ABSTRACT

Most studies on aging and marathon have analysed elite marathoners, yet the latter only represent a very small fraction of all marathon participants. Also, analysis of variance or unpaired Student's t tests are frequently used to compare mean performance times across age groups. In this report we propose an alternative methodology to determine the impact of aging on marathon performance in both non-elite and elite marathoners participating in the New York City Marathon. 471,453 data points corresponding to 370,741 different runners over 13 race editions (1999-2011) were retrieved. Results showed that: i) the effect of aging on marathon performance was overall comparable in both sexes; ii) the effect of aging differed between the fastest and the slowest runners in both sexes; and iii) the magnitude of the sex differences was higher among the slowest runners compared with the fastest ones. Current data suggests that the biological differences between sexes allow men to have a better marathon performance across most of the human lifespan.

Keywords: exercise performance, marathon, aging, sport physiology.

INTRODUCTION

In the last decades, the popularity of the major endurance running race, the marathon (42.2km), has increased dramatically [1], with a parallel growth in the scientific interest for this event. Among other relevant scientific information, major marathon races provide a good opportunity to asses age-associated changes in endurance performance [2]. Marathon performance, expressed in running time, clearly declines with age in both men and women runners irrespective of their competition level [3-5]. Yet the age decline of trained, non-elite runners seems to be more marked after the age of 55 years [6] whereas in elite runners such decline occurs earlier in both sexes, i.e., by 35-39 years [4,6]. An average decrease in performance ≥10% per decade has been postulated [7,8], although higher rates of decline have been reported for elite participants in the New York City (NYC) marathon, i.e., ~6% per year [4]. On the other hand, the rate of age-decline in the top marathon runners seems to be more marked in women compared with men [4,6,9].

Most studies in the field have analysed data on elite marathoners, and yet these runners only represent a very small fraction of all marathon participants compared with their non-elite referents. And, when the latter are studied, they have often been "scrambled" with elite runners [2]. On the other hand, analysis of variance (ANOVA) or unpaired Student's t tests applied to a pooled set are frequently used to compare mean performance times across age groups [4,10,11]. However, the use of these statistical approaches can be confounding because (i) they erroneously assume the existence of a linear relationship between running performance and runners' age, and (ii) consideration of all individual performance data as a pool implies the treatment of all the individual data as independent data, failing to consider the non-negligible number of cases where the same runner participates in several editions of the same marathon, which makes such 'repeated' individual data having a 'panel structure'. Thus, in this report we proposed an alternative methodology to overcome the two above-mentioned problems (see further below). The main purpose of this study was to determine the impact of aging on marathon performance in both non-elite and elite marathoners in the major city marathon that is arguably the most popular running endurance race worldwide, with a wild range of participants in terms of age and performance level, i.e., the NYC marathon.

METHODS

This study involved the analysis of publicly available data and thus individual informed consent was not necessary. The study was approved by the University's Human Ethics Committee and was performed according to the declaration of Helsinki. Sex, age and performance time for all finishers in the NYC marathon over the period 1999-2011 were obtained through the official race website (http://www.ingnycmarathon.org/).

Subjects

471,453 NYC marathon participations (32% women) corresponding to 370,741 different runners over 13 editions of the race (1999-2011) were retrieved. The age was divided into several 5-years age categories (40-44, 45-49, 50-54, 55-59, 60-64, 65-69, 70-74, 75-79 and 80-84 years), except for the younger categories, which were divided in 10-year periods, i.e., 20-29 and 30-39 years. Fastest and slowest runners groups were defined as (and composed by) those runners ranked in the highest (90th) and lowest (10th) percentile of performance relative to their sex and age category, respectively, in each yearly edition of the race.

Statistical analysis

All statistical analyses were performed with STATA (Statistics/Data Analysis, v. 12.2, College Station, Texas USA). Descriptive data are presented as means ± standard deviation (SD) and significance level was set at $P \leq 0.05$.

