MORTALITY

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The heart of the matter: years-saved from cardiovascular and cancer deaths in an elite athlete cohort with over a century of follow-up

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Abstract

To quantify the years of life saved from cardiovascular (CVD), cancer and overall deaths among elite athletes according to their main type of physiological effort performed in the Olympic Games. All French athletes participating in the Games from 1912 to 2012, with vital status validated and cause of death (if concerned) identified by the national registries were included (n = 2814, 455 died) and classified according to 6 groups of effort: POWER (continuous effort < 45 s); INTERMEDIATE (45 s ≤ continuous effort < 600 s); ENDURANCE (continuous effort ≥ 600 s); POLYVALENT (participating in different events entering different classifications), INTERMITTENT (intermittent effort, i.e. team sports); PRECISION (targeting events). The theoretical years-lost method was adapted to calculate gains in longevity (years-saved) according to specific-risks under the competing risks model and was implemented in R software. Considering overall-deaths, all groups significantly saved, on average, 6.5 years of life (95% CI 5.8–7.2) compared to the general population. This longevity advantage is mainly driven by a lower risk of cancer which, isolated, contributed to significantly save 2.3 years of life (95% CI 1.2–1.9) on average in each group. The risk of CVD-related mortality in the ENDURANCE and PRECISION groups is not significantly different from the general population. The other groups significantly saved, on average, 1.6 years of life (95% CI 1.2–1.9) from CVD death. The longevity benefits in elite athletes are associated with the type of effort performed during their career, mainly due to differences on the CVD-risk of death.

Keywords Mortality · Athletes · Cardiovascular · Cancer · Years-saved · Years-lost

Introduction

Elite athletes evidence lower mortality in comparison to their counterparts in the general population [1–6]. Studies, including risk-specific mortality, show that the major causes of death—cardiovascular (CVD) and cancer diseases—tend to be lower in high level athletes [1, 2, 4, 6].

Yet, there is a lack of comprehension on the risk-specific variations through the athletes' lifespan. In addition, risk-specific mortality according to different types of physiological efforts remains unclear. Particularly, the long-term effect on the cardiovascular system of vigorous endurance disciplines (i.e., efforts of long duration requiring sustained cardiac work) is highly debated [7–14].

Quantifying the longevity gains or losses due to specific risks in different categories of physiological efforts requires new analytical approaches. So far, they have mainly been assessed by descriptive tools [1], impeding

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information on the risk variations through lifespan. A theoretical method that allows for quantifying the years-lost to specific cause of death through lifespan was conceived for clinical epidemiology [15–17]. Yet, this milestone statistical approach, based on the competing risks model, requires adaptations to allow the analyses of elite athlete cohorts that most often outlive their counterparts.

Our study has two purposes, methodological and analytical: (1) to adapt the years-lost methodology [15] in a context of a cohort that outlives the reference population; (2) to quantify the longevity gains or losses due to CVD, cancer and overall-deaths among elite athletes according to their main type of physiological effort performed in the Olympic Games.

Study design

Cohort study.

Methods

Data collection

The studied population consists of all female and male French athletes having participated at least once in the Olympic Games (OG) between 1912 and 2012, who had their vital status validated by the French National Registry of Identification of Physical Persons (RNIPP) (supplementary file). The biographical and sport data of each athlete was collected from reliable historians' sources [2, 5]. Previous studies have assured the high quality of this documentation [5, 18], including studies based on French athletes [2, 3]. Data on Olympic athletes have been gathered and archived since the rebirth of the Games in 1896. [19] The worldwide public interest in Olympic athletes is underlying the quality and the extent of the data [20, 21]. Furthermore, the data was verified with the data gathered by the French National Olympic and Sports Committee and the official websites of each French Federation, which has archived data of French athletes since their first Olympic participation. In addition to that, the vital status on January 1st, 2014 (study's endpoint) was verified for every Olympian born after 1891 (the starting time of official vital status collection in France), whose place and date of birth were known (Fig. 1). We followed the official procedures for vital status identification for all medical studies in France. The causes of death were obtained via the Epidemiological Center on Medical Causes of Death (CépiDc), which registers the causes of all deaths having occurred on French territory since 1968 [2, 4, 22]. The identified causes were classified according to the International Classification of Diseases (8th revision before 1978, 9th revision between 1979 and 1999, 10th revision after 2000).

The cohort of 2814 French Olympians (2118 male and 696 female) was then classified according to the main type of effort required for the Games events, in which they were listed.

Classification of the type of effort

In order to classify a wide diversity of sport events over the Olympic era, a constant criterion was required. Throughout the modern Games, French athletes have participated in 448 different events: some of the events had their rules changed; some sports were excluded while others were integrated later in the Olympic program. In addition, there is a large heterogeneity of disciplines, constraints and requirements within a single sport (such as athletics with runs, jumps or throws) as well as heterogeneity related to the participation of the athletes (some have participated in multiple events and some in different sports). Previous classifications reported in the literature [6, 23] could not be applied because they only classify sports existing at the present time. Each athlete was therefore classified according to the effort duration required to accomplish her/his event in the Games.

Continuous efforts were classified according to the main energy system required with threshold points based on physiological principles: the main energy pathway for exercises at near maximal intensity, shorter than 45 s is mostly anaerobic. Efforts above 45 s and up to 600 s, combine anaerobic, lactic and aerobic metabolisms. Efforts longer than 10 min are mainly aerobic [24–28].

