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Sex Differences in Marathon Running with Advanced Age: Physiology or Participation?

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Abstract
The sex difference in marathon performance increases with age and place of the finisher, even at the elite level. Sociological factors may explain the increased sex gap, but there is limited empirical evidence for specific factors.

Purpose
The purposes of this study were to determine the sex difference in velocity for the marathon across the place of finisher (1st–10th place) with advanced age and (2) to determine the association between the sex difference in participation (ratio of men-to-women finishers) and the sex difference in running velocity.

Methods

Running times of the first 10 placed men and women in the 5-yr age brackets between 20 and 79 yr and the number of men and women who finished the New York City marathon were analyzed for a 31-yr period (1980–2010).

Results

The sex difference in running velocity increased between the 1st and the 10th place because of a greater relative drop in velocity of women than men ($P < 0.001$). The sex difference increased with advanced age and decreased across the 31 yr, but more for the older age groups ($P < 0.001$). The number of women finishers also increased relative to men for the 31 yr, but more in the older age groups ($P < 0.001$). Importantly, approximately 34% of the sex difference in velocity among the first-place finishers was associated with the ratio of men-to-women finishers ($r = 0.58$, $r^2 = 0.34$, $P < 0.001$).

Conclusions

The greater sex difference in velocity that occurs with age and with increased place was primarily explained by the lower number of women finishers than men. These data provide evidence that lower participation rates and less depth among women competitors can amplify the sex difference in running velocity above that due to physiological sex differences alone.

Physiological sex differences allow men to run faster over the marathon distance, despite earlier predictions that women would outrun men based on running improvements ([40]). Men have a larger maximal ability to consume oxygen than women ($\dot{V}O_{2max}$) because they have larger hearts, greater hemoglobin concentration, less body fat, and a greater muscle mass per unit of body weight ([2,18,32]). The other two primary factors that limit marathon performance include running economy and the exercise intensity at which a high percent of the $\dot{V}O_{2max}$ can be maintained (also known as the "lactate threshold"), but these do not seem to differ between men and women ([2,17–20,28,35]). The resulting sex difference for fastest marathon times in the world to date is approximately 9%–10% ([13]). However, the widening sex difference in velocity among the lower-placed runners, and among older runners, is greater than the physiological sex differences (∼10%), and therefore the increasing sex difference with age and place is greater than physiologically expected ([13,23,36]).

Our recent data ([13]) showed that the sex difference in running velocity progressively increased between the first- and the fifth-place finishers for each of the seven marathons that constitute the World Marathon Majors series. The widening sex difference among the lower-placed finishers, even at the elite level, was greater than the physiologically expected sex difference and is proposed to be due to the lack of depth in women's running compared with men ([13,16,18,36]) as well as a possible larger issue of lower participation rates of women relative to men. Others have also shown that more men are closer in finishing time to the fastest male competitor than women are to the fastest woman competitor for several distance running events ([3,4]). Historically, men have had more opportunities than women to participate in sports, but in particular for marathon running ([2,10,18]). Women were first permitted to participate in the Marathon World Championships in 1983 (Helsinki, Finland) and the Olympic marathon in 1984 (Los Angeles, California). Although the ratio of men-to-women finishers in marathon events has increased during the last 30 yr, there remains a larger pool of male competitors ([14,23]). Furthermore, although lower participation rates of women have been accompanied by a larger sex difference in performance ([23]), the contribution of participation to the sex difference is not known. Here we used the variability in marathon performance and participation of young and older men and women finishers that was created by recent history to understand and to expose the contribution of participation on the sex differences in running velocity. Understanding such relations will provide insight into the impact of sociological factors on sex differences in performance among even elite runners and the possible influence that sampling bias can have in masking the physiological limits of men and women.

Because of the more recent history of women's participation in the marathon, older women today have not historically been exposed to the same competitive running opportunities as young women (especially before Title IX of the Educational Amendments of 1972, which is a landmark US legislation that bans sex discrimination in schools, whether in academics or athletics). Although running velocity decreases with advanced age for both men and women, the sex difference increases with age ([23]). Physiologically, the sex difference should be similar among older adults because men and women seem to age similarly in those factors that limit endurance performance ([5,7,35,36]), that is, $\dot{V}O_{2max}$, running economy, and lactate threshold ([18,20]). The association between the sex difference in marathon running velocity and participation with advanced age has not been examined, nor whether the place of the finisher further influences the magnitude of the sex difference with advanced age.

Thus, the purposes of this study were 1) to determine the sex difference in velocity for the marathon across the place of finisher (between the 1st and the 10th place) with advanced age for the years that women have been permitted to run the marathon and 2) to determine the association between the ratio of men-to-women finishers and the sex difference in running velocity. To achieve our aims, we examined data between 1980 and 2010 from the New York City (NYC) marathon, which is one of the seven races in the World Marathon Majors series. We hypothesized that 1) the sex difference in velocity with the increased place of the finisher would decrease across the 31-yr time span examined (1980–2010) but would be greater with advanced age and 2) the sex difference in marathon running velocity would be positively associated with the ratio of men-to-women runners. Preliminary data were presented in abstract form ([33]).

