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Running performance in a timed city run and body composition: A cross-sectional study in more than 3000 runners

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Objective: The importance of body composition for running performance is unclear in the general population. The aim of this study was to evaluate whether body composition influences running speed and whether it is a better predictor of running speed than body mass index (BMI).
Methods: The study included 1353 women (38.2 ± 12.1 y of age) and 1771 men (39.6 ± 12.1 y of age) who underwent, for the first time, a measurement of body composition by bioelectrical impedance analysis between 1999 and 2016, before a timed run occurring annually in Geneva. The running distances and times were converted to average speed (km/h). Body composition was expressed as sex-specific quartiles, where quartile 1 (lowest values) was the reference quartile. The relationships between speed and BMI or body composition were analyzed by multivariate linear regressions.
Results: Multivariate regressions showed that the higher the fat mass index (FMI) quartile, the lower the running speed in women and men (all $P < 0.001$). In men, a fat-free mass index (FFMI) in quartile 4 (>20 kg/m^2) was associated with a poor running performance ($r = -0.50$, $P < 0.001$), whereas in women, an FFMI in quartile 2 or 3 (15–16.4 kg/m^2) was associated with a higher running speed ($r = 0.23$, $P = 0.04$; $r = 0.28$, $P = 0.01$, respectively). Body composition predicted speed better than BMI in women ($R^2 = 26.8\%$ versus 14.4%) and men ($R^2 = 29.8\%$ versus 25.4%).
Conclusions: Running speed is negatively associated with BMI and FMI in both sexes. Body composition is a better predictor of running performance than BMI.

Introduction

Running performance depends on physiological and anthropometrical parameters that can both be improved by training [1,2].

For distances <10 km, the physiological determinants of running time are maximal oxygen uptake (VO_2 max); running economy, which corresponds to the steady-state oxygen consumption for a given velocity at an aerobic intensity; and the threshold of anaerobic metabolism [3]. Running performance in longer distances has been associated with VO_2 max; running economy; and fractional utilization of maximal oxygen uptake, which refers to the mean percentage of VO_2 max a person can sustain during a given time or distance [4,5].

Regarding anthropometrical parameters, a high percent of fat mass (%FM), estimated by skinfold values, negatively affected the running performance of men in a marathon [2]. A high %FM, measured by dual-energy x-ray absorptiometry (DXA), also has been negatively related with physical performance in an incremental treadmill test in 120 men [6]. In 140 male conscripts whose body composition was assessed by DXA, a 1% increase in FM decreased

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the distance run by 19.3 m in a 12-min run, but lean mass, in kg, had no effect on performance [7]. These studies suggest that FM may determine running performance in the general population. However, the joint effects of FM and fat-free mass (FFM) is unclear, as is the advantage of measuring body composition rather than body mass index (BMI).

This large cohort study, performed over 18 y, aimed at evaluating whether body composition, measured by bioelectrical impedance analysis (BIA), was associated with running speed in a timed city run and whether body composition predicted running speed better than BMI. We hypothesized that a high FM and FFM were associated with a low running speed.

Materials and methods

This large prospective cohort study included all individuals who underwent a measurement of body composition between 1999 and 2016 at the Course de l'Escalade, a timed city run occurring annually during the first Saturday of December in the city of Geneva. We excluded measurements of body composition performed in individuals <16 y of age because of the absence of normative values, in those who did not perform or finish the run, and duplicate measurements (Supplementary Fig. 1). The study was accepted by the Ethical Committee of Geneva and was registered under ClinicalTrials.gov (NCT03400761). All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional or national research committee and with the 1964 Declaration of Helsinki and its later amendments or comparable ethical standards. Informed consent was obtained from all individual participants included in the study.

Running performance

From 1999 to 2016, the running distances of the Course de l'Escalade were 7.2 km for men and elite women and 4.8 km for non-elite women and men 16 to 18 y of age, but these distances could vary by a few hundred meters every year. The race occurred over a circuit of 2.4 km, which the participants had to run twice (elevation gain and loss: +102 and −111 m) or thrice (elevation gain and loss: +155 and −164 m). The registration in the elite category required an age of 20 to 39 y and a running speed of ≥12 km/h in women and 15 km/h in men, in the previous 2 y, in an official timed run. In 2002, 2007, and 2012, the organizers added another race to the event, with a distance that varied between 18 and 19 km. This race also occurred on the first Saturday of December, except in 2012, when it was on the preceding Friday. In view of the different running distances, running performance was evaluated in terms of average speed in km/h. All running times were measured with a microchip integrated in the bib of the runners.