Hence, athletes who had participated in events demanding an effort shorter than 45 s were regrouped into the category POWER. Those engaged in events lasting more than 600 s, were regrouped into the category ENDURANCE. When their effort was between 45 and 600 s, athletes were regrouped into the category INTERMEDIATE. Athletes competing in different events (e.g. 1500 m and Long Jump), or in combined events (such as Heptatlon), that qualified for various categories, were regrouped into POLYVALENT. Athletes participating in events of intermittent effort, such as team sports, were in the category INTERMITTENT. Finally, the targeting sports, such as Shooting or Archery, formed the category PRECISION. French Olympians were consequently divided into the 6 categories of effort described in Table 1.

This study was approved by the Advisory Committee on Information Processing in Research in the Field of Health (CCTIRS) and the French National Commission for Data Protection and Liberties (CNIL). No informed consent was required.
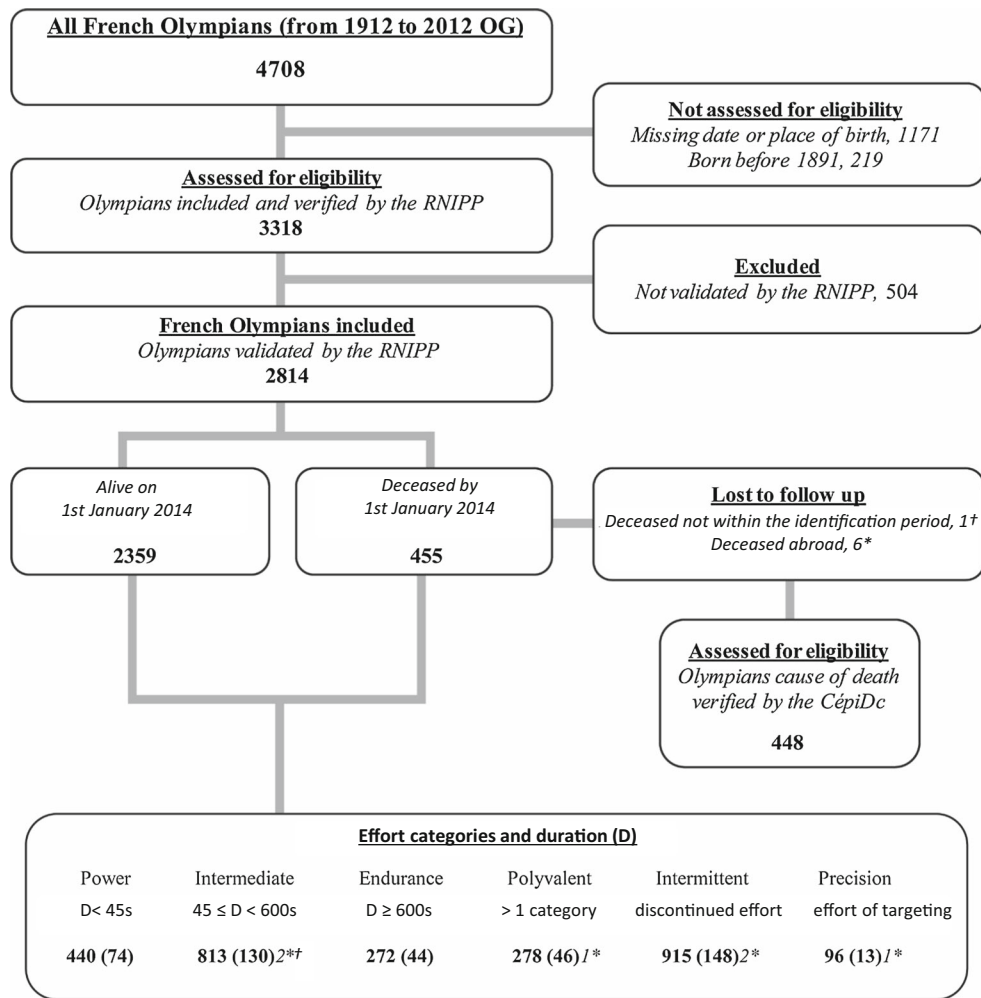
Fig. 1 Flow diagram of Olympian cohorts. () number of deceased Olympians. [†]Deceased not within the identification period. [*]Deceased abroad

Statistical analysis

The athletes were included into the study at the time of their first Olympic participation and followed up until death, up to January 1st 2014 or until the age of 90 [15], whichever came first. The upper age of 90 was chosen to insure validity of death certification [29].

The outcome of interest is the number of years of life lost or saved (YS, in direct opposition to years-lost, meaning that the studied population outlives the reference) from all causes combined (overall), CVD and cancer deaths.

The average lifetime until the age of 90 can be calculated as the area below the survival curve. Then, the average number of life years lost (by the age of 90) is the area below the estimated cumulative probability of dying [$F(t) = 1 - S(t)$] [15]. The survival curve [$S(t)$] was estimated using the Kaplan–Meier method: (1) age was used as the time scale, (2) the starting time for each individual was the time of Olympic participation, (3) all athletes were administratively censored at the age of 90 or at the age they reached by the end of 2013. This way of calculation takes into account both left truncation (not all individuals compete at the OG at the same age, so some enter later) and censoring.

When considering the number of years lost to a particular cause, the area below the cumulative incidence function [$F_k(t)$, estimated by the Aalen–Johansen method] for a certain cause was calculated [25–27]. In both cases (all-cause and cause-specific), the area is calculated under a step-wise constant function, the result is a step-wise linear function.