METHODS

Finishing times of the first 10 men and women finishers in the 5-yr age brackets between 20 and 79 yr and the number of men and women finishers within the 10-yr age brackets were analyzed for the NYC marathon for data during a 31-yr period (1980–2010). Data were retrieved from an online data source (http://www.nycmarathon.org) ([27]) for the years it was publically available when analysis was performed. Because the number of men and women finishers was only available in the 10-yr age brackets, the ratios of men-to-women finishers in each year within the 10-yr age brackets between 20 and 79 yr were recorded and calculated. Running velocity was calculated from the finishing time of the marathon for the first 10 men and women finishers in each of the following 5-yr age groups: 20–24, 25–29, 30–34, 35–39, 40–44, 45–49, 50–54, 55–59, 60–64, 65–69, 70–74, and 75–79 yr. Although there were finishers ≥80 yr, insufficient numbers of women runners prohibited meaningful analysis. Data for the 31-yr period were averaged into the following year brackets for analysis: 1980–1985, 1986–1990, 1991–1995, 1996–2000, 2001–2005, and 2006–2010, which corresponded to 5-yr intervals except for 1980–1985 (6 yr).

Statistical analysis

Data were reported as means ± SD within the text and table to show the degree to which observations within the sample differ from the sample mean. Data are displayed as means ± SEM in the figures to graphically show the bounds of the sample mean. Statistical analysis was performed using the Statistical Package for the Social Sciences (version 19.0; SPSS Inc., Chicago, IL). Univariate ANOVA was used to determine the difference in ratios of men-to-women finishers across years (1980–1985, 1986–1990, 1991–1995, 1996–2000, 2001–2005, and 2006–2010) and with increased age in the 10-yr age brackets (20–29, 30–39, 40–49, 50–59, 60–69, and 70–79 yr). Separate univariate ANOVAs were also used to determine 1) the absolute velocity with increased age (5-yr age groups between 20 and 79 yr) and across years (as previously mentioned, between 1980 and 2010) between men and women and 2) the sex difference in the mean running velocity (difference between men and women as a percent of the men) across age groups (5-yr age groups), years (as previously mentioned, between 1980 and

2010), and place (1st through 10th place). These analyses were also performed with the first-place finishers only included in the data set. Univariate analysis was also conducted on the percent difference in velocity between the 1st and the 10th place for men and women. *Post hoc* analysis (pairwise comparisons) was used to test for differences among pairs within a data set when significant main effects were identified. The strength of an association is reported as the squared Pearson product–moment correlation coefficient (r^2). Regression analysis was performed to determine the best-fit predictive equations for the sex difference in velocity and the decline in running velocity for men and women across age groups. For all analyses, a significance level of $P < 0.05$ was used to identify statistical significance.

RESULTS

Sex differences in participation

The number of men and women runners who finished the NYC marathon increased from 12,294 (1980) to 44,794 (2010), with the largest number of finishers in the 30- to 39-yr and the 40- to 49-yr age groups and the least in the oldest age groups (Table 1). More men finished the marathon than women, but the ratio of men to women decreased across the years from 1980 to 2010 ($P < 0.001$). The ratio of men to women was 6.76 in 1980 and decreased to 1.97 in 2003 and then plateaued thereafter with a small decline by 2010 to 1.79 (Fig. 1A). The ratio of men-to-women finishers increased across age groups (age effect, $P < 0.001$) because the older age groups had relatively more men than women finishers compared with the younger age groups (Fig. 1B). The largest decline in the ratio of men-to-women finishers between 1980 and 2010, however, occurred in the older age groups (age × year interaction, $P < 0.001$; Fig. 1B). For the most recent years averaged (2006–2010), the older age groups still had the greatest ratio of men-to-women finishers ($P < 0.001$).

TABLE 1: Numbers and velocity of men and women for the NYC marathon for 1980 to 2010