Upon contract with the organizing committee, Datasport AG (Obergerlafingen, Switzerland) stores the first and last name of each participant, date of birth, address, running time, and running category. For the purpose of the study, Datasport provided one file containing the running times and running categories of each person who underwent at least one body composition measurement at the Course de l'Escalade (Datasport 1) and one file containing the running distances corresponding to each running category (Datasport 2). These two databases were merged to obtain the running distances and times in a single file.

Body composition measurements

The Nutrition Unit of the Geneva University Hospitals has had a stand at the Course de l'Escalade on the Saturday of the race and the preceding Friday every year since 1991. There, free measurements of body composition by BIA are offered to all individuals whether or not they are participating in the run. BIA measurements are performed before any race to avoid invalid BIA measurements owing to dehydration. A member of the nutrition team checks with the volunteers that this condition is fulfilled before letting them proceed with a questionnaire and the measurement.

Since 1999, the volunteers receive an explanatory flyer regarding BIA measurement and complete a questionnaire containing their date of birth and habitual physical exercise. By signing this questionnaire, which acts as informed consent, the volunteers agree to the use of their body composition data for clinical research.

After completing the questionnaire, the volunteers are weighed wearing lightweight clothes without shoes, with an electronic scale, and their height is measured with a height gauge. The scale and height gauge are calibrated annually by the technical staff of the Geneva University Hospitals. The volunteers then undergo a tetrapolar BIA measurement by previously trained staff. They lie in the supine position, with arms and legs in abduction. Electrodes are stuck on the dorsal surface of the right

