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Original Article

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Abstract

Maximal physical performances are powerful and accurate biomarkers in the understanding of age-related changes during the aging process. Previous studies have characterized age-related changes from *Caenorhabditis elegans* to *Homo sapiens*. We characterized changes in this pattern for *H. sapiens*, decade by decade, from 1970 to 2017. Using 286,916 performances related to age from the world's best performances in each age group, we measured the relative change of 10 different running and jumping events for both women and men. We compared the change in sexual dimorphism with age and showed that the gender gap in maximal performance regarding age increases gradually, especially after the age of 50. Between 1970 and 2017, the performances for all age groups in all events have slightly progressed. However, during the last decades, the relative progression of the best performances for all age groups has decreased in both range and frequency, suggesting that age-related maximal physical performances for *H. sapiens* are reaching their physiological limits.

Keywords: Age-related changes, Age-related physical performance, Master athletes, Maximal sport performance, Upper limits

Physical exercise is a key ingredient of an extended health span (ie the duration of life "in which autonomy, control, independence and well-being are maintained") (1–4). Since the seminal works of A. V. Hill and D. B. Dill, exercise physiology has provided major insights in the understanding of human biology, its adaptation, and its changes with time (4–10). In this regard, the quantitative measurements of physical exercise, and especially maximal physical performances, accurately reflect age-related changes and the aging process (2,7,8). A wide range of elements interact together at different neurophysiological levels to define the optimal chronometric and measured physical performance (5–7,10). Therefore, speed, strength, or endurance are accurate integrated biomarkers in the understanding of age-related changes (2,6,7,9–11).

Previous studies have precisely characterized age-related changes in maximal physical performances throughout the aging process or even during the entire life span (7–13). Investigation throughout the entire life span offers the advantage of a complete view of age-related changes, preventing methodological and theoretical misconceptions about the dynamics of aging. In this regard, the pioneering work of Moore (9) characterized a unique age-related pattern with a gradual progression of maximal physical performances during childhood and adolescence up to a peak between 20 and 30. This progression was then followed by an exponential decline associated with the aging process (9). Analysis of such a pattern in highly trained athletes represents a unique model for the ideal age-related changes during the normal aging process, without these factors being confounded by concomitant disease, as only the best human performances are taken into account (4,13). In fact, this age-related pattern was found not only at both population and individual levels within highly trained athletes, but also in the general population during both cross-sectional and longitudinal studies in a wide range of physical and cognitive parameters (10,11,14). Such patterns were also observed in many different species from *Caenorhabditis elegans* to *Equus caballus* (10).

The last century was a unique period of energetic, scientific, medical, social, nutritional, and industrial improvements that contributed to major health benefits and to the rise, generation after generation, of stronger, taller, healthier, and longer-lived humans (15–18). Such progress has directly impacted the age-related upper limits of physical performances. First, following the Olympic motto "*Citius, Altius, Fortius*," all chronometric and metric world records for youth and elite categories showed considerable improvements (5,18). Professionalization of sports led to an optimization of training methods, nutrition, recovery techniques, and strategies, as well as new technological innovations dedicated to performance (5,19). Meanwhile, democratization of sport increased the population size from which optimal performance could be selected (5,19). Both contributed to the improvement of maximal physical performance in youth, elite, and also in master athletes (athletes older than 35 years) (5,20,21).

Master-level sports and competitions have been markedly developed during the last decades with a growing number of older athletes competing: 1,400 athletes from 32 countries participated in the first World Master Athletics Championships in 1975 and more than 8,085 from 98 countries in 2015 for the 21st edition (20,21). The favorable context of the 20th century increased the health span by delaying the age of onset of chronic diseases and disability and consequently stimulating the gradual progression of physical performances at an advanced age (1).

However, a growing body of evidence suggests that physical performance as well as average height and maximal life span have recently plateaued (18,22–25). Here, using a data set of 286,915 performances related to age, we characterize the progression of age-related performance in 10 different running and jumping events for both women and men over the last four decades. We then measure the relative progression for each age group decade after decade and demonstrate a recent slowdown in the best performance progression rate, likewise for the oldest age group. Finally, we investigate the sexual dimorphism during this period; we show an increase in the gender gap with age, but a reduction of this difference between women and men in the last decades.

Methods

Data

A data set consisting of 286,916 performances was built. All data were collected from the following specialized websites: www.iaaf.org, http://www.mastersathletics.net, http://age-records.125mb.com/, www.all-athletics.com/, and www.tilastopaja.eu. The data set contained the best performances in all age groups from 1970 to 2017 for 10 running and jumping events for both women and men, the running and jumping events included the following:

Men's 100 m event: 23,668 performances
Men's 400 m event: 24,068 performances
Men's 800 m event: 21,880 performances
Men's 1,500 m event: 21,705 performances
Men's 5,000 m event: 22,808 performances
Men's 10,000 m event: 19,965 performances
Men's high-jump event: 13,695 performances
Men's pole-vault event: 12,555 performances
Men's long-jump event: 14,481 performances
Men's triple-jump event: 13,572 performances
Women's 100 m event: 11,071 performances
Women's 400 m event: 7,683 performances
Women's 800 m event: 7,600 performances
Women's 1,500 m event: 7,559 performances
Women's 5,000 m event: 22,109 performances
Women's 10,000 m event: 7,102 performances
Women's high-jump event: 10,915 performances
Women's pole-vault event: 2,872 performances
Women's long-jump event: 10,770 performances
Women's triple-jump event: 10,838 performances

Racing times were converted to average running speed in meters per second. We did not analyze data from throwing events as weights from thrown objects vary according to the age-group category.

