohort, when the population has entirely died out. The horizontal dashed line delimits life span values superior to 80 years within the complete cohort. Isolated life spans are not represented in the figure because of their small density values.

The first Modern Games occurred in 1896. Thus, Olympians born before 1870 participated in the early editions at a more advanced age (42.5 ± 8.1-years-old) relative to the mean age at first participation (26.5 ± 6.6-years-old) of the full cohort.

Olympians' deaths were observed in every age group, ranging from 15 years and 120 days up to 105 years and 305 days. Deaths under 40 years mainly correspond to two birth periods: 1874–1890 and 1896–1915 and include men only.

The denser areas, corresponding to the life span that concentrates the highest number of subjects, is formed by Olympians born between 1900 and 1904 that died around 80-years-old.

None of the Olympians reached the status of supercentenarian; therefore, a gap separates the two populations throughout the entire period.

The denser area among the supercentenarians is formed by subjects born between 1893 and 1895 that died around 111-years-old. The world's record life span is 122 years and 164 days for Jeanne Calment, a French woman born in 1875.

Life-span Upper Limits

The top-left corner in Figure 1 is the focus of the life-span upper limit analysis for both populations as they constitute the life-span upper values of both complete cohorts. The development of different levels of densities, forming life-span layers may be visualized in this corner.

The superior layer, formed by the greatest life-span values of Olympians, creates a survival convex envelope at approximately 98 years. The convex envelope points out the Olympians life-span upper limit observed. The density layers, below this convex envelope, move upward with birth date leveling off with the upper limit envelope.

A similar pattern is present among supercentenarians. Their life span creates a survival convex envelope at approximately 115 years. The densities layers above this envelope evolve with time, but the upper limit remains steady and a plateau may be visualized up to now.

Life-span Density Line Trends

The superior contour of each density layers at the top-left corner on Figure 1 are illustrated in Figure 2A for both populations. We observe a different slope progression of the density lines according to the life span. The density slope of Olympians decelerates with time as their life span increases.

Regarding supercentenarians, the density slope increases slightly with time at the beginning of the observation period, at a similar pace among the densities layers. Then, the density slopes remains stable for the upper values. This results in a plateau attesting a stable phenomenon among supercentenarians in recent years.

Densification Phenomenon

Life span increase leveling off with the upper values entails an accumulation of individuals close to the survival convex envelope and reveals a densification phenomenon. This phenomenon was assessed in the ancillary graphs (Figure 2B and C).

The graphs describe an increased densification trend more continuous and more intense among supercentenarians than among Olympians.

Discussion

Learning From Leaders

This study demonstrates the life-span trends in populations with a propensity to live longer, Olympians and supercentenarians. Among Olympians, we observe a trend of increasing life duration, which