			Participation (No. Finishers)			Velocity	
Age (yr)	Year	Total (number per year)	Men (number per year)	Women (number per year)	Men ($m \cdot s^{-1}$)	Women ($m \cdot s^{-1}$)	Sex Difference (%)
20–29	1980–1985	3159.0	2522.5	636.5	5.26 T 0.1	4.45 T 0.2	15.4 T 1.9
	1986–1990	4347.0	3246.4	1100.6	5.22 T 0.1	4.38 T 0.2	16.2 T 1.4
	1991–1995	5042.8	3447.4	1595.4	5.20 T 0.1	4.32 T 0.3	17.0 T 4.1
	1996–2000	5812.0	3432.8	2379.2	5.27 T 0.1	4.37 T 0.3	17.0 T 3.6
	2001–2005	5188.0	2748.2	2439.8	5.25 T 0.1	4.43 T 0.3	15.5 T 3.4
	2006–2010	5912.0	3021.0	2891.0	5.08 T 0.2	4.36 T 0.2	14.1 T 0.5
30–39	1980–1985	6045.0	5113.5	931.5	5.15 T 0.1	4.32 T 0.2	16.2 T 1.7
	1986–1990	8623.2	6984.0	1639.2	5.19 T 0.1	4.46 T 0.2	14.2 T 1.7
	1991–1995	10,038.8	7749.2	2289.6	5.23 T 0.1	4.43 T 0.2	15.3 T 2.0
	1996–2000	10,987.8	7763.2	3224.6	5.15 T 0.2	4.41 T 0.2	14.3 T 1.9
	2001–2005	12,201.6	8015.4	4186.2	5.17 T 0.2	4.69 T 0.1	9.4 T 0.6
	2006–2010	13,227.4	8385.2	4842.2	5.26 T 0.1	4.60 T 0.2	12.7 T 1.2
40–49	1980–1985	3526.7	3136.3	390.3	4.68 T 0.1	3.89 T 0.2	16.9 T 1.7
	1986–1990	6627.8	5642.0	985.8	4.73 T 0.2	3.88 T 0.2	18.0 T 2.0
	1991–1995	8143.2	6635.2	1508.0	4.69 T 0.2	3.86 T 0.2	17.6 T 1.0
	1996–2000	8328.8	6383.6	1945.2	4.68 T 0.2	3.92 T 0.2	16.3 T 1.0
	2001–2005	9605.6	6886.0	2719.6	4.63 T 0.2	3.97 T 0.2	14.3 T 0.9
	2006–2010	13,320.6	9224.8	4095.8	4.67 T 0.1	4.01 T 0.2	14.1 T 2.4
50–59	1980–1985	989.2	923.3	65.8	4.13 T 0.1	3.18 T 0.2	23.0 T 2.6
	1986–1990	2160.8	1926.0	234.8	4.25 T 0.2	3.40 T 0.2	20.3 T 1.3
	1991–1995	3292.8	2812.0	480.8	4.20 T 0.1	3.40 T 0.2	19.1 T 1.3
	1996–2000	4368.4	3609.0	759.4	4.15 T 0.1	3.38 T 0.1	18.5 T 0.7
	2001–2005	4446.6	3453.2	993.4	4.10 T 0.1	3.44 T 0.1	16.2 T 0.6
	2006–2010	6276.4	4682.8	1593.6	4.22 T 0.1	3.56 T 0.1	15.6 T 1.2
60–69	1980–1985	162.3	151.7	10.7	3.53 T 0.2	2.35 T 0.4	33.5 T 7.7
	1986–1990	387.8	342.8	45.0	3.61 T 0.2	2.71 T 0.2	24.9 T 1.2
	1991–1995	625.6	552.0	73.6	3.68 T 0.2	2.84 T 0.2	22.9 T 2.4
	1996–2000	1073.6	952.8	120.8	3.73 T 0.2	2.86 T 0.1	23.3 T 0.6
	2001–2005	1066.6	882.8	183.8	3.63 T 0.2	2.86 T 0.2	21.4 T 0.8
	2006–2010	1557.2	1251.6	305.6	3.68 T 0.1	3.12 T 0.2	15.2 T 2.0

70–79	1980–1985	20.5	19.7	0.8	2.63 T 0.3	2.14 T 0.4	18.5 T 4.5
	1986–1990	53.8	49.4	4.4	2.84 T 0.2	1.99 T 0.3	29.9 T 5.3
	1991–1995	87.0	76.6	10.4	2.83 T 0.2	1.95 T 0.3	31.3 T 6.4
	1996–2000	118.4	99.6	18.8	2.88 T 0.2	2.12 T 0.3	26.3 T 4.3
	2001–2005	134.2	116.0	18.2	2.83 T 0.2	2.03 T 0.3	28.3 T 4.5
	2006–2010	178.2	152.2	26.0	3.01 T 0.2	2.38 T 0.3	20.8 T 2.3

Data shown are averaged for the 5-yr intervals (except 6 yr for 1980–1985) and averaged for the 10-yr age groups for simplicity rather than the 5-yr age groups in which analysis was performed. Shown in columns are the mean numbers of men and women finishers, the velocity of running, and the sex difference in the velocity of the top 10 men and women. Values are presented as mean T SD. Refer to text for significant effects and interactions.

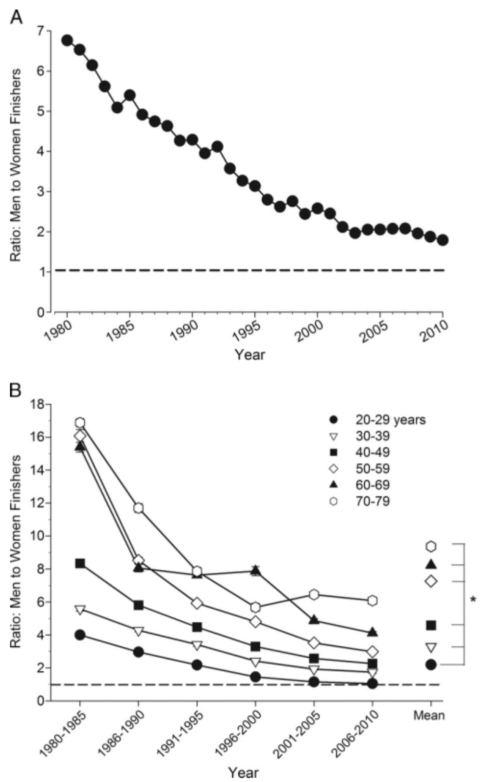

FIGURE 1: Ratio of men-to-women finishers in the NYC marathon (A) between 1980 and 2010 (total) and (B) in the 10-yr age categories between 20 and 79 yr. In panel B, the data points represent the 10-yr age categories averaged for the 5-yr intervals except 1980–1985 (6 yr). Shown are the mean ± SEM values. The horizontal dashed line is placed at the 1:1 ratio on each panel. The ratio of men-to-women finishers increased with the age group ($P < 0.001$) and declined between 1980 and 2010 ($P < 0.001$) but more so for the older age groups (age × year, $P < 0.001$) (B). In panel B, the mean of all the years (31 yr) for each age group are shown on the right side of the x-axis. *The 20- to 29-yr age group differs with each of the older age groups ($P < 0.001$).