Mean tests for unpaired percentages with unequal variances were calculated for analysing potential significant differences when comparing men and women in each category, using

Welch's proposal [12]. Ordinary least squares (OLS) linear regression was calculated to assess the association between sex ratios (women: men) and editions. The average of editions ran by one runner were calculated.

Defining the model: Measuring the effect of sex, age and competition level on running time

Regarding the non-linear relationship between aging and endurance running performance, we used a log-linear relationship between running performance time and age, since this functional form fits properly the relationship found in the data, as displayed in Figure 2 (see further below). Thus, our base model was as follows:

$$time_{it} = e^{\beta_0 + \beta_1 age_{it} + \sum_{j=2}^{11} \beta_j Dage_{j,it} + u_{it}} \tag{A}$$

where *i* denotes runner; *t*, edition; *time*, finishing time; *age*, runners' age; $Dage_j$ is a dummy variable that takes a value of 1 when a specific runner belongs to the age category *j*; β_j with $j = (2,...,11)$ are the unknown parameters; and u_{it} refers to the usual model error term. Model (A) could be estimated by OLS, considering the data as a pool data set, after a simple linearization into the following log-linear model:

$$\ln(time)_{it} = \beta_0 + \beta_1 age_{it} + \sum_{j=2}^{11} \beta_j Dage_{j,it} + u_{it} \tag{B}$$

However, model (B) can still benefit from the panel structure of our data through the following specification:

$$\ln(time)_{it} = \beta_0 + \beta_1 age_{it} + \sum_{j=2}^{11} \beta_j Dage_{j,it} + \alpha_i + \varepsilon_{it} \tag{C}$$

Model (C) introduces a new error component, α_i, which gathers the effect of all those variables that, although are relevant to explain runner *i*'s marathon performance time, were not included in the model because they are unobservable. This new term α_i is considered a random term, since runners are a random sample from a larger population. The α_i term is distributed identically and independently with mean = 0 and variance = σ_α^2, $\alpha_i \sim IID\left(0, \sigma_\alpha^2\right)$. The ε_{it} term refers to the usual model error term and is assumed to follow a N$(0, \sigma_\varepsilon^2)$ distribution. From the estimation point of view, this new error term, $u_{it} = \alpha_i + \varepsilon_{it}$, requires the use of the Generalised-Least-Squares (GLS) method to get efficient estimators of the unknown parameters (β_j with), instead of the OLS method [13].

From the abovementioned parameters we could estimate the finishing time for all sex and age groups of interest, and evaluate whether there were significant differences among groups. We also calculated the percentage change in marathon finishing time when changing to the next (older) age category and evaluate whether this change was significant.

Defining the model: Effect of sex on marathon performance time

Apart from age, another relevant variable in our dataset is sex. Hence, the next step consisted of determining whether our model parameters should be different for men and women. If that was the case, model (C) should be generalized as follows:

$$\ln(time)_{it} = \beta_0 + \beta_1\, age_{it} + \sum_{j=2}^{11} \beta_j Dage_{j,it} + \gamma_0\, Dw_i + \gamma_1\left(Dw_i \cdot age_{it}\right) + \sum_{j=2}^{11} \gamma_j\left(Dw_i \cdot Dage_{j,it}\right) + \alpha_i + \varepsilon_{it} \qquad \text{(D)}$$

where Dw_i is a dummy variable that takes a value of 1 when runner *i* is a woman and 0 otherwise, and the unknown parameters are, now, the following: β_j, γ_j with $j = \left(2, ..., 11\right)$.