The dynamics of progression were analyzed for each event. For each decade since 1970, the best performance for each age was selected (before 1970, the range of data was too limited to characterize the dynamics, due to the absence of official competitions for master athletes). Then, the Moore equation was used to characterize the age-related pattern by decade. The relative change (in %) was precisely calculated for each decade. To increase the accuracy of this measurement, master athlete ages were grouped every 5 years following the International Association of Athletics Federations classification beginning with the 35–39 category up to the 100+ category. We completed the analysis by adding four younger categories: 15–19 years, 20–24 years, 25–29 years, and 30–34 years.

The relative change for the different categories was precisely calculated for each decade, which means that the relative percentage between the best performance of each age group recorded during the decade was compared to the past all-time best performance.

Age-Related Pattern Characterization

Data selection

For all events, in each decade, we determined and selected the single best performance for each age among all the individuals.

Estimating the age-related pattern

Data were fitted with the Moore equation using MATLAB software (9–11):

$$P(t) = a\left(1 - e^{-bt}\right) + c\left(1 - e^{dt}\right) \text{ with } a,b,c,d > 0$$

where $P(t)$ is the performance (t is the age), a and c are scaling parameters, and b^{-1} and d^{-1} the characteristic times of the exponential growth and decline. Coefficients were determined using a least-square nonlinear regression (more details in Berthelot and colleagues (11).). The quality of each fit was estimated by the coefficient of determination R^2 and the root mean square error (see details in Supplementary Material).

Relative Progression by Age Group Decade After Decade

We grouped all data into 5-year age groups from 15–19 years to 100–104 years. Then, for all age groups, we calculated the relative progression (in %) between the best performance (*bp*) of the decade and the previous all-time best performance (*at*) using the following formula:

$$\text{Relative progression (in\%)} = \left(\frac{bp - at}{at}\right) * 100$$

Gender Difference in 1990 and 2017

We calculated the relative difference (in %) between women (*w*) and men (*m*) for each age group regarding the all-time best performance in 1990 and then in 2017 using the following formula:

$$\text{Relative difference (in\%)} = \left(\frac{m - w}{w}\right) * 100$$

Results

The Moore equation was adjusted for each event as well as gender. These adjustments revealed a similar age-related pattern (Figure 1, see details in Supplementary Material). However, this progression is not constant nor similar for every age group. The relative change (in %) for the different categories was specifically calculated for each decade (Tables 1A–D and 2A–D). Results showed a gradual slowdown in the relative progression of the best performance in each age group.

There is a wide difference in relative progression regarding the events and the age groups for women. The average relative progression showed that the improvement of the performance for youth and elite female athletes (age groups between 15 and 34 years) gradually decreased from a major improvement during the 1980s to either a minor improvement and, on occasion, to a performance regression during the last period (2000–2017).

For these age groups during the 1980s, 82.6% of maximal performances had a relative progression compared to the past best all-time performance: maximal performances progressed extensively with many new all-time records for different events and age groups. On the contrary, 64.1% of the best performances during the 2000–2010 period showed a relative regression: these performances did not improve in comparison with the best all time performances achieved prior to this period. In the 35–39 to the 50–54 women's age groups, the peak of improvement is seen in the 1990–2000 decade. Then, similarly, there is a decline in improvement with a regression of 37.5% of the best performances. Finally, for older age groups (60–64 years to 90–94 years), major relative improvements were recorded during the 2000–2010 period, with significant improvements related to particular individuals. During the 2000–2010 period, 13.6% of the best performances for these age groups also experienced a regression.

For men, most age groups (from the 15–19 to the 100–104 group) followed a progressive drop from positive relative progression during the 1980s to either a minor progression or regression during the last period (2000–2017). From 1980 to 1990, 85.0% of all men's best time performances progressed for all age groups and events. Conversely, from 2000 to 2010, 46.2% experienced a regression (67.5% of the young elite men's age groups—from 15 to 34 years—and 39.2% for the older groups).

Regarding the changes in sexual dimorphism in running and jumping events, results showed that gender gaps have remained similar in elite athletes during the last 30 years (Figure 2). However, the difference in maximal performance changes regarding age increases gradually, especially after the age of 50 (Figure 3).