Age differences in velocity

Velocity of running slowed with increased age after 35 yr (age effect, $P < 0.001$). For the top 10 male and top 10 female finishers, pairwise comparison indicated that those in the 30- to 34-yr age group were the fastest runners and were significantly faster than all other age groups ($P < 0.001$), except the 25- to 29-yr-olds for both men and women ($P = 0.47$). Thus, the age-related decline in velocity was significant between the 30- to 34- and the 35- to 39-yr age groups for both men and women ($P < 0.001$; Fig. 2A). The fastest running velocity of the top 10 women occurred in the 30- to 34-yr age group, and this was equivalent in velocity to the 45- to 49-yr-old men (Fig. 2A). Running velocity was similar between 1980 and 2010 (year effect, $P = 0.93$) with no interactions (age × year, $P = 1.00$) (see Table 1).

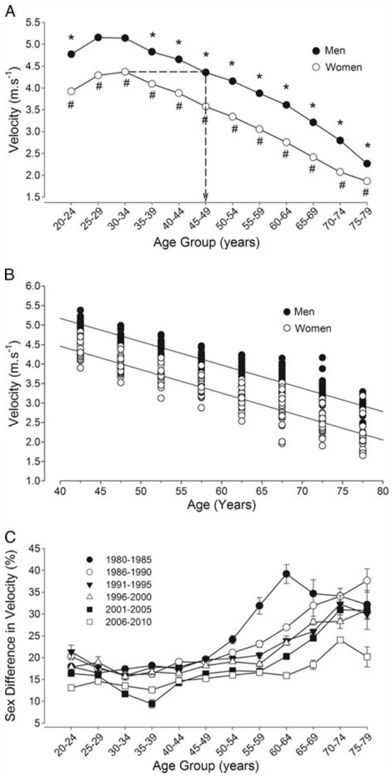

FIGURE 2: (A and B) Running velocity and (C) sex difference in running velocity in the 5-yr age brackets between 20 and 79 yr from 1980 to 2010. Data are presented as mean ± SEM in panels A and C. (A) Running velocity of the 5-yr age groups for all years and the first 10 finishers averaged for the men and women. *Age difference between the 30- to 34-yr age group and each other age atP < 0.001; #Sex differences within an age group at P < 0.001. The fastest age group for the women (30–34 yr) was similar in velocity to the 45- to 49-yr-old men and indicated by the dashed line. (B) Linear regression of velocity with increased age between 40 and 79 yr for the first-place men and women. For men, velocity = 7.56 − 0.0598 × age, r2 = 0.90 (P < 0.001), and for women, velocity = 6.86 − 0.060 × age, r2 =0.86 (P < 0.001). (C) Sex difference in running velocity (% difference) across the 5-yr age brackets between 20 and 79 yr from 1980 to 2010. The years are averaged into 5-yr categories except 1980 to 1985 (6 yr). The sex difference increased with age (P < 0.001) and decreased across years (P < 0.001) more for the older age groups (age × year, P < 0.001).

For the first-place finishers in each age group (men and women pooled), velocity declined, but there was no significant difference between the 20- and the 44-yr-olds (5-yr brackets) ($P > 0.05$), although the 30- to 34-yr-olds had the highest velocity value of all the age groups. Velocity was significantly slower in the 45- to 49-yr and older age groups compared with the 30- to 34-yr group (pairwise comparison, $P < 0.001$) but failed to reach significance between the 30- to 34- and the 40- to 44-yr age groups ($P = 0.076$). Linear regression was performed on velocities for the age groups between 40 and 79 yr to determine the rate of loss of absolute velocity and time with increased age among the first-place finishers. Both men and women showed reductions in velocity at a rate of 0.30 $m{\cdot}s^{-1}$ loss every 5 yr (or 8 min and 3 s loss every 5 yr) for both men (velocity = 7.56 − 0.0598 × age, r^2 = 0.90, $P < 0.001$) and women (velocity = 6.86 − 0.060 × age, r^2 = 0.86, $P < 0.001$) (see Fig. 2B).

Sex differences in velocity across years and age groups

Men were faster than women across all age groups, years, and places between the 1st and the 10th place (Fig. 2A, $P < 0.001$). The first-place men were 16.9% ± 6.3% faster than the women for all years and ages (Fig. 3A). This sex difference among first-place finishers was 19.9% ± 7.7% in 1980–1985 and declined to 12.6% ± 4.0% by 2006–2010 (pairwise comparison, $P = 0.004$). The relative sex difference in velocity of the first-place finishers progressively increased with age (age effect, $P < 0.001$) with the least sex difference within the 30- to 34-yr old age group (11.8% ± 1.1%) and the greatest within the 75- to 79-yr-olds (24.3% ± 11.4%).