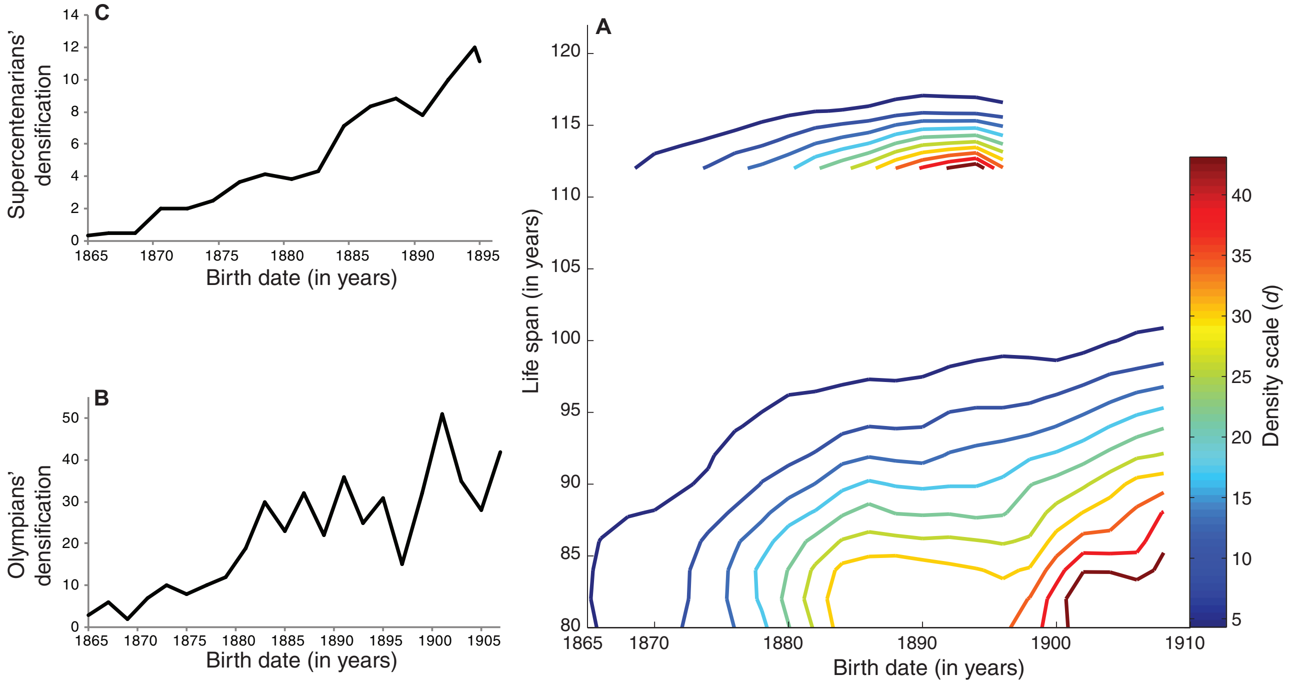

Figure 2. (**A**) Contour of the life-span density layers of Olympians and supercentenarians. Selected window: $X_{(Olympians)}$ in [1865;1906] (first year forming a density layer up to the last year of a complete cohort); $Y_{(Olympians)}$ in [80;123]; and $X_{(supercentenarians)}$ in [1865;1897]; $Y_{(supercentenarians)}$ in [110;123]. (**B**) Olympians' densification phenomenon. (**C**) Supercentenarians' densification phenomenon. The y-axis in B and C represents the sum of the differences in the Y (life span) direction ($\Sigma\alpha j$) between the density layers by birth date (see Supplementary Material). Graphs (B) and (C) represent the increase of the density layers with time in the direction of the upper life span values measuring the densification phenomenon.

slows down at advanced ages. The dynamics observed leads to a densification phenomenon, as a result of a life span compression between the denser areas and the maximum ages.

Olympic participants undergo a highly selective phenotypic process based on rare physiological aptness (16). At the age of cohort entry, they were healthy subjects under favorable conditions (genetic and environmental) (17) reaching high standards of physical performances. Studies have shown that Olympians have healthier lifestyles after their career and maintain a good physical condition (18). All these factors contribute to greater longevity (18–20). The selection criteria for Olympians' may explain their survival advantage over the general population, but it is not enough to allow them to reach the supercentenarians status: Olympians and supercentenarians have different performance-advantage sets. A gap clearly discriminates both populations attesting that the factors contributing to enhance general populations' longevity may not be sufficient to highlight the path required to become a supercentenarian. Accordingly, a longitudinal analysis of centenarians and supercentenarians has demonstrated a significant association between better physical function with survival advantage until 110 years. Beyond that age physical function or biomedical parameters may less accurately predict mortality (20).

Despite the gap, Olympians and supercentenarians present similar life-span trends and densification phenomenon, intensified among supercentenarians. This common pattern may indicate that both populations are under similar mortality pressures, despite the different phenotypic selection criteria of each population. Such forces increase with age, and both populations respond similarly by a densification phenomenon.

Concerning supercentenarians, the increasing density slope at the beginning of the observation period may be related to the greater number of recruited subjects and to a more reliable registry. Thereafter, the stable trends observed attest for a life-span plateau over the recent years. Mathematically speaking, Jeanne Calment's life-span record may have been beaten by people born until 1891. After this record, only a single person (born in 1880) has lived for 119 years, and since then, no one has lived to more than 116 years. Accordingly, the life-span density trends provide no signs of a recent increased longevity pattern among the longest-lived, despite of an intense densification phenomenon.

We find better support to explain our results in arguments such an "invisible barrier," as previously suggested (1,21). This scenario seems to be represented here, through the densification phenomenon, alluding to a rectangularization of the survival curves (22,23). The slower pace in the trend of life span maximum observed among Olympians is even more stable among supercentenarians illustrating a "barrier" represented by the survival convex envelope. To support life-span extension forecasts, we would expect to find signs of expansion trends, people living each time longer at advanced ages (2). This scenario is hardly supported by the description of supercentenarians' and Olympians' current trends.