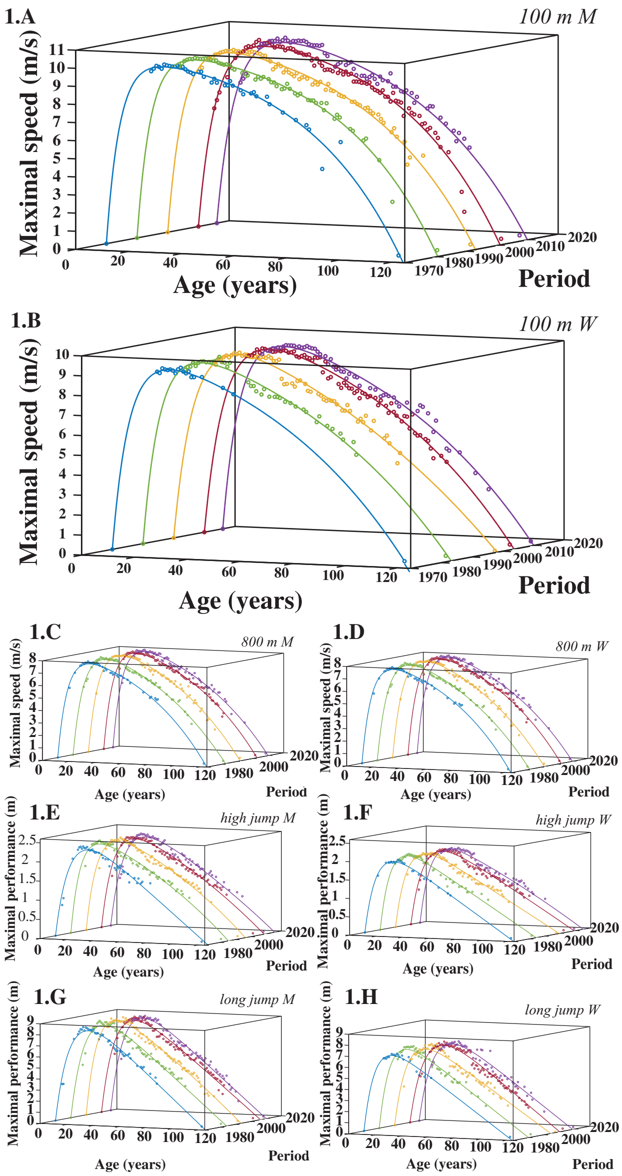

Figure 1. Best performance by age progressively delineates a similar age-related pattern toward the potential upper physiological limits. Age-related changes for maximal performance by age were characterized using the Moore equation decade by decade for 10 events including men's 100 m event (**A**), women's 100 m event (**B**), men's 800 m event (**C**), women's 800 m event (**D**), men's high-jump event (**E**), women's high-jump event (**F**), men's long-jump event (**G**), and women's long-jump event (**H**). Best performances by age are represented by the corresponding colored lines online: blue until 1980, green until 1990, orange until 2000, red 2010, and purple until 2017.

This difference is currently from 8.9% to 14.2% in elite athletes depending on the running event and varies from 18.8% to 69.3% in master athletes older than 80. The difference is greater in jumping events: 15.6% to 21.1% in elite athletes and 21.8% to 50.3% in master athletes over the age of 80. Overall, the gender gap for all age groups after 40 years old decreased between 1990 and 2017. On average, in all events studied, only the 15–19 and 30–34 year age groups had a minor increase in the gender gap, +0.04% and +0.27%, respectively. On the contrary, for all age groups over 40, the reduction is, on average, more than 4% and this reduction changes with age from –4.7% for the 40–44 age group to –13.0% for the 80–84 age group.

Table 1. Recent Relative Progression in Percentage (%) for Maximal Performance Per Age Group by Period in Male Athletes