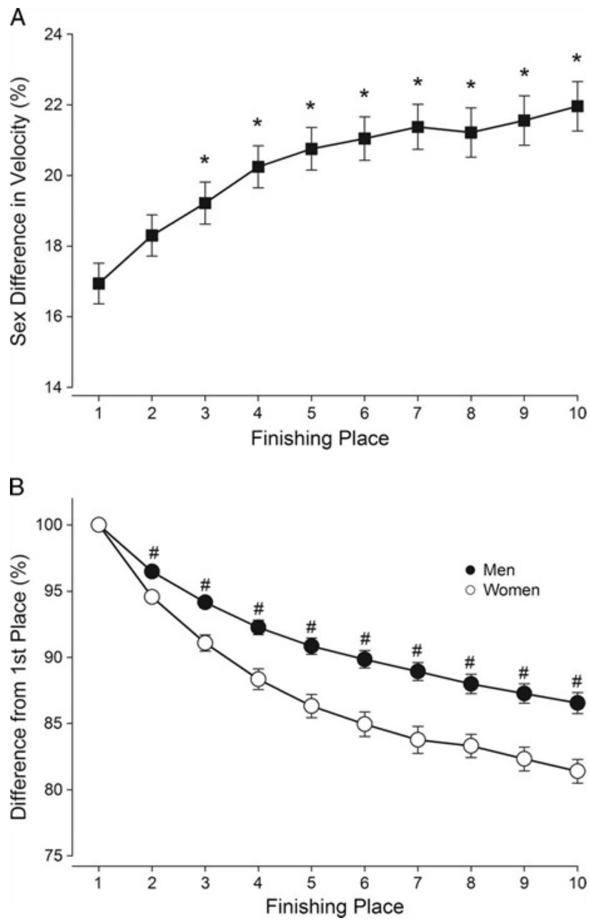

FIGURE 3: Sex difference in running velocity across place of finisher. (A) Sex difference in running velocity (% difference, mean ± SEM) across the finishing place of the runner. All 31 yr and age groups (20–79 yr) are pooled. *Age differences from the first place (P < 0.001). (B) The running velocity across the first 10 finishing places relative to the first place for the men and women. Shown are the mean ± SEM values of all the years and age groups averaged for the men and women. The women had a greater decline than the men (sex effect, P < 0.001; place × sex, P= 0.001). #Difference between men and women (P < 0.001).

When the velocities of the first 10 male and female finishers were pooled across the years and age groups, men were 20.2% ± 6.8% faster than women. The sex difference increased across the age groups (age effect, $P < 0.001$) from 15.0% ± 2.9% for the 30- to 34-yr-olds and 15.2% ± 3.7% for the 34- to 39-yr-olds (fastest age groups) to 29.5% ± 5.9% for the 70- to 74-yr-olds and 27.6% ± 9.1% for the 75- to 79-yr-olds. There was no difference between these 70- to 74- and 75- to 79-yr age groups in sex difference in running velocity (pairwise comparisons, $P = 0.29$). The sex difference also decreased between 1980 and 2010 (year effect, $P < 0.001$) but more for the older age groups (age × year interaction, $P < 0.001$, Fig. 2C).

Sex and age differences in velocity with place

The sex difference progressively increased with the finishing place of the runner from the 1st place to the 10th place across all age groups and years (place effect, $P < 0.001$, Fig. 3A). Pairwise comparisons indicated that the sex difference in the first place was less than the sex difference from the third place and higher (i.e., 3rd–10th place). A comparison of the relative reductions in velocity between the 1st and the 10th place shows that the women had greater reductions in velocity between the 1st and the 10th place than the men (sex × age interaction, $P = 0.001$, Fig. 3B). The average 10th place finisher ran at 81.4% ± 7.2% the velocity of the first-place finisher for the women and 86.5% ± 6.7% for the men.

The widening sex difference between the 1st and the 10th place occurred consistently across the years and the age groups. The increase in the sex difference across place of the finisher was at a similar rate across the years (year × place interaction, $P = 1.00$, Fig. 4A) and age groups (age × place interaction, $P = 1.00$, Fig. 4B).