Defining the model: Effect of performance level on marathon performance time

To accomplish our objective of analysing the behaviour of runners with different performance levels, i.e., the fastest vs. the slowest, we defined the following two dummy variables: i) $Dfastest_{it}$ which equals 1 if the ith runner belongs to the percentile of runners with the fastest (i.e., lowest) finishing time in edition *t*, for their respective age category (and 0, otherwise); and ii) $Dslowest_{it}$ which equals 1 if the ith runner belongs to the percentile of runners with the highest (i.e., slowest) finishing time in edition *t*, for their respective age category (and 0, otherwise). In case there were differences between the two (fastest, slowest) groups, heterogeneous parameters for the two groups were estimated using the following model:

$$\begin{aligned}
\ln(time)_{it} &= \beta_0 + \beta_1\, age_{it} + \sum_{j=2}^{11} \beta_j Dage_{j,it} + \gamma_0\, Dw_i + \gamma_1 \left(Dw_i \cdot age_{it}\right) + \sum_{j=2}^{11} \gamma_j \left(Dw_i \cdot Dage_{j,it}\right) \\
&+ \delta_0 \cdot Dfastest_{it} + \delta_1\, age_{it} \cdot Dfastest_{it} + \sum_{j=2}^{11} \delta_j \left(Dage_{j,it} \cdot Dfastest_{it}\right) + \mu_0 \left(Dw_i \cdot Dfastest_{it}\right) + \mu_1 \left(Dw_i \cdot age_{it} \cdot Dfastest_{it}\right) + \sum_{j=2}^{11} \mu_j \left(Dw_i \cdot Dage_{j,it} \cdot Dfastest_{it}\right) \\
&+ \tau_0 \cdot Dslowest_{it} + \tau_1\, age_{it} \cdot Dslowest_{it} + \sum_{j=2}^{11} \tau_j \left(Dage_{j,it} \cdot Dslowest_{it}\right) + \theta_0 \left(Dw_i \cdot Dslowest_{it}\right) + \theta_1 \left(Dw_i \cdot age_{it} \cdot Dslowest_{it}\right) + \sum_{j=2}^{11} \theta_j \left(Dw_i \cdot Dage_{j,it} \cdot Dslowest_{it}\right) \\
&+ \alpha_i + \varepsilon_{it}
\end{aligned} \tag{E}$$

where the unknown parameters are now the following: $\beta_j,\ \gamma_j,\ \delta_j,\ \mu_j,\ \tau_j,\ \theta_j$ with $j = (2,...,11)$. In next section we will obtain evidence on the most appropriate specification for our data.

Estimation results considering a possible structural break by sex

To determine whether the effect of aging on marathon performance differs by sex, we tested the null hypothesis of no sex differences through the Chow's test [14].

From estimated parameters in model (D), we estimated the finishing time (in minutes) by sex and age categories. Furthermore, within the same age category, sex differences could be determined. We also estimated the effect that changing to the upper age category had on performance time, and whether this effect differed by sex.

Estimation considering a possible structural break by sex and quality

Here we determined whether there was a different behaviour based on the competition level of runners. We tested the null hypothesis of homogeneous behaviour through the Chow's test [14].

RESULTS

The total participation rate in NYC marathon has continuously increased with the only exception of a drop in the 2001 edition, which is likely attributable to the terrorist attack that occurred just ~2 months before. The number of finishers per year corresponding to the study period was 12,055 ± 2,914 (range: 6,590-17,201) for women and 24,211 ± 3,795 (range: 15,968-29,886) for men. The male/female ratio for the 1999 edition was 2.46, and has continuously decreased since them, to reach a value of 1.74 by year 2011.

General participation trends: sex and age

The age of the finishers included in our study averaged 37.7 ± 9.6 (women) and 41.3 ± 10.1 years (men). **Figure 1** shows the distribution of finishers by sex and age category among the fastest (upper panel) and slowest runners (lower panel). For both sexes, the age group with the largest participation was clearly the 30-39 years group and the percentage of total runners under 50 years old accounted for more than 80% of total. The results also indicated that, for all age categories, there was a significant difference between sexes (all $P<0.05$) (20-29 years: 35,971 women *vs* 37,398 men; 30-39 years: 57,521 women *vs* 10,5021 men; 40-44 years: 26,040 women *vs* 60,571 men; 45-49 years: 17,073 women *vs* 42,885 men; 50-54 years: 11,731 women *vs* 35,512 men; 55-59 years: 4,971 women *vs* 17,727 men; 60-64 years: 2,348 women *vs* 10,222 men; 65-69 years= 739 women *vs* 3,554 men; 70-74 years= 220 women *vs* 1,398 men; 75-79 years: 77 women *vs* 367 men ; 80-84 years: 23 women *vs* 84 men).