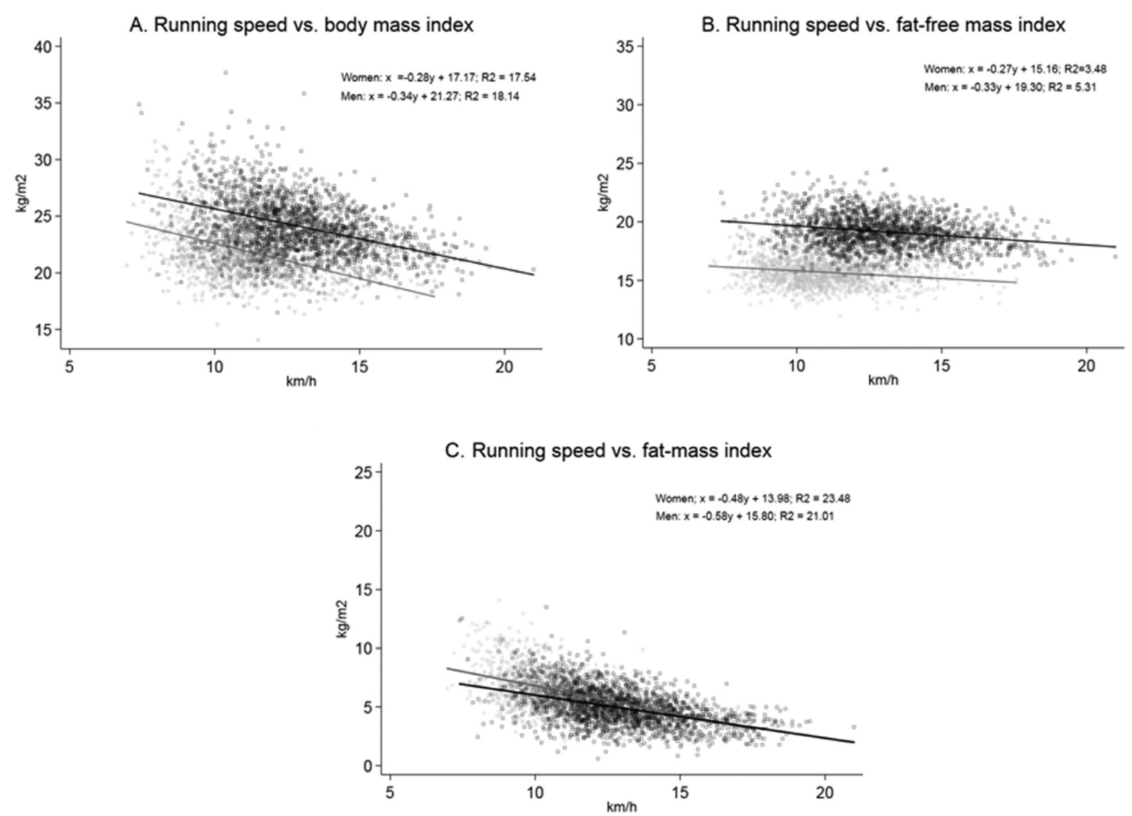

Fig. 1. Scatterplots between (**A**) running speed (km/h) and body mass index, (**B**) fat-free mass index, or (**C**) fat mass index in women (gray circles) and men (black squares). On each figure, the linear regression lines are shown for women (gray) and men (black), in addition to their equation and R^2. All linear regressions were highly significant ($P < 0.001$).

hand, wrist, ankle, and foot, as described elsewhere [8]. A generator applies an alternative electrical current (800 mA; 50 kHz) to these electrodes and measures the resulting resistance and reactance. From 1999 to 2001, the BIO-Z (Spengler, Paris, France) or Eugedia (Eugédia-Spengler, Cachan, France) BIA device was used. Since 2002, the Nutriguard (Data Input GmbH, Darmstadt, Germany) BIA device has been used. For all BIA devices, a calibration jig (CJ 4000; Xitron Technologies) was used to calibrate phase angle and impedance at 50 kHz, with a limit of tolerance set at ±2 degrees and ±5 Ω, respectively. The agreement for FFM between all devices used in the Nutrition Unit is 0.03 kg (95% confidence interval [CI], −1.7 to 2.1 kg) and between observers is 0.02 kg (95% CI, −1.3 to 1.3 kg) [9].

The anthropometric and electrical data of the volunteers were transferred onsite on software to calculate BMI, FFM (kg) by the Geneva formula [10], and FM (kg) by subtraction of FFM from body weight. The Geneva formula was developed and validated against DXA in the Geneva population [10]. FFM and FM are divided by height (m^2) to be converted into FFM index (FFMI) and FM index (FMI). The body composition data were then printed and handed to each volunteer. The results are compared by a senior member of the nutrition team to normative values for the population living in the Geneva area [11] and to the previous BIA measurements of the volunteer performed at this event, if available. Overall, completion of the questionnaire, BIA measurement, and printing of the results take approximately 10 min.