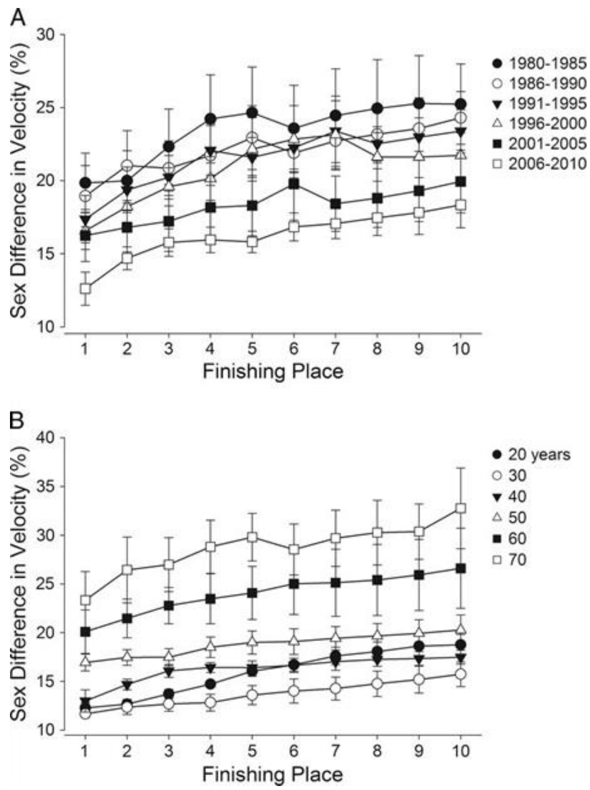

FIGURE 4: Sex difference in running velocity across place of finisher with year and age. Sex difference in running velocity (% difference) across the finishing place of the runner for (A) 31 yr and (B) age groups. Shown are the mean ± SEM values. (A) Sex difference in running velocity across the top 10 places for 31 yr between 1980 and 2010. The years are averaged into 5-yr categories except 1980 to 1985 (6 yr), and age groups are pooled. There were main effects of place and year ($P < 0.001$). (B) Sex difference in running velocity across the top 10 places for the 5-yr age brackets between 20 and 79 yr. All 31 yr are pooled. There were main effects of place and age group ($P < 0.001$).

Associations between sex difference in velocity and participation ratios

We also determined the association between the sex difference in velocity (averaged within the 10-yr age brackets) and the ratio of men-to-women finishers within that age group for each of the 31 yr. For the first-place finishers, the association was positive ($r = 0.58$, $r^2 = 0.34$, $P < 0.05$) such that the greater the ratio of men-to-women finishers, the larger the sex difference in velocity. Linear regression showed the predictive equation as $y = 10.4 + 0.998x$ (Fig. 5A). Thus, when the ratio of men to women was 1 (equal numbers men and women), the sex difference in velocity was predicted to be 11.4% among the first-place runners.

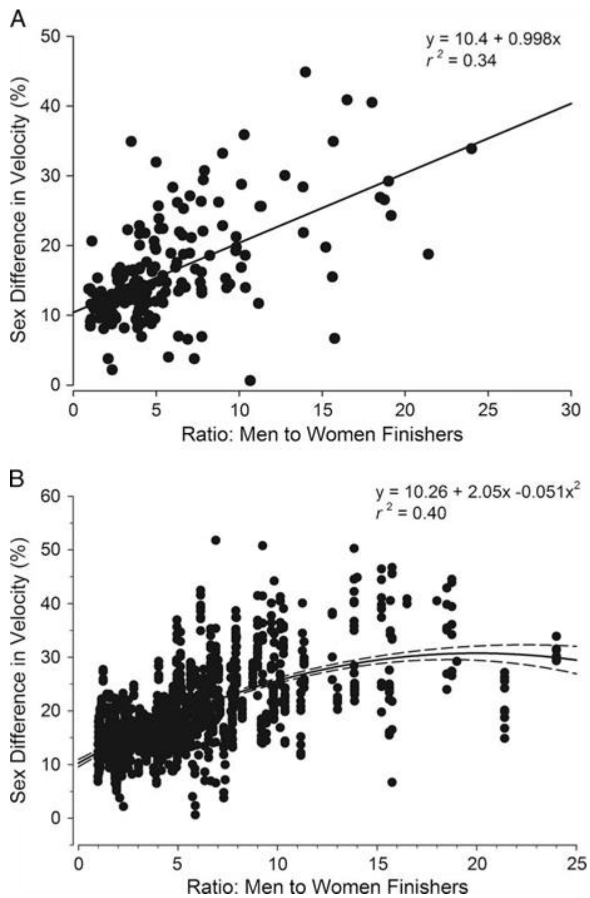

FIGURE 5: Relations between the ratio of men-to-women finishers and the sex difference in running velocity. Data points represent the ratio of men-to-women finishers for the 10-yr age group (between 20 and 79 yr) in 1 yr (between 1980 and 2010) plotted against the sex difference in running velocity for (A) the first-place finisher and (B) the top 10 finishers. (A) There was a positive association for the first-place finishers between the ratio of men to women and the sex difference in velocity (r = 0.58, r2 = 0.34, P < 0.001). Linear regression showed the best prediction with y = 10.4 + 0.998x (n = 184 pairs). (B) For the sex difference in velocity for the top 10 finishers, the relation with ratio of men to women was best fitted as a quadratic equation (r = 0.63, r2 = 0.40, P < 0.001). The sex difference for each of the 10 places for each of the 31 yr in the 10-yr age brackets is plotted. Shown is the best-fit quadratic regression (solid line) and 95% confidence band (dashed line) for the predictive equation y = 10.26 + 2.05x − 0.051x2 (n = 1763 pairs).

When the top 10 runners were included (the sex difference and ratio for 10 places for each of the 31 yr in the 10-yr age brackets), the relation was quadratic ($r = 0.63$, $r^2 = 0.40$, $P < 0.001$) (Fig. 5B). The predictive equation was $y = 10.26 + 2.05x - 0.051x^2$ ($n = 1763$) such that when the ratio was 1 (equal numbers of men and women in each age group), the sex difference was predicted to be 12.3%.