The athletes were then compared to the general population of the same age and sex, living in the same calendar period. Data of the general population's mortality was obtained from the French civil population mortality tables. At each age (time-scale) only individuals who were at risk at that age were considered. An individual who died or was no longer at risk did not contribute to the population mortality curve [$F_P(t)$]. The hazard of dying obtained

Table 1 Description of the Olympians cohort characteristics per category of effort

Categories	Power N = 440	Intermediate N = 813	Endurance N = 272	Polyvalent N = 278	Intermittent N = 915	Precision N = 96
Median time of effort duration* (s)	10.0	174.4	3015.0	240 [120]†	–	–
Mean age at olympics, in years (SD)	24.1 (3.7)	24.2 (5.1)	25.6 (4.4)	22.3 (4.0)	25.6 (4.1)	28.5 (7.2)
Number of deaths (%)	74 (17.0)	130 (16.0)	44 (16.2)	46 (17.0)	148 (16.2)	13 (14.0)
Mean follow-up time, in years (SD)	29.6 (20.4)	27.0 (19.3)	27.2 (18.3)	29.0 (20.4)	26.5 (19.3)	21.9 (17.2)
Female olympians (%)	26.8	27.7	21.5	33.4	19.8	25.0
Median weight (kg)	71.0	70.0	65.0	65.0	75	73

*Continuous effort only

†Polyvalent Olympians participate in events classified in different groups. The time gap between their shortest and longest effort was measured (the median of this measure is presented here, for this category only)

from the population mortality tables changes with the increasing age and calendar time for each individual, since the period of observation in this study is particularly long. These changes had to be taken into account: in addition to all the time points at which the risk set of the observed athletes changed, monthly intervals were added, thus never assuming the hazard to be constant for more than a month. The number of years lost in the population was then calculated as the area below the F_P curve. The hazard of death in the first 15 years after the Games and late mortality, from 50 years old onwards is also calculated to assess the effect of follow-up time. The difference between the average number of years lost in the population and the number of years lost by the athletes gives the number of years saved by the athletes (overall or decomposed by causes).

A Wald test was used to compare number of years lost between groups [asymptotic normality and calculation of SE established in [15], the population life expectancy was considered as given (not random)]. The confidence intervals were calculated accordingly.

All the analyses were repeated in the subsample of Olympians engaged in track and field events, in order to assess a more homogeneous cohort: this sport involves the largest number of French Olympians (n = 537); has been present since the rebirth of the modern Games, and covers all categories of continuous effort: POWER (n = 243), INTERMEDIATE (n = 139), ENDURANCE (n = 78) and POLYVALENT (n = 77).

The effect of covariates, (1) type of effort, (2) the period in which the Olympians lived, divided into quartiles, and (3) gender, was assessed using a linear regression model with years lost/saved to a certain age as the outcome.

Pseudo-observations for years lost/saved were used to enable analysis despite censored data (which relates to the data of living individuals) [30].

We accounted for the left-truncation (the athletes' entry in the cohort at different ages) by assuming that Olympians of a certain age are comparable regardless of the age they were when they first competed in the Games. The regression model analyses were performed conditional on athletes surviving to a certain age and excluding those who competed in the OG at a later age. When adjusting for covariates, the issues of informative censoring are avoided by limiting the data (and hence the calculation of pseudo-observation) only to athletes that could be observed throughout the follow-up time considered (e.g. if considering years saved between the age 50-80, only individuals who were born by the end of 1932 could be considered, to allow them to reach 80 by the end of the study).

Sensitivity analyses were performed to estimate the effect in the direction of the findings of (1) the seven deaths lost to follow-up (Fig. 1); (2) the inclusion of young Olympians in the cohort—those participating in the Games after 2000 and therefore having lower probability of death; and (3) the assumption that Olympians are comparable regardless of the age they were when they first competed in the Games.

Confidence intervals were stated at the 95% level. A 2-tailed p value < 0.05 was considered as evidence of statistical significance. Statistical analyses were carried out using R software v3.2.0. All the programs allowing to properly take into account the specificities of the studied cohort and calculate years-saved have been implemented in R software and are available upon request.

Results

Analyses were performed on 2814 French Olympians. The mean (SD) age at first Olympic participation is 24.7 ($\pm$ 4.7). The median follow-up was 52.7 years for the 455 subjects, who died before January 1st, 2014, and 20.7 years for the subjects alive at this date.

Olympians and the general population

French Olympians demonstrate significantly lower probability of death (all-causes) in comparison to their counterparts in the general population, resulting in 6.5 years of life saved in total (95% CI 5.8–7.2) until the final age-point of 90 years. Olympians start saving years shortly after the OG participation; with reduced probability of death from the first 15 years after the OG participation ($p < .001$). The longevity advantage persists even when considering only subjects from 50 years old onward, who significantly saved 4.6 years (95% CI 4.0–5.2) (Fig. 2a).

The total number of years-saved depends on the period in which the Olympians lived. By the age of 70 the first quartile of the studied cohort, consisting of Olympians aged 35 before 1968, saved 1.6 more years (95% CI 1.1–2.1) than the second quartile, i.e. Olympians aged 35 in 1968–1992. By the age of 50, the first quartile saved 0.3 more years (95% CI 0.2–0.4) than those aged 35 in 1992–2000 (Fig. 2b).

The main causes of death among Olympians are CVD (28.8%) followed by cancer (26.6%) and external causes of death (10.0%). The other causes, altogether, account for 34.5% of the total. The whole cohort of Olympians show a significantly lower risk of death due to CVD ($p < .001$) and cancer ($p < .001$), significantly saving 1.6 years (95% CI 1.2–1.9) from CVD and 2.3 years (95% CI 1.9–2.6) from cancer death until age 90 in comparison to the general population (Fig. 2b). The burden of the other causes of death altogether contribute to the remaining 2.6 (95% CI 2.2–3.2) years of life saved.

Male and female Olympians show lower probability of death in comparison to their counterparts in the general population ($p < .001$). Compared to female Olympians, male Olympians significantly saved 2.7 more years of life (95% CI 0.5–4.9) until the final age-point (Fig. 2c).

Years saved with respect to the effort performed

All categories of effort significantly saved years until the age of 90 due to a lower risk of death (all-causes) in comparison to the general population (Fig. 3a).