Runners with more than one participation

On average each runner included in our study finished 1.3 marathon editions; 84.9% of the total sample had finished only 1 marathon, 9.7% had finished 2, and 2.4%, 0.6%, 0.2% and 0.1% had finished 3, 4, 5 and 6 editions of the race, respectively.

Fastest vs. slowest runners

The distribution of fastest women and men per age group is displayed in **Figure 2**. **Figure 2A** shows performance time for the entire sample, and **Figure 2B** and **2C** show performance times for the fastest and the slowest runners, respectively. All three Figures clearly show that the relationship between age and marathon performance is not linear.

Estimation results considering a possible structural break by sex

The value of Chow´s test was 32,191.08 ($P<0.001$). Consequently, the null hypothesis of homogeneous behaviour among sexes was rejected and, therefore model (D) outperformed model (C).

Results of the differences between running time within the same age category and sex are shown in **Table 1**. Women ran significantly slower than men with the only exception of the 75-80 years category. The effect of aging (as reflected by changing to the following age category) by sex on marathon performance is shown in **Table 2**. Model (D) shows that the change to the following age category from 44 years of age and onwards resulted in a significant decrease in marathon-running speed, except only for the change from 70-74 years to the following age category in women. On the other hand, the slowing effect of aging on marathon performance was more marked in women than in men, except for old ages (60-80 years).

Estimation results considering a possible structural break by sex and competition level

The Chow's test reached a value of 580,000 ($P<0.001$). Thus, the sample model expressed in (E) was not rejected by the data and differences by runners' competition level are expected.

We estimated running time for the different groups of interest as well as the effect of sex in running time among groups depending on their competition level, and the results are shown in **Table 3**. In both sexes the fastest runners' time was ~50% of the slowest runners' time. Running performance was significantly better in men than women in both fastest and slowest groups, with the exception of upper-age categories (≥70 years and ≥81 years for the fastest and slowest group, respectively). **Table 4** shows the relative (%) effect on running performance time of changing to the following age category by sex and performance groups. In general, a rise in age category implied a significant decrease in performance, with the exception of the change from 20-29 to 30-39 years in the slowest runners of both sexes and from 75-80 to 81-84 years in the slowest female runners. On the other hand, both sexes showed a similar pattern in that the worsening in performance (i.e., increase in finishing time) when changing to the next age category was more marked in the fastest runners compared with the slowest group.

DISCUSSION

Our main finding was that the effect of aging on marathon performance was overall comparable in both sexes, with running time showing significant increases (and thus performance worsening) with changes to an upper age category. On the other hand, marathon performance was better in men than in women until the age of 64 years and thereafter between-sex differences were attenuated in the fastest runners. The effect of aging differed among the fastest and the slowest runners within both sexes: in the fastest runners, performance consistently decreased with increases in age category, yet the performance of the slowest runners actually improved when changing from 20-29 to 30-39 years of age. Further, the magnitude of the sex differences was higher among the slowest runners compared with the fastest runners. In the latter, between-sex differences in performance were attenuated with aging such that, at the age of 70-74 years the fastest women actually outran the fastest men. This result could have been biased by the smaller size of the group of women compared to men in the oldest categories, e.g. n=220 women vs. 1,398 men, respectively, for the 65-69 years category; in fact, men were faster than women for all the rest of age categories in both slowest and fastest runner groups.