Relative Progression (%)	Age Group (year)																		
		15–19	20–24	25–29	30–34	35–39	40–44	45–49	50–54	55–59	60–64	65–69	70–74	75–79	80–84	85–89	90–94	95–99	100+
Between 1980 and 1990																			
	100 m	0.20	0.50	0.91	1.80	0.19	0.00	−0.92	3.35	1.77	−1.67	—	6.13	6.72	—	−4.00	—	—	—
	400 m	2.67	2.68	0.20	0.56	1.12	3.41	1.29	1.32	3.88	—	—	3.86	0.44	—	—	—	—	—
	800 m	0.61	1.29	1.67	0.87	−1.97	2.67	1.40	0.58	3.06	—	3.42	−0.51	−4.93	—	—	—	—	—
	1,500 m	0.78	0.14	0.91	1.62	3.97	1.10	1.66	3.26	1.29	0.13	6.13	0.67	—	—	—	—	—	—
	5,000 m	1.16	0.71	1.29	0.95	−0.01	−3.82	3.80	2.76	1.11	0.21	4.86	4.12	3.48	—	—	—	—	—
	10,000 m	4.49	0.55	0.87	1.01	1.54	−2.39	0.79	1.24	0.50	−0.34	2.44	6.13	1.24	10.99	—	—	—	—
	High jump	0.85	3.39	4.80	6.31	−0.46	0.98	5.26	7.43	5.92	4.40	3.33	0.68	—	—	—	—	—	—
	Pole vault	3.39	4.51	4.84	3.71	6.04	8.54	0.00	3.04	−2.91	−2.05	4.72	−6.36	—	—	—	—	—	—
	Long jump	−0.72	3.75	4.78	8.44	3.15	2.29	8.83	3.74	−4.76	—	5.23	—	12.47	—	—	—	—	—
	Triple jump	0.57	0.17	3.04	1.85	5.29	5.30	2.01	7.90	2.06	2.02	—	—	—	—	—	—	—	—
	Mean progression	1.40	1.77	2.33	2.71	1.89	1.81	2.41	3.46	1.19	0.39	4.31	1.84	3.24	—	—	—	—	—
Between 1990 and 2000																			
	100 m	−0.10	0.71	1.33	1.83	3.42	0.94	−1.82	−1.87	−2.33	0.85	−0.48	−1.47	−1.76	7.32	1.87	—	—	—
	400 m	−1.77	−0.48	1.80	3.84	−0.24	−0.48	1.14	0.41	−0.98	2.52	6.69	1.80	1.94	−0.26	3.62	0.33	—	—
	800 m	0.07	−1.56	0.59	0.98	5.65	0.75	0.09	1.47	0.30	1.69	4.59	10.00	−1.45	−4.88	0.61	4.25	—	—
	1,500 m	0.94	2.75	1.09	−0.38	0.69	2.04	0.39	−1.53	0.72	−1.26	0.70	4.06	2.29	−5.07	−3.75	0.35	—	—
	5,000 m	3.11	3.68	2.51	2.22	0.40	0.30	−2.16	1.16	0.07	1.92	3.50	1.08	2.99	−6.01	7.94	13.14	—	—
	10,000 m	0.41	3.15	2.87	0.95	−1.58	0.15	−2.02	2.60	−0.39	0.40	4.26	0.14	−2.40	−7.51	2.91	14.95	—	—
	High jump	0.00	−1.64	2.08	0.42	5.09	3.86	−1.00	6.38	2.23	3.61	7.10	2.70	−1.39	7.20	6.19	—	—	—
	Pole vault	1.72	0.00	1.16	4.60	4.09	5.57	8.51	3.86	3.40	0.26	−4.24	−4.24	5.17	—	—	—	—	—
	Long jump	5.40	−1.35	2.17	1.49	3.79	−0.79	−0.28	2.70	0.79	−3.29	−1.10	4.64	−3.97	6.08	14.33	—	—	—
	Triple jump	−1.20	0.00	1.78	2.49	−3.71	5.61	10.01	−3.41	7.53	4.53	7.57	3.11	−3.48	7.96	—	—	—	—
	Mean progression	0.86	0.53	1.74	1.84	1.76	1.79	1.29	1.18	1.14	1.12	2.86	2.18	−0.21	0.53	4.22	6.60	—	—
Between 2000 and 2010																			
	100 m	1.21	2.92	1.03	−0.30	−0.60	3.31	0.75	0.73	0.36	−2.26	4.25	0.95	−1.03	0.35	−0.81	3.14	—	—
	400 m	−1.77	−0.37	−1.50	−2.70	1.55	0.10	−0.68	−0.04	0.54	−0.76	1.60	2.97	2.45	6.80	9.69	26.11	—	—
	800 m	0.89	0.00	−1.37	−0.29	−1.90	1.73	1.73	−0.13	0.80	−0.67	−0.80	−3.23	4.94	0.27	4.68	9.54	—	—
	1,500 m	1.27	−1.44	0.53	1.14	−0.03	1.01	4.28	−0.25	−2.06	0.38	−1.92	−2.02	0.83	−1.28	6.26	15.61	—	—
	5,000 m	0.14	0.32	−1.32	−0.54	1.52	−1.20	−1.22	0.27	0.50	−0.40	−6.83	0.11	4.63	−3.35	−0.31	5.92	—	—
	10,000 m	1.84	0.88	−0.20	1.83	1.63	−0.16	−1.45	0.36	0.58	−1.11	−5.88	0.86	6.69	−3.65	−8.92	−10.21	—	—
	High jump	0.00	−2.46	−2.86	0.00	1.76	0.00	2.00	−5.00	1.09	4.65	−1.20	4.61	0.69	0.75	1.67	10.58	13.95	—
	Pole vault	−1.69	−0.33	−1.31	−2.12	0.51	3.82	0.78	7.22	7.98	3.58	0.27	3.03	0.00	9.56	7.02	14.38	—	—
	Long jump	−5.92	−3.27	−2.46	−1.47	−4.71	1.05	−0.41	−3.80	−2.36	−0.49	0.74	0.58	1.05	4.06	0.53	—	—	—
	Triple jump	−1.09	0.33	−2.13	−1.55	2.22	−7.30	−3.01	2.63	−7.36	−2.13	−2.76	0.94	−2.49	−1.23	3.29	9.65	—	—
	Mean progression	−0.51	−0.34	−1.16	−0.60	0.20	0.24	0.28	0.20	0.01	0.08	−1.26	0.88	1.78	1.23	2.31	9.41	—	—