Regarding CVD related mortality, ENDURANCE (YS = 0.4 years; 95% CI − 1.1 to 1.8; $p = 0.60$) and

PRECISION (YS = 1.0 year; 95% CI − 1.0 to 3.0; $p = 0.32$) categories show no significant difference with the general population. All other categories significantly saved years of life until the age of 90 due to a lower risk of CVD (Fig. 3b).

Considering the risk of cancer, all categories significantly saved years of life compared to the general population (Fig. 3c).

We tested effect modification on the associations between the type of effort and the years-saved by modelling and controlling the effect of covariates (Table 2). The greater difference among the categories of effort is associated with cardiovascular longevity. The ENDURANCE category does not save years of life through cardiovascular death reduction and, according to the adjusted models performed, tends to save significantly less years in total than the other categories, especially when compared to POLYVALENT, INTERMEDIATE or PRECISION. The differences of total number of years-saved between ENDURANCE and the other categories are greater when considering the Olympians from 50 years of age onward; the larger number of deaths observed providing larger power. Regarding cancer deaths, the ENDURANCE category consistently saved years of life and, according to the adjusted models, tends to save more years than the other categories of effort (Table 2).

Athletics sub-analysis

All categories of effort present in athletic events saved years of life due to a lower risk of death (all-causes) in comparison to the general population until 90 years: POWER (YS = 7.2 years; 95% CI 5.4–9.0), INTERMEDIATE (YS = 8.7 years; 95% CI 6.8–10.5), ENDURANCE (YS = 6.3 years; 95% CI 2.6–9.9) and POLYVALENT (YS = 10.4 years; 95% CI 8.0–12.9).

Regarding CVD mortality, only the ENDURANCE category does not show significant difference with the general population (YS = − 1.8 years; 95% CI − 4.8 to 1.3; $p = 0.26$); all the other categories significantly saved years of life in terms of CVD until 90 years (Fig. 4).

Considering the risk for cancer death, all categories significantly saved years of life compared to the general population: POWER (YS = 2.6 years; 95% CI 1.6–3.7), INTERMEDIATE (YS = 1.7 years; 95% CI 0.2–3.2), ENDURANCE (YS = 4.5 years; 95% CI 3.7–5.3), POLYVALENT (YS = 3.0 years; 95% CI 1.5–4.6).

Sensitivity analyses

The relation between years-saved from all-cause and specific-cause of death within the categories of effort are similar after a sensitivity analysis including the seven
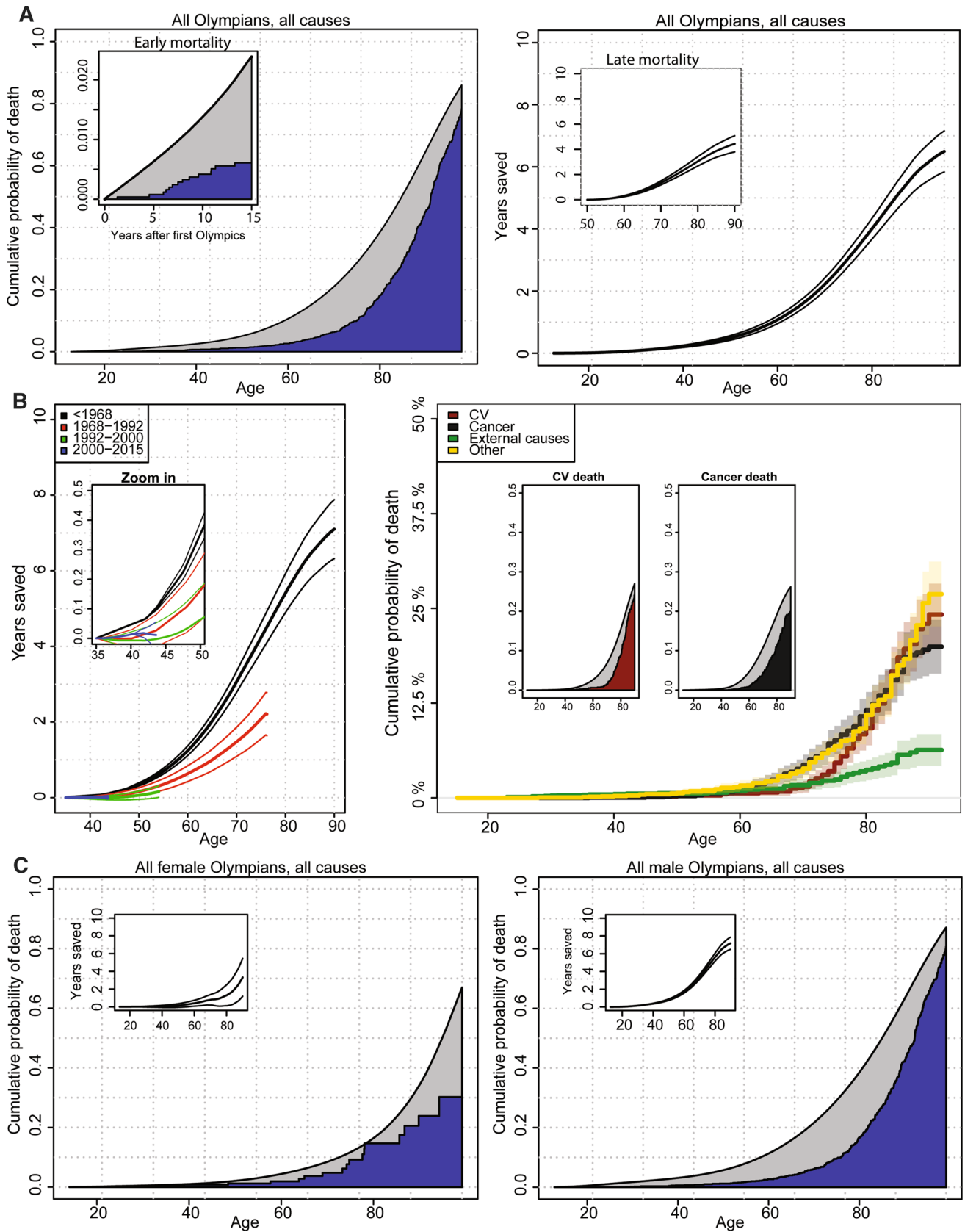
◀**Fig. 2** Probability of death and years-saved with respect to the general population. **a** row: left. Cumulative probability of death for Olympians (blue) by age in relation to their counterparts in the general population (grey). The shadow area between the curves represents the lower risk of death among Olympians. Left frame. Cumulative probability of death for Olympians within the first 15 years after the OG participation. Right. Years-saved among Olympians by age. Right frame. Years-saved among Olympians from the age of 50 onward, for individuals who were alive at 50 and took part in the OG before the age of 35. **b** row: left. Years-saved among Olympians according to the calendar year split by quartiles for individuals entering the Games before the age of 35. Left frame. Zoom in the years-saved among Olympians from 35 to 50 years according to the period of the OG participation. Right. Cumulative probability of CVD (red), cancer (black), external causes (green) and all other causes of death (yellow) among the Olympians by age. Right frame. Cumulative probability of death from CVD (red) and cancer (black) among Olympians by age in relation to their counterparts in the general population (grey). **c** row: Cumulative probability of death for female (right) and male (left) Olympians (blue) by age in relation to their counterparts in the general population (grey). Frame. The respective years-saved among Olympians by age per gender