After controlling for major confounders (non-linearity of the age/performance relationship and panel structure of the data), it seems that men, even those with a lower competition level, are able to maintain superior performances compared to women over most of the lifespan, although such difference seems to be attenuated at older ages in the more competitive runners. The physiological main factors that determine marathon performance are maximal oxygen consumption (VO_{2max}), the lactate threshold (i.e., the ability to sustain high percentages of VO_{2max} before lactate starts to accumulate in blood) and running economy [4,9,15,16]. In this regard, there are biological differences between sexes that favour men's performance vs. women across most of the human lifespan. These include higher heart size, muscle mass and haemoglobin concentration in the former, together with lower body fat, all of which contribute to explain the higher VO_{2max} values that are usually found in men compared to age-matched women [4,17-19]. Seemingly, however, the two other major physiological factors that influence marathon performance, fractional utilization of VO_{2max} at the lactate threshold and running economy, do not differ between sexes [4,18,20,21]. On the other hand, the influence of aging on the physiological factors associated with marathon running performance might differ between both sexes [18,22]. In humans, the aging process is inevitably characterized by a reduction in muscle mass, maximum heart rate, maximum cardiac output, as well as in the running speed eliciting the lactate threshold, all of which compromise aerobic exercise capacity, as typically exemplified by aging decline in VO_{2peak} [23-25]. However, whether the age-decline in aerobic capacity differs between both sexes and, most important, whether this potential sex difference has an actual effect of how aging affects marathon performance in men vs. women remains to be elucidated. Samson et al. [26] observed a more accelerated decrement in the muscle strength of women above the age of 55 years compared with men, which is in accordance with the drastic changes that occur with menopause in the female sexual hormone system [27]. It remains nonetheless to be elucidated whether such sexrelated change in endocrine function affects differently the marathon performance of women and men. Although some authors have reported no differences in the age-decline of physiological function between male and female elite marathon runners [3,9], our data suggest that the running time of the fastest women tended to approach those of men with aging, such that at 70-74 years the best women outran the best men. Our finding that the magnitude of the performance difference between sexes was higher in the slowest compared with the best runners partly agrees with previous data from a study by Hunter et al. [9], where it was found that the sex difference in running velocity increased from first to fifth place across years in the world major marathons (NYC, Boston, Chicago, London, Berlin, Tokyo). Hunter et al. [9] also concluded that there were no sex differences in the physiological determinants of the age at which elite male and female runners reached their peak marathon performance [9]. With regard to this, our data would suggest the existence of a similar phenomenon also in the less competitive runners, i.e., no major sex difference in the age at which best performance is reached.

PRACTICAL APPLICATIONS

The present study analysed the influence of sex and performance level on the impact that aging has on marathon performance, using the NYC marathon paradigm. Since this race congregates a large sample of subjects allowing conducting well powered statistical analyses, we believe our results could be demonstrative of the actual influence that aging has on both sexes depending on the runner's performance level. Nevertheless, our study has some methodological limitations. The longitudinal decrease in functional performance of elite marathon runners could be non-linear due to potential confounders that cannot be taken into account in our model, such as the low number of runners in the oldest categories, actual biological aging, changes in exercise training regimen, or injuries [28]. Also, as Hunter et al. [4,9] reported previously, the ratio of men to women has decreased among editions.

CONCLUSION

In summary, current data suggests that the biological differences between sexes allow men to have a better marathon performance compared with women across most of the human lifespan, although between-sex differences are attenuated at older ages in the more competitive runners. On the other hand, the magnitude of the sex differences seems to be higher among the slowest runners compared with the fastest runners. The effect of aging also differs between the fastest and the slowest runners in both sexes. In the fastest runners, performance consistently decreases with increases in age category, whereas the running time of the slowest runners would improve in some age categories.

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Figure legends.

Figure 1. Percentage of women and men in the fastest and slowest group by age category.

Figure 2. Finishing time (minutes) by sex, age and performance level (2A, all runners; 2B, fastest runners; 2C, slowest runners).