All the data pertaining to the body composition measurements performed at the Course de l'Escalade over the years were stored on a protected computer database of the Geneva University Hospitals.

Meteorologic conditions

Meteorologic conditions of Geneva from 1999 to 2016, per day and per hour, were retrieved from the Internet [12]. For the purpose of the study, data on air temperature (Celsius) and relative humidity (%) 2 m above ground was kept. As races were performed throughout the day, we reported the mean values of each racing day (i.e., from 08:00 am to 12:00 pm).

Merging of the different databases

The flowchart summarizing the data merging and cleaning is presented in Supplementary Figure 1. The Datasport file was merged with the body composition data from the Nutrition Unit using the following parameters: first and last name, sex, and date of birth. This merging highlighted that 6506 BIA measurements (49.4% of the total BIA measurements) were performed in individuals who run the race that same year.

As we could keep only one measurement per person for a clean cross-sectional statistical analysis, we kept the first BIA measurement with simultaneous running time for each individual with repeated data. These data were merged with the database containing the meteorologic conditions of the racing day.

Statistical analysis

The characteristics of the participants are shown as means ± standard deviation (SD) for continuous data and absolute numbers and percentages for categorical data. We compared continuous data between women and men, or elite and non-elite runners, with unpaired *t* tests and categorical data with Mann−Whitney U tests. Significance of *P* values, set initially at $P < 0.05$, remained at $P < 0.05$ after adjusting for multiple comparisons by the Benjamini−Hochberg method [13]. We performed scatterplots of speed versus BMI, FFMI, or FMI and derived the sex-specific regression lines and equations for each association.