causes of non-identified death (Fig. 1). Likewise, restricting the cohort to Olympians competing before 2000 did not alter the results. We tested the assumption made to deal with the left-truncation parameter and observed that Olympians are comparable regardless of the age they were when they first competed in the Games.

Discussion

Adapting the years-saved method in a cohort of elite athletes provided three major findings. First, French Olympians, regardless of the type of effort performed in the Games saved years of life in comparison to the general population, 6.5 years-saved on average. Second, the main contribution to Olympians greater longevity is a lower risk of cancer, which, isolated, explains almost one third (2.3 years) of the years-saved in each effort category. Third, cardiovascular longevity benefits are more heterogeneous: reduced risk of CVD related mortality contributed to years-saved among Olympians in the categories of POWER, INTERMEDIATE, POLYVALENT, and INTERMITTENT efforts, but not in the category of PRECISION, nor ENDURANCE resulting in less years-saved in total among the Olympians participating in endurance efforts. Despite such heterogeneity, no risk (related to cause of death, age or type of effort) was prominent enough to completely jeopardize the global longevity benefits of Olympians.

Olympians longevity

Our findings suggest that either intense training at an early age has positive longlasting effects on health or that the selective methods of detection and training (including resilience to this intense process) select athletes with predisposition associated with survival advantage. Both however contribute to the health benefits that vary according to the types of activity performed.

The advantage of the Olympians over the general population may be interpreted in light of a selection effect. Recent studies have related fitness and genetic predisposition to greater longevity, and human performance has been shown to be a strong predictor of mortality [31–33]. Nonetheless, the differences found relating type of effort and cardiovascular longevity show that the physical activity practiced by elite athletes may actually play a major role on their lifespan, besides solely genetic background or healthy lifestyle [34, 35], commonly put forward to explain the athletes' survival advantage.

First, athletes are probably healthier: individuals who die at an early age often have a condition that does not allow them to become athletes. Also, few athletes may come from deprived socio-economical environments, so, a comparison to the general population mortality may not be the most appropriate method. We do not have the data to test the latter effect, but the extent of the former may be much lower than expected in light of the persistent advantage displayed by Olympians, when analysed from the age of 50 onward.

There is also no evidence of a greater mortality among Olympians shortly after the OG participation, contrary to what was found in elite road cyclists [4]. Even though the mortality rates among youth in the general population is very low, the athletes still survive better. Similarly, female Olympians also show a survival advantage over women of the general population, despite the low mortality rates (when compared to men). The difference in mortality rates in the general population, in addition to a shorter follow-up of female Olympians (up to 1948, very few women participated in the OG) may explain the greater amount of years-saved among male compared to female Olympians. Similarly, the earlier Olympians could save more years than later ones, as the mortality rates in the general population were higher.