Table 1. Estimated marathon performance time by age category and sex

Age category	Finishing time, men ($Dw = 0$)	Finishing time, women ($Dw = 1$)	Sex differences (men *minus* women)
20-29 years	252.6 min	276.0 min	-23.4 min* (-9.3%)
30-39 years	252.7 min	280.1 min	-27.4 min* (-10.8%)
40-44 years	253.3 min	282.0 min	-28.7 min* (-11.3%)
45-49 years	258.2 min	290.3 min	-32.1 min* (-12.4%)
50-54 years	266.1 min	301.5 min	-35.4 min* (-13.3%)
55-59 years	279.6 min	318.2 min	-38.6 min* (-13.8%)
60-64 years	292.2 min	333.3 min	-41.1 min* (-14.1%)
65-69 years	315.4 min	352.0 min	-36.6 min* (-11.6%)
70-74 years	336.0 min	367.4 min	-31.4 min* (-9.3%)
75-79 years	367.6 min	379.1 min	-11.5 min (-3.1%)
80-84 years	398.3 min	427.0 min	-28.7 min* (-7.2%)

* denotes statistical significance was reached (P<0.05) for the comparison between sexes. See text for the explanation of the abbreviation '*Dw*'

Table 2. Effect of aging (as reflected by changing from one specific age category to the next upper age category) on % change in marathon performance

Aging (change in age category)	% change in finishing time, men	% change in finishing time, women
From 20-29 to 30-39 years	0.0%	1.5%*
From 30-39 to 40-44 years	0.2%	0.7%*
From 40-44 to 45-49 years	2.0%*	2.9%*
From 45-49 to 50-54 years	3.1%*	3.9%*
From 50-54 to 55-59 years	5.1%*	5.5%*
From 55-59 to 60-64 years	4.5%*	4.7%*
From 60-64 to 65-69 years	7.9%*	5.6%*
From 65-69 to 70-74 years	6.6%*	4.4%*
From 70-74 to 75-79 years	9.4%*	3.2%
From 75-79 to 80-84 years	8.4%*	12.6%*

*denotes statistical significance was reached (P<0.05) for the comparison between sexes.

Table 3. Estimated marathon performance depending on age category groups and performance level (fastest vs. lowest percentile).

	FASTEST			SLOWEST		
Age category	**Finishing time, men**	**Finishing time, women**	**Fastest men minus fastest women**	**Finishing time, men**	**Finishing time, women**	**Slowest men versus slowest women**
20-29 years	186.8 min	194.0 min	-7.2 min*(-3.9%)	359.8 min	361.9 min	-2.1 min* (-0.6%)
30-39 years	188.1 min	194.1 min	-6.00 min (-3.2%)	358.2 min	361.5 min	-3.3 min* (-0.9%)
40-44 years	190.0 min	196.3 min	-6.3 min* (-3.3%)	358.8 min	363.0 min	-4.2 min* (-1.2%)
45-49 years	194.8 min	201.3 min	-6.5 min* (-2.3%)	365.4 min	372.8 min	-7.4 min* (-2.0%)
50-54 years	201.3 min	206.0 min	-4.7 min* (-2.3%)	377.3 min	383.5 min	-6.2 min* (-1.6%)
55-59 years	210.3 min	214.5 min	-4.2 min* (-2.0%)	398.0 min	406.3 min	-8.3 min* (-2.1%)
60-64 years	218.8 min	224.6 min	-5.8 min* (-2.7%)	417.4 min	420.3 min	-2.9 min* (-0.7%)
65-69 years	230.2 min	237.1 min	-6.9 min* (-3.0%)	443.9 min	449.4 min	-5.5 min* (-1.2%)
70-74 years	245.7 min	243.7 min	2.0 min (0.8%)	454.1 min	469.7 min	-15.6 min* (-3.4%)
75-79 years	271.1 min	273.7 min	-2.6 min (-1.0%)	472.9 min	509.9 min	-37.0 min* (-7.8%)
80-84 years	318.8 min	324.7 min	-5.9 min (-1.9%)	475.0 min	487.2 min	-12.2 min (-2.6%)

*denotes statistical significance was reached (*P*<0.05) for the comparison between sexes.