DISCUSSION

The unique findings of this study were that for the NYC marathon, the sex difference in running velocity 1) increased with the place of the runner due to a greater relative drop in velocity between the 1st and the 10th place in women compared with men for both young and older age groups, 2) was greatest for the older age groups and also declined markedly for the 31 yr examined (1980–2010) for all age groups, and 3) was positively associated with the ratio of men-to-women finishers for first-place runners and when all 10 places were included. Thus, approximately 34% of the sex difference of marathon running velocity was attributed to lesser numbers of women finishing relative to men. Our equation predicted that the sex difference for the first place would decline from 16.9% to approximately 11% with equal numbers of men and women finishers. These are the first known data to indicate that a substantial portion (one-third) of the sex difference in marathon performance at an elite level in age-placed runners was attributed to the numbers of men and women finishing and relatively less depth in the women's pool of finishers; it accounts for most of the nonphysiological factors contributing to the sex difference in running velocity. There are also broad implications for women's health and understanding the true physiological limitations of the sexes to exercise and intervention.

Velocity in running declines with age

The decline in velocity among the first-place men and women finishers in the NYC marathon from 40 to 79 yr was 8 min and 3 s every 5 yr (or 1 min 36 s every year). The velocity of marathon running declines with age as seen in this cohort and others before ([14,23,35]). Because we analyzed the data in the 5-yr age groups (rather than the 10-yr age groups), we found that the velocity was significantly reduced by 35–39 yr from the fastest age group (30–34 yr) for both men and women when the top 10 finishers were included. An analysis of data with greater proportions of recreational runners ([24]) found that the age decline in velocity did not occur until the 55-yr age group, which likely reflects the contribution of sociological factors to age-related differences in performance in this cohort.

Among elite runners, the rate of decline in running velocity can be as low as approximately 6% per decade starting in the late 30s ([18]) and usually tracks the age-related reduction in $\dot{V}O_{2max}$ until approximately 70 yr. The greatest contributor to this decline in $\dot{V}O_{2max}$ is an age-related reduction in maximal heart rate that is altered minimally with training ([6,29,35,38]). Improvements in running economy, which can occur in runners especially early on in running careers ([15,19,20]), may offset these initial age-related reductions in maximal heart rate, at least until the mid to late 30s. Similar to our findings for men (Fig. 2A), running and swimming endurance performance of elite athletes (e.g., world record holders of masters athletes ([18,35,36])) showed a linear decline until the mid-70s in age, with more rapid reductions thereafter ([35]). The rapid decline in distance running velocity with advanced age could be due to greater rates of sarcopenia and injury in surviving runners that can inhibit intense training ([26,29,35]), or possibly a reduced pool of runners due to death (the average life expectancy in the United States for men in 2012 is 76.1 yr and for women is 81.1 yr ([37])). Interestingly, the age for the greater reduction in velocity in distance running seems to have differed for men and women in past years. Joyner ([18]) examined the 1990 world record times for the 10,000-m road races and showed the more rapid decline in running velocity in women as early as 50 yr. However, the greater change in velocity with age for the marathon world record in more recent years occurs at approximately 80 yr for both men and women ([35]). This apparent large shift for the last 20 yr in the age of the rapid decline in running velocity for women likely reflects sociological factors ([18]), and our results would suggest that the participation levels of women could have been a major contributor.

Sex differences in running velocity

We found men were always faster than women across each of the age groups. The peak velocity of the women in the 30- to 34-yr age group (fastest age group) was equivalent to that of 45- to 49-yr-old men, therefore representing a 15-yr age gap in velocity between the sexes (Fig. 2A). Our study, however, presents several levels of evidence that the sex difference in marathon running velocity was larger than that due to physiological sex differences alone (i.e., greater than 10%–11%) and that the nonphysiological difference can be explained by lower number of women finishers than men. First, the sex difference in velocity decreased markedly across the 31-yr time span for all age groups but in particular among the older age groups (see Fig. 2C). This decrease in the sex difference in velocity was accompanied by an increase in the number of women finishers relative to men.

Second, the sex difference in running velocity increased with the age of the finisher, despite the evidence that men and women age similarly in those physiological factors that limit running performance ([18]). Physiologically, men and women seem to decline in $\dot{V}O_{2max}$ at similar relative rates (∼10%–11% per decade) ([6,29]) and is the most influential predictor of marathon running performance across age and sex ([18,35]). Furthermore, elite men and women on average reach peak running velocity of the marathon at similar ages (∼29 yr) ([13]). Although we showed that first-place men and women have similar absolute declines in velocity with advanced age, the relative decline for women was greater across age groups. The widening sex difference with advanced age, which was as high as 29.5% among the 70- to 74-yr-olds, decreased across the years examined as the participation of women increased at greater rates than men among these age groups. A comparison of long distance swimmers where participation rates of men and women are more equivalent than for distance running shows the sex difference to be less among first-place distance swimmers across the age groups (∼11%) ([34]) compared with the sex differences for running in this study (16%–17% for all years and ∼15% for the last 5 yr examined) and as shown by others ([18,36]).