Finally, the differences found relating type of effort and cardiovascular longevity show that the physical activity practiced by elite athletes may actually play a major role on their lifespan.
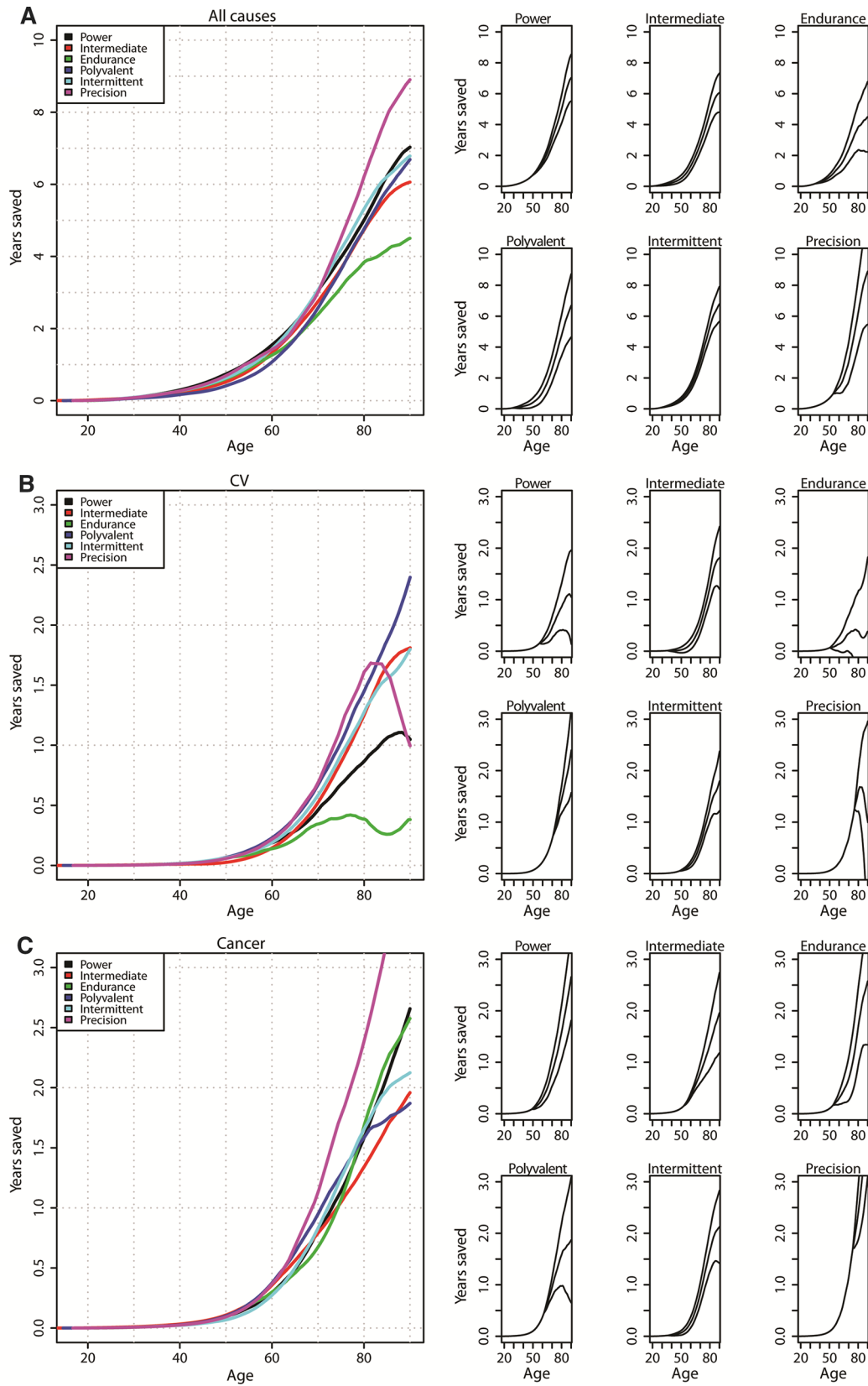
Fig. 3 Years-saved from **a** all-causes, **b** CVD and **c** cancer deaths according to the Olympians' type of effort by age. At right, every curve of years-saved is represented with its confidence interval for each graph

Table 2 Years-saved according to the main effort performed in the Games

	YS (95% CI)	Difference in YS compared to Endurance category (95% CI)				
	ENDURANCE	POWER	INTERMEDIATE	POLYVALENT	INTERMITTENT	PRECISION
MODEL 1						
N = 1273 (Deaths)	131 (28)	210 (38)	353 (62)	123 (23)	415 (70)	41 (4)
All−causes	4.5 (3.7 to 5.4)*	0.1 (−0.9 to 1.1)	0.9 (0.1 to 1.8)*	0.9 (−0.1 to 1.9)	1 (0.1 to 1.8)*	1.3 (0.3 to 2.3)*
CVD	0.2 (−0.6 to 1)	0.4 (−0.6 to 1.4)	1 (0.1 to 1.8)*	1 (0.1 to 1.9)*	0.9 (0.1 to 1.8)*	1.2 (0.2 to 2.1)*
Cancer	1.3 (0.4 to 2.1)*	0.1 (−9 to 1.1)	−0.3 (−1.3 to 0.7)	−0.1 (−1.2 to 1)	0.2 (−0.7 to 1.1)	0.6 (−4 to 1.7)
MODEL 2						
N = 2127 (Deaths)	204 (23)	349 (35)	615 (59)	217 (26)	696 (70)	46 (46)
All− causes	6.4 (5.5 to 7.3)*	0 (−1.1 to 1.1)	0.5 (−0.5 to 1.5)	0.9 (−0.2 to 1.9)	0.7 (−0.3 to 1.7)	1.1 (−0.1 to 2.3)
CVD	0.5 (−0.4 to 1.4)	0.4 (−0.7 to 1.4)	0.7 (−0.3 to 1.6)	1 (0.1 to 2)*	0.7 (−0.3 to 1.6)	1.1 (0.1 to 2.1)*
Cancer	1.8 (0.9 to 2.7)*	−0.4 (−1.5 to 0.7)	−0.6 (−1.6 to 0.4)	−0.3 (−1.5 to 0.9)	−0.2 (−1.2 to 0.8)	−0.2 (−1.5 to 1.1)
MODEL 3						
N = 470 (Deaths)	39 (17)	91 (29)	127 (43)	50 (16)	149 (54)	14 (1)
All−causes	3.9 (2.3 to 5.4)*	1 (−0.7 to 2.4)	1.6 (0.1 to 3.1)*	1.6 (0.1 to 3.1)*	1.5 (−0.1 to 3)	1.7 (0.1 to 3.3)*
CVD	0 (−1.5 to 1.4)	0.7 (−0.9 to 2.4)	1.5 (0.1 to 3)*	1.6 (0.1 to 3.1)*	1.4 (−0.1 to 2.9)	1.7 (0.1 to 3.3)*
Cancer	2.4 (2.4 to 2.5)*	−0.8 (−1.3 to 0.3)*	−1 (−1.5 to 0.4)	−1 (−1.8 to −0.3)*	−1 (−1.6 to −0.5)*	0 (−0.1 to 0.1)
MODEL 4						
N = 388 (Deaths)	30 (13)	78 (24)	107 (37)	50 (16)	118 (45)	5 (0)
All−causes	6.3 (4.5 to 8.1)*	0.7 (−1.3 to 2.6)	1.4 (−0.3 to 3.1)	1.4 (−0.3 to 3.1)	1.2 (−0.6 to 2.9)	1.9 (0.2 to 3.6)*
CVD	0.5 (−1.2 to 2.2)	0.4 (−1.5 to 2.3)	1.3 (−0.4 to 3)	1.4 (−0.4 to 3.1)	1.1 (−0.7 to 2.9)	2 (0.2 to 3.8)*
Cancer	2.8 (2.7 to 2.8)*	−0.9 (−1.4 to −.3)*	−1.1 (−1.7 to −0.5)*	−1 (−1.8 to −0.3)	−1.1 (−1.7 to − 0.5)	−.1 (−0.2 to 0.1)