Table 1. Continued

Relative Progression (%)		Age Group (year)																	
		15–19	20–24	25–29	30–34	35–39	40–44	45–49	50–54	55–59	60–64	65–69	70–74	75–79	80–84	85–89	90–94	95–99	100+
Between 2010 and 2017																			
	100 m	1.21	2.92	1.03	−0.30	−0.60	3.31	0.75	0.73	0.36	−2.26	4.25	0.95	−1.03	0.35	−0.81	3.14	—	—
	400 m	−0.79	0.60	−0.53	−1.51	2.56	1.83	1.63	1.30	−3.53	−3.23	0.16	-7.71	4.65	0.86	1.90	1.06	—	65.54
	800 m	0.97	0.10	-1.08	-0.97	-0.64	0.70	3.93	-0.57	1.70	1.45	-2.78	-9.02	1.25	0.27	6.51	11.77	—	—
	1,500 m	0.68	-0.83	-0.28	-0.68	-4.05	0.35	-0.08	2.91	0.06	1.38	-2.16	1.60	-0.72	2.06	2.87	6.58	—	46.32
	5,000 m	0.66	-1.23	-1.55	0.03	1.00	4.62	1.47	0.03	0.79	-4.36	-6.99	1.63	-8.08	3.87	3.30	4.75	—	—
	10,000 m	-0.86	-1.65	-1.28	-1.26	-1.65	2.49	1.02	0.34	1.87	0.85	-3.70	-3.30	-6.78	4.27	3.37	-22.08	—	—
	High jump	-1.69	-0.41	-1.22	0.00	0.00	6.05	0.49	-2.50	2.70	0.56	1.20	-1.26	4.83	2.22	2.46	-8.70	—	—
	Pole vault	0.00	0.00	-1.31	-2.61	0.34	-8.41	-6.61	-2.86	-3.91	-7.41	2.91	2.65	5.90	-12.73	-6.56	12.02	—	—
	Long jump	-5.01	-3.16	-3.35	-4.28	-5.53	-3.12	-3.85	-4.53	-3.31	-4.94	0.18	-3.45	-1.45	-11.24	0.00	-14.72	—	—
	Triple jump	1.09	0.56	-0.44	-1.77	-2.18	4.46	-10.45	-8.03	2.02	-5.52	-5.36	1.77	0.50	1.01	-13.10	-19.42	—	—
	Mean progression	-0.37	-0.31	-1.00	-1.33	-1.07	1.23	-1.17	-1.32	-0.12	-2.35	-1.23	-1.61	-0.09	-0.91	0.00	-2.56	—	—

Note: Relative progression (in %) between the best performance of the decade and the previous all-time best performances was calculated for all age groups in all men's events. Most age groups followed a progressive drop from positive relative progression during the 1980s to either a minor progression or regression during the last period.

Discussion

Since the 1970s, and the democratization of sport, more athletes in all age groups were able to approach their maximal age-related performance. However, with time, this improvement has decreased in both range and frequency suggesting that age-related maximal physical performances are reaching their potential upper limits among all age categories. As a consequence, in the absence of major breakthroughs or modification of competition rules (eg allowing new technological innovations), the age-related physical limits might now be accurately determined by the Moore equation for *Homo sapiens* (5,18).

Homothetic Expansion

We hypothesized that the contour of the age-related pattern has expanded with time according to a homothetic transformation. In fact, the Moore curve (which describes the progression of individual and species life course performances) integrates all the relations between performance and time—including genome, energy, and environmental impacts (5,11). These relations have been at the heart of living systems for millions of years (as have been demonstrated in *C. elegans*, *Mus Domesticus*, or in *H. sapiens*) (10). Such deep-rooted relations should not change in only a few decades.

A lack of data, especially for youth and master athletes, prior to 1970, limits an accurate characterization (such as the Moore equation fitting) throughout the last 120 years. However, we are able to show two key elements that directed this transformation during the 20th century. First, the peak of the relation, age at maximal performance, is associated with a rise of the best performances (World Record Holders or Top 10 performers) since 1891 (5). For example, the 100-m running event showed an improvement from 10.80 seconds in 1891 to the 9.58 seconds by Usain Bolt in 2009. To that respect, the yearly top 10 performers list provides more accurate information to estimate the homothetic progression of the pattern throughout the modern Olympic era (5).