Categorizations of continuous values were performed to better visualize the progressive effect of these variables on running speed in subsequent linear regression models. BMI was categorized as <18.5, 18.5 to 24.9, 25 to 29.9, and ≥30 kg/m^2; FMI and FFMI were categorized as sex-specific quartiles, where quartile 1 corresponds to the lowest value and reference category; and age was grouped as 16 to 24, 25 to 34, 35 to 44, 45 to 54, 55 to 64, and >65 y. Because measurements were performed over 18 y, we split the calendar time into six periods: 1999 to 2001, 2002 to 2004, 2005 to 2007, 2008 to 2010, 2011 to 2013, and 2014 to 2016. We calculated trends of anthropometric characteristics and speed across

Table 1
Characteristics of the study population (N = 3124)

	All			Women			Men			
	n	%	Mean ± SD	n	%	Mean ± SD	n	%	Mean ± SD	*P*-value*
Continuous										
Age at measurement (y)	3124	100	39.02 ± 12.14	1353	43	38.23 ± 12.09	1771	57	39.63 ± 12.14	0.001
vBody weight (kg)	3124	100	68.15 ± 11.59	1353	43	59.17 ± 7.59	1771	57	75.03 ± 9.15	<0.001
Height (cm)	3124	100	171.04 ± 9.20	1353	43	163.90 ± 6.47	1771	57	176.51 ± 6.94	<0.001
Body mass index (kg/m^2)	3124	100	23.18 ± 2.68	1353	43	22.02 ± 2.44	1771	57	24.07 ± 2.50	<0.001
Fat-free mass index (kg/m^2)	3124	100	17.66 ± 2.16	1353	43	15.70 ± 1.16	1771	57	19.16 ± 1.42	<0.001
Fat mass index (kg/m^2)	3124	100	5.52 ± 1.78	1353	43	6.32 ± 1.66	1771	57	4.91 ± 1.61	<0.001
Fat mass (%)	3124	100	23.64 ± 6.33	1353	43	28.34 ± 4.68	1771	57	20.06 ± 4.92	<0.001
Running speed (km/h)	3124	100	12.10 ± 2.14	1353	43	10.94 ± 1.65	1771	57	12.98 ± 2.02	<0.001
Categorical										
Age (y)										
15−24	433	14		213	16		220	12		0.046
25−34	792	25		355	26		437	25		
35−44	931	30		388	29		543	31		
45−54	653	21		273	20		380	21		
55−64	255	8		103	8		152	9		
≥65	60	2		21	2		39	2		
Body mass index (kg/m^2)										
< 18.5	68	2		59	4		9	1		<0.001
18.5−24.9	2323	74		1144	84		1179	67		
25−29.9	692	22		140	10		552	31		
≥ 30	41	1		10	1		31	2		
Racing distance (km)										
< 5	1337	43		1302	96		35	3		<0.001
5-10	1661	53		13	1		1648	93		
> 10	126	4		38	3		88	5		
Calendar time (y)										
1999−2001	731	23		287	21		444	25		<0.001
2002−2004	612	20		265	19		347	20		
2005−2007	561	18		244	18		317	18		
2008−2010	460	15		199	15		261	15		
2011−2013	353	11		171	13		182	10		
2014−2016	407	13		187	14		220	12		

*Comparisons between women and men: unpaired *t* test for continuous variables, Mann−Whitney U tests for categorical variables.

Table 2
Quartiles of fat-free mass index and fat mass index (N = 3124)

	Fat-free mass index			Fat mass index		
	n	%	kg/m^2	n	%	kg/m^2
Women						
Quartile 1	339	25	<14.9	339	25	<5.2
Quartile 2	338	25	15–15.6	338	25	5.2–6.1
Quartile 3	338	25	15.7–16.4	338	25	6.2–7.2
Quartile 4	338	25	>16.4	338	25	>7.2
Men						
Quartile 1	443	25	<18.2	443	25	<3.8
Quartile 2	443	25	18.2–19	443	25	3.9–4.7
Quartile 3	443	25	19.1–20	443	25	4.8–5.8
Quartile 4	442	25	>20	442	25	>5.9

categories of calendar time and quartiles of FFMI and FMI using the Cuzick's nonparametric test.