YS years-saved

Shaded blue*: significant ($p < .05$) number of YS compared to the general population. Shaded green*: significantly ($p < .05$) more YS compared to the Endurance category. Shaded orange*: significantly ($p < .05$) less YS compared to the Endurance category. Model 1: Olympians that entered the Games before 50 years of age, survived at least until the age of 50, followed up to 80 years of age, unadjusted. Model 2: Olympians entered the Games before 30 years of age, survived at least until the age of 30, followed up to 80 years of age, unadjusted. Model 3: Olympians entered the Games before 50 years of age, were at least 50 years old by the end of 1982, adjusted for gender, calendar year, and followed up to 80 years of age. Model 4: Olympians entered the Games before 50 years of age, were at least 30 years old by the end of 1962, adjusted for gender, calendar year, and followed up to 80 years of age

Longevity benefits and type of effort

The longevity of the cardiovascular system was found to be associated with the type of effort performed in the Games and seem to illustrate an optimal relation: Olympians combining different types of effort, saved more years from CVD, such is the case of sports of intermediated duration, like middle distance runners, or intermittent sports, like collective events, or polyvalent Olympians, who were engaged on different events. Efforts of very short or very long duration confers little to no gains, which are the cases of ENDURANCE and PRECISION categories. While the findings in the PRECISION category may be interpreted in light of the limited statistical power, only ENDURANCE significantly saved less years of life in total compared to the other categories. The findings on a more homogeneous track and field cohort are consistent with the findings on the whole Olympian cohort: the athletes saved around 8 years of life in total, but the number of years-saved among endurance runners could not be attributed to greater cardiovascular longevity.

Excessive endurance exercise has been suggested to provoke cardiac overuse injury, based mainly on clinical findings, animal overuse models, or dose–response studies based on the general population [9, 11–13, 36–45].

Some suggested mechanisms to the adverse cardiac effects include increased vascular oxidative stress and inflammation, myocardial fibrosis, functional and structural remodelling of the heart [46]. A question currently debated is whether the excessive endurance training jeopardizes the overall benefits of physical activity [10, 47, 48]. Our findings, based on the far end of a dose–response relationship, show that even in the absence of long-term cardiovascular advantage, endurance athletes saved years of life. In addition, endurance Olympians seems to benefit the most of reduced cancer risk. However, further research is certainly needed since the regression model results are based mostly on men who competed in earlier Games.
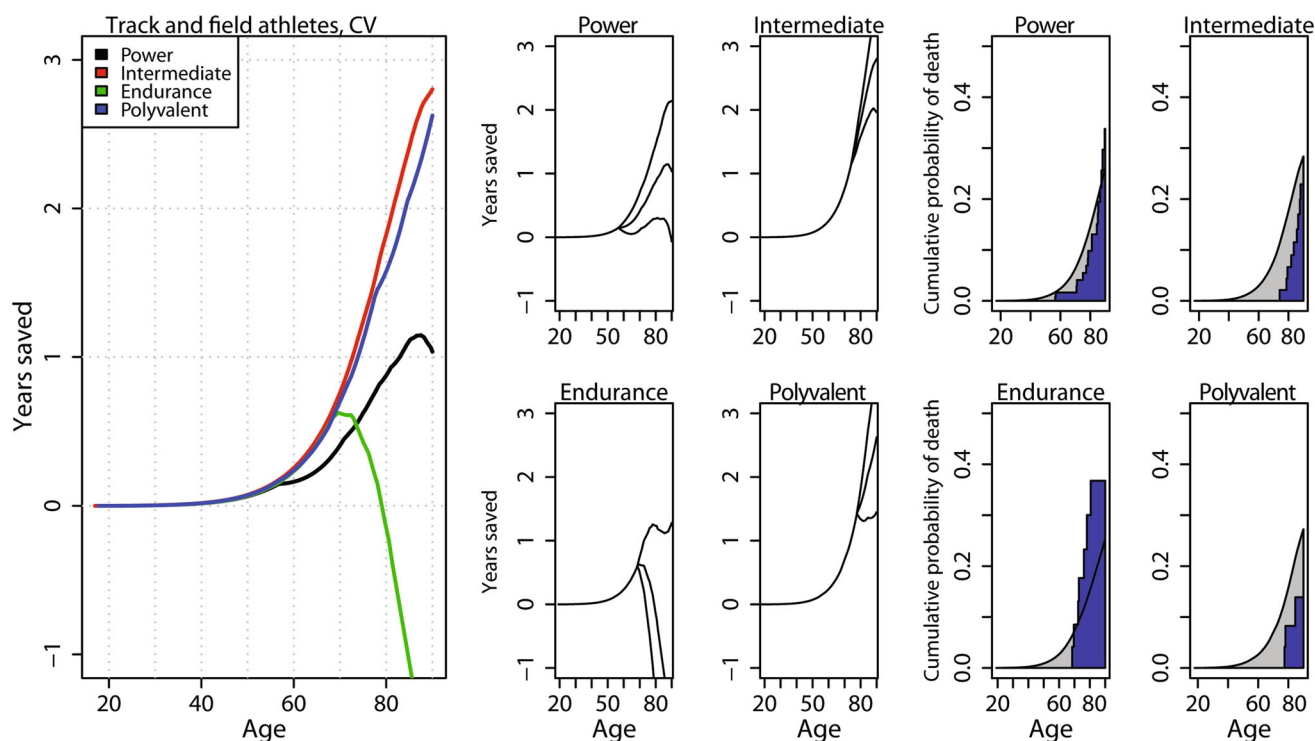
Fig. 4 Left. Years saved from CVD deaths according to the type of effort performed by athletes in track and field events by age. Center. 95% Confidence interval for each years-saved curve on the left. Right. Cumulative probability of death for athletes (blue) by age in relation to their counterparts in the general population (grey) for each category of effort in track and field events