Third, a novel and important finding of this study was the widening sex difference in running velocity across the place of the finisher (1st–10th place) that occurred across all age groups and years because women had a greater decline in velocity from the first-placed to the lower-placed finishers than the men (Fig. 3B). We previously showed that the widening sex difference occurred among all of the premiere marathon races (Marathon Majors Series) among the top 5 men and women ([13]); however, in this study, we expanded the findings to show the greater rate of decline among the lower-placed women relative to men. The widening sex difference in velocity with place was not unique to older age groups or earlier years. Older age groups had large sex differences among the first-place finishers (see Fig. 4A), so that the relative widening of the sex difference with the increased place of the finisher was at a similar rate to the younger competitors. The widening sex difference with finishing place that occurs across all of the age groups and years was accompanied by lower numbers of women finishers relative to men across the age groups and years.

Finally, one of the most important findings of this study was the strong relation between the sex difference in marathon performance and the ratio of men and women finishers. Although cross-sectional studies are often regarded as limited in determining rates of decline in performance with increased age because of historical bias and sampling, here we used the variability in performance and participation created by history to understand and expose the role that participation can influence sex differences in performance. For the first-place runners in this cohort, approximately 34% of the sex difference was explained by the ratio of men-to-women finishers. Thus, we predicted that for equal numbers of men and women finishers in a large pool of runners in each age group, the sex difference in velocity among the first-place finishers would be approximately 11.4%, which is 32.5% less than reported here for the NYC marathon and considerably closer to what is expected due to physiological sex differences. It is also similar to elite swimmers where participation of women is more equivalent to men, and women have been competing for many more years than marathon running ([34,35]). For the top seven marathons (World Marathon Majors series), the sex difference was 10.9% for the first-place finishers and 11.6% for the top five finishers pooled ([13]). The sex difference for the current world fastest times is 9.5% and is held by Patrick Makau (September 2011: 2 h, 03 min, 38 s) for men and Paula Radcliffe (April 2003: 2 h, 15 min, 25 s) for women. Thus, the portion (approximately one-third) of the sex difference in running velocity, which is above the approximately 10% sex difference attributed to physiological sex differences alone, can be attributed to the lower numbers of women finishers relative to men. Similarly, the sex difference for those who placed between the 1st and the 10th place was 20.2% ± 6.8%, and given the equal numbers of men and women, we predicted this sex difference could be reduced to 12.3%. Our study therefore shows that at least one-third of the sex difference in velocity, which accounts for most of the nonphysiological portion of the sex difference in running velocity, can be attributed to lesser numbers of women than men finishing the marathon.

Here we present evidence that lower participation rates of women than men can have a large impact on the magnitude of the sex difference in running even at the elite level in a marathon that attracts large absolute numbers of runners. Past social expectations have played a role in limiting women's participation and still have an influence especially among older women. Before the late 1970s, women were not permitted to compete in the marathon; women first competed in the World Championship Marathon in 1983 and Olympic marathon in 1984. In those early years, the 70- to 79-yr-olds from the 2010 race were approximately 40 yr old, and lifestyle exercise habits and social expectations were likely established for participation in competitive events ([31]). Social expectations, lack of social support and opportunity, and previous exercise habits in early life are factors that can play a significant role in determining exercise habits, especially in women ([9,31,39]). A pivotal event in the United States for increasing opportunity and participation in competitive running was the 1972 Title IX educational amendment to legislation, allowing women greater athletic participation and opportunity. We predict that as the number of women competitors who have benefited from Title IX gradually increases among older age groups, new running records will be set and will approach the physiological potential of women at all ages.

Although our study indicates that participation plays a major role in the larger sex difference with place of runner and advanced age, there are other hypotheses for the increased sex difference. Differences in prize money that were once considered a motivating and contributing factor do not seem to drive the larger sex difference in running velocity ([3]). Deaner ([3,4]) however hypothesized that men are more "competitive" than women and hence more motivated to perform. Physiological laboratory data using electrical and cortical stimulation ([12,21,25,30,41]) indicate that young women are just as motivated at the start and end of a short-term fatiguing exercise ([11]). The "competitiveness hypothesis" could be relevant to the range of motivations for men and women entering races and competing especially at recreational levels.

Our study results have broad implications for women's health. First, this is a potent example of how sampling bias may mask the physiological limits of women. These data provide further support that the sex bias that persists in the trials and treatments within biomedical research ([22]) can hamper a true understanding of the physiological responses of women. Second, these data remind us that women are still widely reported to be less physically active than men across all age groups ([1]). Although women have opportunities to participate, there are still forces at work that translate into less active women in society, even still among young women. Thus, women's health is potentially compromised because women do not seem to be experiencing the same protective benefits of exercise ([8]) that men experience. These issues deserve further attention.

In conclusion, we provide evidence that a lack of depth in women's running contributed to at least one-third of the sex difference in running velocity in the NYC marathon for a 31-yr period at the elite level of age group marathon finishers. This portion accounts for most of the sex difference in marathon running velocity that is not explained by physiological differences between men and women. The widening sex difference in performance with increased place of the finishers was due to the greater relative drop off in running velocity with increased place among the women than the men. The sex difference in running velocity was larger among older men and women and also decreased for a 31-yr period that women have been permitted to run the marathon. Thus, the sex differences in velocity were larger than could be explained by physiological sex differences and directly related to lower number of women finishers compared with men. Lesser numbers of women participants than men (sampling bias) therefore can have a large impact in understanding the physiological limits of women in running and possibly other events with a sex bias in participation.

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