Sex-specific univariate linear regression models evaluated the association of speed and categories of age, BMI, FFMI, FMI, running distance, calendar time, temperature, and relative humidity. We performed two sex-specific multivariate linear regression models, adjusted for categories of age, racing distance and calendar time, and temperature and relative humidity, to predict speed. Model 1 evaluated the effect of BMI, and model 2 the effect of FMI and FFMI quartiles. For each multivariate linear regression model, we calculated the regression coefficients, their standard errors, and 95% confidence interval (CI), in addition to the adjusted R^2, which corresponds to the variance of running speed explained by the model. The higher the R^2, the better the regression model explains the running speed.

All statistical analyses were performed with Stata software version 15.1 (StataCorp., College Station, TX, USA). We did not perform any power analysis because %FM seemed related to running performance in smaller studies [7] and our sample size was large.

Results

The study included 3124 participants (43% women), whose characteristics are detailed in Table 1. As expected in view of the running categories, most women ran <5 km and most men between 5 and 10 km. Women had a higher BMI and FMI, but a lower FFMI and running speed than men. Elite runners (79 women, 152 men) had a lower BMI, FMI, FFMI, and running speed than runners in the other racing categories (Supplementary Table 1). Over all calendar years, mean temperature and relative humidity on the racing day were 1.9°C (SD 1.1) and 79% (SD 5.9), respectively.

The scatterplots of running speed versus BMI, FFMI, or FMI and the derived regression lines are shown in Figure 1. Based on the R^2, FMI was the best predictor of running speed in both women and men. An FMI decrease of 1 kg/m^2 was associated with a 0.5 km/h increase in running speed. This corresponds to an improvement in running time by 1.5 min over 7.2 km in a person running originally at 12 km/h.

Table 3
Multivariate linear regression models to predict running speed (km/h) in women (n = 1353)

	Univariate regressions					Multivariate regression models									
						Model 1 (R^2 = 14.4%)					Model 2 (R^2 = 26.8%)				
	Coefficient	SE	*P*-value	95% CI		Coefficient	SE	*P*-value	95% CI		Coefficient	SE	*P*-value	95% CI	
Age (y)															
15–24	0.00					0.00					0.00				
25–34	−0.47	0.14	<0.001	−0.75	−0.20	−0.41	0.13	0.002	−0.68	−0.15	−0.38	0.12	0.002	−0.62	−0.13
35–44	−0.59	0.14	<0.001	−0.86	−0.32	−0.55	0.13	<0.001	−0.81	−0.29	−0.58	0.12	<0.001	−0.82	−0.34
45–54	−0.77	0.15	<0.001	−1.06	−0.48	−0.75	0.14	<0.001	−1.03	−0.47	−0.65	0.13	<0.001	−0.91	−0.39
55–64	−1.35	0.19	<0.001	−1.73	−0.97	−1.29	0.18	<0.001	−1.66	−0.93	−1.14	0.17	<0.001	−1.47	−0.80
≥65	−1.73	0.37	<0.001	−2.46	−1.01	−1.62	0.35	<0.001	−2.31	−0.93	−1.42	0.33	<0.001	−2.07	−0.79
Body mass index (kg/m^2)															
<18.5	0.98	0.21	<0.001	0.57	1.39	0.84	0.21	<0.001	0.44	1.25					
18.5–24.9	0.00					0.00									
25–29.9	−1.27	0.14	<0.001	−1.55	−1.00	−1.13	0.14	<0.001	−1.40	−0.86					
≥30	−2.40	0.50	<0.001	−3.38	−1.42	−2.36	0.49	<0.001	−3.32	−1.41					
Fat-free mass index (kg/m^2)															
Q1	0.00										0.00				
Q2	−0.08	0.13	0.542	−0.32	0.17						0.23	0.11	0.041	0.01	0.44
Q3	−0.16	0.13	0.204	−0.40	0.09						0.28	0.11	0.013	0.06	0.50
Q4	−0.69	0.13	<0.001	−0.93	−0.44						0.19	0.12	0.110	−0.04	0.43
Fat mass index (kg/m^2)															
Q1	0.00										0.00				
Q2	−0.77	0.11	<0.001	−0.99	−0.55						−0.81	0.11	<0.001	−1.02	−0.60
Q3	−1.30	0.11	<0.001	−1.52	−1.08						−1.35	0.11	<0.001	−1.56	−1.13
Q4	−2.10	0.11	<0.001	−2.32	−1.88						−2.06	0.12	<0.001	−2.30	−1.83
Racing distances (km)															
<5	0.00					0.00					0.00				
5–10	0.03	0.46	0.951	−0.87	0.93	0.20	0.44	0.652	−0.67	1.06	0.08	0.41	0.837	−0.71	0.88
>10	−0.12	0.27	0.667	−0.65	0.42	−0.19	0.26	0.469	−0.69	0.32	−0.26	0.23	0.272	−0.73	0.21
Calendar time (y)															
1999–2001	0.00					0.00					0.00				
2002–2004	0.15	0.14	0.290	−0.13	0.42	−0.05	0.15	0.738	−0.35	0.25	−0.34	0.14	0.018	−0.63	−0.06
2005–2007	−0.20	0.14	0.155	−0.48	0.08	−0.28	0.15	0.054	−0.57	0.00	−0.52	0.14	<0.001	−0.80	−0.25
2008–2010	−0.09	0.15	0.569	−0.38	0.21	−0.25	0.27	0.341	−0.77	0.27	−0.60	0.25	0.015	−1.09	−0.12
2011–2013	−0.57	0.16	<0.001	−0.88	−0.26	−0.72	0.26	0.006	−1.23	−0.20	−1.08	0.24	<0.001	−1.56	−0.61
2014–2016	−0.56	0.15	<0.001	−0.86	−0.26	−0.75	0.21	<0.001	−1.16	−0.34	−0.98	0.19	<0.001	−1.36	−0.60
Meteorologic conditions															
Temperature (°C)	0.01	0.01	0.683	−0.02	0.03	−0.02	0.02	0.288	−0.06	0.02	−0.05	0.02	0.013	−0.08	−0.01
Relative humidity (%)	0.02	0.01	<0.001	0.01	0.03	0.01	0.01	0.442	−0.01	0.02	0.00	0.01	0.911	−0.02	0.01