The second major factor relates to the ending point of the curve: the maximal life duration and its gradual progression up to Jeanne Calment's 122.5 years in 1997. Maximal life duration also showed a progressive improvement during the 20th century until the stagnation over the last two decades (18,25). Put together, these two elements draw the contours of the homothetic expansion of our upper physiological limits. Such growth was based on a more favorable environment resulting from the energetic, scientific, medical, social, nutritional, or industrial improvements of the last two centuries (15–18). In fact, as previously suggested (Figure 3 in Berthelot Age 2011), here, we are able to provide a more precise contour of the homothetic expansion of our upper capacities.

Such an expansion concept, which integrates best performances from birth to death in a population, generation after generation, is of interest in model organisms. This concept assists in measuring how maximal performance related to age can be used to study other species with or without interventions (10). With this goal, assays to measure the decline of physical functions have been designed in different mammal and non-mammal species (2) such as *C. elegans* (10,26), zebra fish (27), or rodents (2). Previous studies using rats or mice have examined this selection of animals for wheel running capabilities (28,29). In mice, selection for wheel running activity showed that animals from the 15th generation ran 150% farther than control mice (29). On the contrary, the 11th generation of rats selected for their low aerobic capacity revealed higher metabolic and cardiovascular risk factors (28).

Table 2. Recent Relative Progression in Percentage (%) for Maximal Performance Per age Group by Period in Female Athletes

Relative Progression (%)	Age Group (year)																
		15–19	20–24	25–29	30–34	35–39	40–44	45–49	50–54	55–59	60–64	65–69	70–74	75–79	80–84	85–89	90–94
Between 1980 and 1990																	
	100 m	−0.09	1.39	2.96	5.01	—	−0.25	−0.40	—	—	—	—	—	—	—	—	—
	400 m	0.55	0.68	10.63	2.69	−2.19	−2.83	—	0.64	—	—	—	—	—	—	—	—
	800 m	−0.35	0.14	−0.88	3.28	0.96	−1.40	4.36	−0.62	—	—	—	—	—	—	—	—
	1,500 m	2.81	−1.04	−0.64	/	0.35	−1.11	3.14	1.80	—	—	—	—	—	—	—	—
	5,000 m	—	—	—	—	—	5.62	12.18	40.17	—	—	—	—	—	—	—	—
	10,000 m	—	—	—	—	—	5.04	—	—	—	—	—	—	—	—	—	—
	High jump	4.15	6.63	1.99	5.73	8.67	4.29	1.97	−1.36	5.38	9.57	10.91	—	—	—	—	—
	Pole vault	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
	Long jump	9.14	5.95	6.06	2.34	−1.38	11.89	7.80	4.17	—	—	—	—	—	—	—	—
	Triple jump	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
	Mean progression	2.70	2.29	3.35	3.81	1.28	2.66	4.84	7.46	—	—	—	—	—	—	—	—
Between 1990 and 2000																	
	100 m	−0.18	1.22	−1.04	0.00	—	9.19	1.63	4.80	2.26	2.02	3.23	3.72	6.03	0.89	—	—
	400 m	0.16	−0.74	−1.35	−2.62	−0.61	3.17	1.72	7.33	6.32	6.55	−0.07	−2.07	1.36	−8.57	—	—
	800 m	0.23	0.06	−1.61	−1.32	−0.22	6.08	8.60	1.45	—	—	6.82	2.19	0.76	—	—	—
	1,500 m	3.74	3.01	−1.24	−0.19	—	8.72	14.24	2.19	6.15	3.47	3.63	5.33	11.91	—	—	—
	5,000 m	0.92	2.99	2.86	−0.42	3.37	4.59	2.28	2.81	1.48	−2.79	2.16	1.41	1.18	6.37	—	—
	10,000 m	—	—	2.42	−0.50	3.15	1.82	−0.23	0.91	2.23	1.52	−1.35	6.54	—	—	—	—
	High jump	−2.49	−2.39	0.00	0.99	3.19	2.94	13.55	6.80	8.03	9.52	4.10	7.96	3.70	7.53	—	—
	Pole vault	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
	Long jump	−6.22	−2.27	−0.53	7.00	7.54	3.22	3.98	2.86	6.60	6.98	−6.71	21.84	17.08	20.83	—	—
	Triple jump	6.87	10.37	6.60	—	—	9.96	—	13.12	8.88	13.59	—	—	—	—	—	—
	Mean progression	0.38	1.53	0.68	0.37	2.74	5.52	5.72	4.70	5.24	5.11	1.48	5.87	6.00	5.41	—	—
Between 2000 and 2010																	
	100 m	−1.09	−0.47	−2.42	1.32	−2.27	−1.70	8.02	7.11	0.00	1.61	0.99	5.00	0.82	−3.13	6.81	—
	400 m	−0.94	−0.88	−2.64	−2.91	0.58	1.19	1.19	1.47	2.98	1.66	8.06	0.90	4.16	−0.25	−2.71	—
	800 m	2.79	−0.70	−1.53	−1.96	−0.85	−1.97	−8.77	3.68	0.35	1.47	5.93	6.22	9.14	4.36	5.59	—
	1,500 m	−3.46	−2.42	−1.20	−0.11	−0.94	−7.99	−8.24	0.86	−0.06	3.99	3.96	2.72	2.01	−0.39	3.58	—
	5,000 m	1.04	1.99	2.11	1.57	1.32	−1.39	−0.63	5.87	3.70	2.09	5.14	5.66	7.31	5.98	—	—
	10,000 m	0.71	−1.23	0.95	0.53	2.73	2.16	−6.27	2.32	1.74	6.56	5.30	−1.69	4.26	0.44	—	—
	High jump	−2.49	−0.96	1.46	0.00	3.61	1.71	−6.25	1.91	4.73	6.52	7.87	6.56	4.46	8.00	17.50	—
	Pole vault	1.81	11.09	7.66	—	10.59	12.50	3.55	0.59	20.31	23.32	51.90	9.26	19.41	—	—	—
	Long jump	−5.00	−2.81	−1.33	−4.54	−1.57	3.59	−2.96	0.19	−0.60	−0.42	3.80	−1.89	−3.98	5.17	9.13	—
	Triple jump	−1.30	−0.26	−1.03	0.39	3.50	8.57	−3.67	6.48	10.47	10.07	5.54	9.91	24.88	15.93	−15.27	—
	Mean progression	−0.79	0.34	0.20	−0.63	1.67	1.67	−2.40	3.05	4.36	5.69	9.85	4.27	7.25	4.01	3.52	—