Life-span Record Holders

The fittest subjects of each country compose the worldwide Olympians cohort (11).This population is mostly formed by athletes from regions that have historically dominated sport performances and the world record for life expectancy as well. Olympians are not the only longer lived cohort, although they are the largest one, comprising various ethnicities and originating from a wide range of social conditions. Even though in the absolute sense Olympians constitute a small subset of gifted athletes, validated supercentenarians compose an even smaller subset of outliers. Women usually live longer than men, but the Olympian cohort is mainly supported by male data because women's entry in the first Games was restricted. Yet, Olympian women present the same pattern of density layers as men, and their superior life-span density synchronizes with the men's.

Olympians Follow General Population Trends

The analysis of Olympians' deaths—observed in every age group—highlights a pronounced heterogeneity even in a highly selected population.

The two periods concentrating most deaths under 40 years can be attributed to both world wars, which reveal that Olympian men were neither excluded from the war effort nor spared its consequences.

The trend among most Olympians toward an increased lifetime throughout the century is similar to what has been described in terms of life expectancy (5,24) and life-span modal analyses (3) in record-holding countries. Modal age at death, estimated in United States, Canada, and France, show similar increasing trends. Japan, however, has recently leveled off (3) comparably to Olympians life-span trend at advanced ages.

The Gap

The gap between Olympians and supercentenarians may indicate a potential for further life expectancy increase. But even among a highly selected population of Olympians, surpassing the general population in terms of average age of death (11), none reached the status of a supercentenarian attesting the exceptional character of reaching 110 years (25). The similar densification among Olympians and supercentenarians and their unclosing gap both strengthen the arguments defending that human biology may not allow most of us to become a centenarian (26). Indeed, becoming one of them takes a complex sequence of rare and specific circumstances, involving constant favorable interactions between genetics (27) and environment (28). Hence, it seems appropriate to distinguish the interpretation of actuarial trends on all-cause mortality from biologic aging possibilities.

Method Considerations

Our study reinforces biologic forecasts (10,25,29) contrasting with extension claims (7,30,31). However, our period of observation is restricted, and the size of the population studied is relatively small. In addition, life expectancy increase has been discontinuous due to historical changes; our cohorts could reveal a transitional trend only. But it is unlikely this may occur synchronically for both studied populations, in view of the different cohorts' selection criteria. Nevertheless, analyses of the most recent centenarians' birth cohort are time limited to 1914. After this period, all demographic forecasts are based on period life tables (death rates from a calendar year applied to people still alive) and remain speculative (9). The underlying assumptions are deterministic—based on the premise that the future will repeat past trends. In addition, death rates at extremely older ages are uncertain (32). Hence, analyzing a concrete cohort presenting a survival advantage may be an alternative method for understanding the present dynamics of maximal age trends.

In light of the continuous reductions in mortality rates at advanced ages in high-income countries (6) possibly the densification phenomenon will intensify in most developed countries. For instance, compression of deaths above the mode—a comparable measure for densification—has been observed in high-income countries (3). Then, the probability of surviving people, pushing the limits forward and leading to a life-span extension may be bigger. However, this scenario defended by prolongevists, seems to be possible only if nutritional, climatic, social, or economic conditions continuously improve. Important medical and technological advances may also lead to life extension (31), but major health determinants already contribute to reduce life expectancy progression in developed countries (33,34). In addition, the current tendency in world climate change and environmental resources degradation may result in adverse health consequences especially affecting the eldest individuals (35).

Conclusion

Most Olympians follow the general population tendency of a life span increase with time, a trend which decelerates as life span increases. At advanced ages, the slow pace on life duration progression leads to a densification of subjects dying simultaneously after reaching the highest ages. Similar but intensified tendencies are observed among supercentenarians resulting in the stagnation of mankind's oldest women and men—despite a sharp increase in the number of new supercentenarians.

The common trends between Olympians and supercentenarians indicate similar mortality pressures over both populations. These forces increase with age, scenario better explained by a biologic barrier limiting further life-span progression. Although this forecast may be felt to be less optimistic, to consider the line of reasoning underlying it may contribute to a better understanding of life-span trends and better prevent what may decelerate further progression.

Supplementary Material

Supplementary material can be found at: http://biomedgerontology.oxfordjournals.org/

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Conflicts of Interest

The authors confirm that there are no conflicts of interest. All authors read and approved the final version of the manuscript.

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