SE, standard error; CI, confidence interval.

Table 4
Multivariate linear regression models to predict running speed (km/h) in men (n = 1771)

	Univariate regressions					Multivariate regression models									
						Model 1 (R^2 = 25.4%)					Model 2 (R^2 = 29.8%)				
	Coefficient	SE	*P*-value	95% CI		Coefficient	SE	*P*-value	95% CI		Coefficient	SE	*P*-value	95% CI	
Age (y)															
15–24	0.00					0.00					0.00				
25–34	−0.76	0.16	<0.001	−1.07	−0.45	−0.65	0.15	<0.001	−0.94	−0.35	−0.42	0.15	0.004	−0.71	−0.13
35–44	−0.94	0.15	<0.001	−1.23	−0.64	−0.73	0.15	<0.001	−1.02	−0.44	−0.45	0.15	0.002	−0.73	−0.16
45–54	−1.42	0.16	<0.001	−1.74	−1.11	−1.21	0.16	<0.001	−1.52	−0.91	−0.86	0.15	<0.001	−1.16	−0.55
55–64	−2.34	0.20	<0.001	−2.73	−1.95	−2.12	0.19	<0.001	−2.49	−1.74	−1.68	0.19	<0.001	−2.06	−1.31
≥65	−3.63	0.33	<0.001	−4.28	−2.99	−3.37	0.31	<0.001	−3.97	−2.77	−2.90	0.30	<0.001	−3.49	−2.31
Body mass index (kg/m^2)															
<18.5	0.45	0.63	0.478	−0.79	1.68	0.15	0.59	0.796	−1.00	1.31					
18.5–24.9	0.00					0.00									
25–29.9	−1.44	0.10	<0.001	−1.63	−1.25	−1.21	0.09	<0.001	−1.39	−1.03					
≥30	−2.91	0.34	<0.001	−3.59	−2.24	−2.84	0.32	<0.001	−3.46	−2.21					
Fat-free mass index (kg/m^2)															
Q1	0.00										0.00				
Q2	−0.30	0.13	0.025	−0.56	−0.04						−0.04	0.12	0.707	−0.27	0.18
Q3	−0.62	0.13	<0.001	−0.88	−0.36						−0.21	0.12	0.068	−0.44	0.02
Q4	−1.13	0.13	<0.001	−1.39	−0.87						−0.50	0.12	<0.001	−0.74	−0.26
Fat mass index (kg/m^2)															
Q1	0.00										0.00				
Q2	−0.51	0.12	<0.001	−0.75	−0.27						−0.43	0.12	<0.001	−0.66	−0.20
Q3	−1.34	0.12	<0.001	−1.58	−1.10						−1.14	0.12	<0.001	−1.37	−0.91
Q4	−2.34	0.12	<0.001	−2.58	−2.10						−1.93	0.12	<0.001	−2.17	−1.68
Racing distances (km)															
<5	0.00					0.00					0.00				
5–10	−0.17	0.35	0.621	−0.85	0.51	0.40	0.31	0.201	−0.21	1.01	0.52	0.30	0.09	−0.08	1.11
>10	−0.64	0.40	0.113	−1.43	0.15	−0.13	0.37	0.728	−0.85	0.59	−0.01	0.36	0.97	−0.71	0.69
Calendar time (y)															
1999–2001	0.00					0.00					0.00				
2002–2004	−0.35	0.14	0.014	−0.63	−0.07	−0.60	0.15	<0.001	−0.88	−0.31	−0.70	0.14	<0.001	−0.98	−0.43
2005–2007	−0.22	0.15	0.130	−0.51	0.07	−0.38	0.14	0.006	−0.65	−0.11	−0.42	0.14	0.002	−0.69	−0.15
2008–2010	−0.38	0.16	0.015	−0.68	−0.07	−0.78	0.25	0.002	−1.27	−0.29	−0.89	0.24	<0.001	−1.37	−0.41
2011–2013	−0.94	0.18	<0.001	−1.29	−0.60	−1.31	0.25	<0.001	−1.80	−0.81	−1.39	0.25	<0.001	−1.88	−0.91
2014–2016	−1.04	0.16	<0.001	−1.36	−0.72	−1.37	0.19	<0.001	−1.75	−0.99	−1.46	0.19	<0.001	−1.83	−1.10
Meteorologic conditions															
Temperature (°C)	0.01	0.01	0.683	−0.02	0.03	−0.05	0.02	0.022	−0.08	−0.01	−0.05	0.02	0.005	−0.09	−0.02
Relative humidity (%)	0.02	0.01	<0.001	0.01	0.03	0.00	0.01	0.832	−0.02	0.01	0.00	0.01	0.644	−0.02	0.01

SE, standard error; CI, confidence interval.

The sex-specific cutoffs of FFMI and FMI quartiles are shown in Table 2. Over the years of measurements, the participants became younger, heavier, taller, and slower in both sexes (Supplementary Table 2). The trends of age, BMI, FFMI, and FMI were different across quartiles of FFMI (Supplementary Table 3) and FMI (Supplementary Table 4). As the quartile of FMI increased, the age, BMI, and FFMI increased but the running speed decreased.

Univariate linear regressions showed that speed decreased progressively with higher categories of age, BMI, FMI, and FFMI in both sexes but racing distance had no effect on running speed in women (Table 3) and men (Table 4). All multivariate regression models were highly significant with a $P < 0.001$. In women (Table 3), model 1 confirmed the negative association between running speed and BMI. Model 2 highlighted that a high FMI was related with poor running performance, whereas having an FFMI in quartile 2 or 3 was beneficial. Running speed in women was much better predicted by body composition (model 2) than by BMI (model 1), with an R^2 of 26.8% and 14.4%, respectively. Men showed similar results to women. The higher the BMI (model 1) or the FMI (model 2), the slower the running speed. However, in contrast to women, a high FFMI (quartile 4) was associated with a slower running speed than in quartile 1. In men, running speed was also better predicted with body composition (R^2 = 29.8%) than with BMI (R^2 = 25.4%).

Discussion

The present study demonstrated that, in univariate linear regression models, running performance is negatively associated with BMI, FMI, and FFMI in both sexes. After adjusting for age, racing distance, calendar time, and meteorologic conditions, a high BMI and a high FMI remain predictors of poor running performance. Regarding FFMI, its effect on speed is controversial because a high FFMI appears rather beneficial in women but is detrimental in men. In both sexes, body composition predicts running speed better than BMI.