Table 2. Continued

Relative Progression (%)	Age Group (year) 15–19	20–24	25–29	30–34	35–39	40–44	45–49	50–54	55–59	60–64	65–69	70–74	75–79	80–84	85–89	90–94
Between 2010 and 2017																
100 m	−0.27	−0.47	−1.96	−0.56	−3.16	−4.02	−7.73	−7.67	2.07	−3.26	−2.15	−0.88	4.16	5.10	0.05	0.13
400 m	−0.92	−2.37	−3.17	−2.58	0.26	−7.53	−4.52	−5.61	2.94	3.70	−6.30	3.84	6.74	10.13	29.10	—
800 m	−2.22	−0.24	−1.50	−4.08	−4.77	−8.13	−8.12	2.25	−7.61	0.45	1.38	4.70	3.37	3.14	11.21	—
1,500 m	−2.40	0.17	−1.54	0.15	−0.83	−5.37	−9.87	1.92	2.11	−1.21	5.52	5.10	−0.31	9.56	15.29	—
5,000 m	−0.28	−0.37	0.03	−0.28	−3.63	1.74	−4.86	−3.50	2.24	−8.60	1.57	5.58	−2.26	4.83	13.97	—
10,000 m	4.44	−0.20	−2.96	1.66	3.62	13.89	7.43	−5.29	5.84	−15.06	−21.63	25.00	—	28.87	0.79	—
High jump	−1.00	−1.44	−0.48	0.00	0.00	8.99	−6.25	−2.50	−5.16	−4.76	3.65	0.00	6.84	1.85	1.06	—
Pole vault	4.44	−0.20	−2.96	1.66	3.62	7.89	−8.33	−5.29	5.84	−21.47	−21.63	25.00	—	30.71	—	—
Long jump	−7.70	−5.08	−3.59	−2.40	−0.72	−0.75	−1.39	−1.85	1.00	−8.21	−6.03	0.47	2.12	13.11	22.59	—
Triple jump	−1.85	−1.96	−2.97	−0.52	2.14	3.76	3.42	−7.89	−9.39	−13.41	3.46	−6.24	3.93	13.28	−7.09	—
Mean progression	−0.78	−1.22	−2.11	−0.70	−0.35	1.05	−4.02	−3.54	−0.01	−7.18	−4.22	6.26	3.07	12.06	9.66	—

Note: Relative progression (in %) between the best performance of the decade and the previous all-time best performances was calculated for all age groups in all women's events. There is a wide difference in relative progression regarding the events and the age groups for women. The average relative progression showed that the improvement of the performance for youth and elite women athletes gradually decreased from a major improvement during the 1980s to either a minor improvement and, on occasion, to a performance regression during the last period.

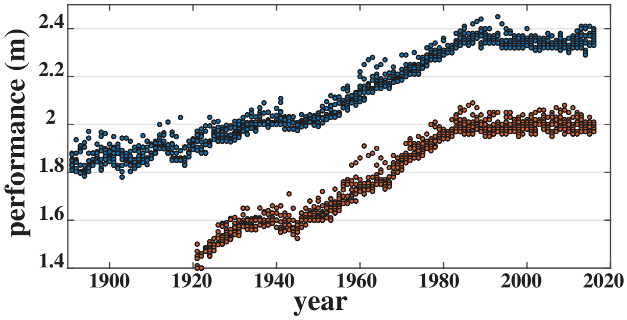

Figure 2. Gender gaps have remained similar in elite athletes during the last 30 years. The annual world's 10 best performances from 1921 to 2016 in women (lower solid circles, solid orange circles online) and from 1896 to 2016 in men (upper solid circles, solid blue circles online) in high jump show that there has been no major change in gender gap during the last 30 years for elite athletes.