Also, well controlled intervention studies in the general population are important given the growing number of intense endurance practitioners worldwide [46, 49]. Even though the doses of training among amateurs are lower than among Olympians, people less predisposed to sports or with less technical and medical surveillance may potentially be more vulnerable to adverse cardiac effects [10, 43, 50, 51].

In light of the current findings, it may be of interest of endurance athletes aiming for cardiovascular benefits, to combine different types of training post-career, adhering to the Physical Activity Guideline Recommendations [52].

Methods considerations

To the best of our knowledge this is the first study isolating the long-term consequences on the cardiovascular system of being an elite athlete. The relevance of such historical cohort is highlighted by our findings, since significant differences among groups of effort appears later on in an athletes' life. Past studies assessing CVD mortality in elite endurance athletes [1, 3, 4, 6, 53, 54] have shown a lower cardiovascular mortality among them with respect to the general population or healthy controls, through indirect standardization of mortality. Although this is a classical and reliable method [55], it is a transversal measure that

does not capture the time or age dependence. The few studies investigating CVD-risks among athletes in different sports, found the highest life expectancy among endurance athletes [5, 6, 54]. To assess the effect of a specific-risk on life expectancy by comparing life expectancy with and without that risk rely on the unverifiable assumption that the causes of deaths are independents of each other, what could be underlie the contrasting findings.

We extended the decomposition of years-lost by cause of death to the context of years-saved providing confidence intervals, which facilitate its use. The years-saved method under competing risks provides a meaningful interpretation of longevity findings [15, 26] with the additional attractiveness of its positive output. This method allows for isolation of the burden of a given disease, preserving the coherence that the sum of the years-saved by each cause corresponds to the total number of years of life saved. The regression model coefficients are particularly intuitive, since they directly describe the average number of years-saved due to a certain covariate.

Several adaptations of the years-lost methodology [15] were required to broaden its use. These were mainly in view of the uniqueness of elite athlete cohorts, which was followed over a century and required specific methods to handle left-truncation, and to compare it with the general population in which the mortality had substantially

changed along the observation period. Some theoretical limitations were also revealed: pseudo-observations, which are the basis for the regression modelling, cannot handle left-truncation and the informative censoring with respect to year of entry could not be adjusted.

Limits and strengths

The type of training endured before the Olympics could only be indirectly assumed according to the effort duration at the Olympics. However, such training was successful enough for the athletes to reach the top world performances which may not have been possible without a great amount of very specific training, usually 10,000 h prior an Olympic participation [56]. A second limit is related to the Olympians post-career lifestyle: physical activity habits and life risk factors remain unknown. Worth note, exercising 150 min/wk as recommended [52] from the age of 30 to 80 years corresponds to a total of 0.74 years of life exercising [46]. Before their first Games, usually before 25 years old, Olympians have already spent, on average, 1.14 years of their life practicing. Finally a third limit regards the underlying genetic predisposition that might also contribute to their longevity and the extent of it that contributes to their survival advantage is still unknown.

The strengths of this study include the robust methodology adapted and applied to investigate the longevity of a physically active cohort; this allowed for distinguishing specific gains among overall benefits and provided results that are easily comparable for future studies. In addition, the findings rely on an extensive cohort follow-up, with death certification, and a focus on athletes of the highest level, among whom the impacts of intense training are maximal.

Perspectives

The year-saved method may benefit future studies investigating healthy behaviours promoting life advantage, assessing longevity gains rather than losses. The relation between type of physical activity and specific health benefit needs to be better understood to strengthen recommendations and screening of competitive athletes, and for a relevant public health approach specifying exercise prescription [57]. These novel findings require replication in other elite populations, especially regarding endurance athletes and CVD mortality.

Conclusion

The longevity benefits in elite athletes are associated with the type of effort performed during their Olympic career: all groups of Olympians saved years of live compared to the general population, 6.5 years-saved on average, mainly driven by a lower risk of cancer death but, contrary to other groups of effort, the years-saved among Olympians engaged in endurance events is not explained by the avoidance of cardiovascular death. The years-saved method enables the analysis of the burden of a specific disease over the lifespan of individuals in cohorts that outlive the reference.

Compliance with ethical standards

Conflicts of interest The authors declare that they have no conflict of interest.

Ethical approval All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards.

Formal consent For this type of study formal consent is not required.

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