This large cohort study confirmed the negative effect of FM on running performance found in smaller field studies where FM was derived from skinfold thickness [2,14]. It also demonstrated the negative linear relationship between FM and running speed in the general population. However, this association may not occur in ultra-endurance athletes. Running time was not associated with %FM determined by skinfolds in 17 ultra-endurance runners who finished a 1200-km run within 17 d consecutively [15]. Similarly, in 17 athletes participating in a triathlon consisting of 11.6 km of swimming, 540 km of cycling, and 126.6 km of running, there was no link between body weight and %FM and endurance performance [16]. Thus, although FM is a determinant of running performance in the general population, other elements, such as physiological and psychological parameters, prevail in ultra-endurance athletes who likely have a very low FM.

The present study demonstrated that, in men, an FFMI > 20 kg/m^2 (quartile 4) hampered performance compared with an FFMI < 18.2 kg/m^2 (quartile 1). In their study, Matilla et al. did not find any effect of lean body mass on the distance run within 12 min in Finish men 19.8 $\pm$ 1 y of age [7]. However, their participants had a lower mean BMI and FFMI than the individuals in quartile 4 of FFMI. Skeletal muscle mass also was not a determinant of performance in ultra-endurance male runners [16]. Therefore, it is likely that only a very high FFM is detrimental for running speed in men. In women, an FFMI between 15 and 16.4 kg/m^2 had a more positive effect on performance than an FFMI <15 kg/m^2. It is unclear why a high FFMI appears beneficial in women but not in men. Perez-Gomez et al. reported better running performance over 300 m for a given percentage of muscle mass in men than in women [17]. The authors attributed these differences, at least in part, to a higher anaerobic capacity, owing to a higher volume of type II fibers and a higher aerobic capacity expressed as VO_2 max/kg body weight, in men. This study suggested that muscle mass may be metabolically more efficient in men during exercise and that they can reduce their FFMI more than women to improve their running performance.

In the present study, body composition predicted running speed better than BMI, likely because it differentiates FM from FFM. Body composition is a component of physical fitness and reflects physical activity. The lower the FMI, the more likely the person is physically active. In contrast, BMI masks body composition and does not differentiate individuals who are fit and have a low FM from those who are sedentary and likely have a higher proportion of FM [18]. Thus, the present result is not surprising. However, it highlights the importance of measuring and tracking body composition in elite or ambitious recreational runners. Although DXA often is considered a gold standard for measuring body composition, it requires trained staff and expensive devices and leads to an irradiation of the participants. Therefore, it is not the ideal method for repeated measurements in a field setting in contrast to anthropometrics or BIA. As skinfold measurements may have a poor interobserver reproducibility in adults when performed by non-trained individuals [19], BIA represents an interesting alternative and has the advantage of being inexpensive, more reproducible, and easy to perform (e.g., directly in the office of sports physicians).

The strength of this study was its large number of participants. We had access to the precise running distance and time of each participant and could adjust results for the meteorologic conditions of the racing day.

The interpretation of this study was limited by lack of knowledge on comorbidities of the runners. However, the studied population seemed to be healthy, as they were able to run. Body composition was measured by BIA. The derived results depended on the used devices and formulae and subject (e.g., hydration and health state) [20]. However, we limited these biases by using cross-calibrated BIA devices, calculating body composition by a BIA formula validated in healthy adults living in the Geneva area [10], and measuring the volunteers before any race by individuals who had been trained previously by the Nutrition Unit. An adjustment for physiological parameters would have been ideal, but measurement of VO_2 max for instance is unrealistic in view of the large number of individuals measured yearly over 2 d. It would have been interesting to take into account the elevation gain or loss during each race, which varied by running categories. However, this variable likely does not affect the results as most women and men ran on a very similar running circuit over the years. Finally, as BIA measurement was performed on a voluntary basis, there is a selection bias that could affect the generalization of the results. However, this did not influence the association between body composition and running speed.

Conclusions

The present study demonstrated the negative association between running speed, BMI, and FMI in men and women. Interestingly, body composition predicted running speed better than BMI, which highlights the importance of its measurement and follow-up in ambitious runners. In a future study, we will determine the evolution of running performance according to the changes in body composition.

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