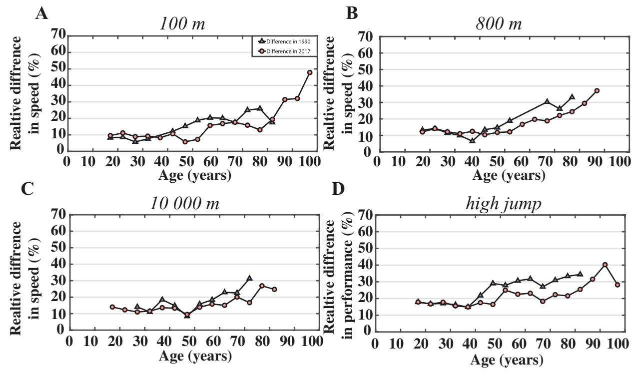

Figure 3. The gender gap increases with age. The difference in maximal performance changes regarding age increases gradually, especially after the age of 50, in all events including 100 m event (**A**), 800 m event (**B**), 10,000 m event (**C**), and high-jump event (**D**). However, regarding the different age groups between 1990 (solid triangles, solid blue triangles online) and 2017 (solid circles, solid red circles online), this gender gap decreased overall.

Future studies should also carefully compare age-related changes in maximal performance and voluntary activity. The decline for both elite athletes and the general population might be different for maximal performance (activities that push the organism's limits) and voluntary activity (walking speed). Precisely characterizing the age-related patterns of other molecular, cellular, or physiological "aging clocks" might also give relevance to the general population (30,31).

Structural and Functional Boundaries Are Highly Dependent on Age

Upper performance limits are related to structural and functional boundaries of the human body and their interactions with the environment (10). In particular, the irreversible entropic process of aging gradually alters all structures and functions at every level of the organism (10). At the cellular level, cells are limited by their replicative capacity, which, together with accumulated damage, leads to dysfunction with a gradual loss by senescent, necrotic, or apoptotic processes (32,33). As a consequence, the aging process gradually restricts maximal capabilities for all individuals, with some variability, and shapes the age-related upper limits of physical performance (10,31).

Sexual Dimorphism of *H. sapiens* Increases With Age

Structural and functional differences also appear at all levels of male and female organisms (34). For 82 different swimming and running events, such distinctions result in a 10% average difference in maximal performance (35). This gap in elite athletes has not changed for the last 30 years and therefore, could be considered a precise standard value. Gender gap also depends on age (21,34). In fact, before puberty, the physical gap between girls and boys is much smaller (3%–4% for children's best sprinting performance in 10-year-olds), and then this gap gradually increases (21). Our results confirm previous studies showing that the difference increases progressively with age in cycling, swimming, or running events, resulting from both sociological and physiological aspects (21,34). In other words, the decline in maximal physical performance is more pronounced in women than men, and depends on gender-based biological (muscle characteristics, hormonal, etc) and psychological (motivation) changes with aging (21). However, recent decades have shown a reduction of the gender gap for the older groups. Such a decrease is due to a synergistic effect of the gradual democratization of master competitions with more and more highly competitive women, who have progressively optimized their training methods, nutrition, and recovery strategies (21,35).

Are We Reaching the Limits of Age-Related Maximal Physiological Performances of *H. sapiens*?

Our findings suggest that *H. sapiens* are now close to their ultimate limits in physical performance, at all age groups, at least for the sports that have been examined. Major progress has been realized during the last few decades in the understanding of aging, in particular, thanks to model organisms (36–39). Nevertheless, the human body is a finite organism, as any living species, with structural and functional boundaries, and with irreversible alterations as age progresses (18).

In this sense, such an age-related characterization in the absence of major breakthroughs and new "technological" gains may come closer and closer to ultimate human limits. A few of these barriers may still slightly improve in the coming decades. For example, older age groups with exceptionally talented athletes will benefit from easier access to sport and competitions, especially if encouraged by "political actions" targeting life quality improvement or the extension of a population-wide healthy life span. In fact, even if the absolute limits of our species come closer, there is still a large margin of optimization at the individual and population level. This aim will be one of the most intense challenges of this century, especially with the new pressure of anthropocentric activities responsible for deleterious effects on both human and environmental health (18,36–39).

Conclusions

Our study suggests the potential upper physiological limits at the interface between *H. sapiens* fitness and environment have been reached. As Jeanne Calment recorded the maximal longevity of *H. sapiens* in 1997, the age-related pattern might now characterize the upper age-related performance of our species. The next challenge might be to extend health span of the general population; maximal physical performance could be a simple and useful indicator of such an improvement.

Supplementary Material

Supplementary data are available at *The Journals of Gerontology, Series A: Biological Sciences and Medical Sciences* online.

Conflict of Interest

None reported.

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