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Impact of aging on maximal oxygen uptake in female runners and sedentary controls

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ABSTRACT

The present study aimed to compare VO_2max (absolute, adjusted to total body mass, and adjusted to lean mass) in recreational runners and sedentary women < and > 50 yr and verify the effect of aging and physical activity level on the three types of VO_2 max expression. The study included 147 women:85 runners (45.7 ± 14.1 yr) and 62 sedentary controls (48.8 ± 9.8 yr). They were subjected to cardiopulmonary exercise testing for VO_2 max measurement and a body composition test by dual-emission X-ray absorptiometry system. VO_2max were expressed as absolute values (L/min), relative to total body mass values (mL/kg/min), and relative to lean mass values (mL/kgLM/min). The two-way analysis of variance revealed a significant interaction [$F(2,131) = 4.43$, $p < 0.001$] and effects of age group [$F(2,131) = 32.79$, $p < 0.001$] and physical activity group [$F(2,131) = 55.64$, $p < 0.001$] on VO_2max (mL/min). VO_2max (mL/kg/min) and VO_2 max (mL/kgLM/min) were significantly influenced by age and physical activity levels. The multiple regression model explains 76.2 % of the dependent variable VO_2max (mL/kg/min), age ($\beta = -0.335$, $t = -7.841$, $p < 0.001$), and physical activity group ($\beta = -0.784$, $t = -18.351$, $p < 0.001$). In conclusion, female runners had higher VO_2 max values than sedentary women at all ages, even though aging has a greater impact on VO_2 max in the runners group. In addition to cardiorespiratory fitness, women's metabolic lean mass function, as measured by VO_2max adjusted by lean mass, is significantly influenced by aging. Finally, physical activity has a greater impact on VO_2 max levels than aging.

1. Introduction

Non-communicable chronic diseases are the primary cause of death worldwide. In this context, cardiovascular diseases (CVDs) are the most common cause of death (Haakenstad et al., 2022). In 2019, CVD accounted for ~35 % of total deaths in women (Haakenstad et al., 2022). Despite several initiatives and grassroots campaigns to reduce CVD in women, the prevalence of CVD has remained stable over the last decade (Vogel et al., 2021). Physical inactivity was identified as one of the strongest predictor of CVD (Elagizi et al., 2020) and an independent predictor of all-cause and disease-specific mortality (Booth et al., 2012), accounting for approximately 1.9 million deaths worldwide (Weintraub et al., 2011). This situation is particularly important for women, who tend to be less physically active than men (Bellettiere et al., 2019).

The most studied index of aerobic exercise capacity is the maximum oxygen uptake (VO_2max) (Booth et al., 2012; Bassett and Howley, 2000), which represents the highest rate of oxygen intake and use by the body. This is one of the main variables in exercise physiology (Bassett and Howley, 2000). However, the association between VO_2max and CVD varies depending on how VO_2max is expressed, including absolute (L/min), adjusted to total body mass (mL/kg/min), or adjusted to lean mass (mL/kgLM/min) (McMurray et al., 2011).

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The absolute value of VO_2max is an excellent indicator of cardiorespiratory fitness, which is primarily limited by the heart, especially the maximal systolic volume, and, consequently, the maximal cardiac output (Bassett and Howley, 2000). Despite the importance of absolute VO_2max, it is ineffective for comparing individuals with different body structures or compositions (Goran et al., 2000; Buskirk and Taylor, 1957). Significant body mass loss, such as following bariatric surgery, can lead to improved exercise tolerance without affecting VO_2max absolute value (Remígio et al., 2018; Dereppe et al., 2019; Kanoupakis et al., 2001). These findings could be because of decreased body mass, which reduced the energy requirement for exercise but provided no significant benefits to the cardiorespiratory system or aerobic gain (Remígio et al., 2018).

VO_2max can be adjusted to total body mass (mL/kg/min) instead of absolute values (L/min), making it easier to compare individuals of different body sizes (Bassett and Howley, 2000). The most commonly used variable for assessing aerobic performance is VO_2 max adjusted to total body mass (VO_2max/BM). In healthy adults, values >31.5 mL/kg/min are recommended (Novák and Štork, 2023), and low VO_2 max/BM values have been associated with an increased risk of CVD, diabetes mellitus, and hypertension, regardless of sex, age, and presence of obesity (Neto et al., 2019). Since 1992, Mancini et al. (Mancini et al., 1991) proposed that VO_2 max/BM < 14 mL/kg/min can indicate heart transplantation for patients with heart failure. Despite the importance of this variable and the indisputable evidence that it helps compare individuals with different body sizes, it is not generally considered an adequate measurement of cardiac fitness in all participants (Hothi et al., 2015). Obese women may have a low value of VO_2 max/BM, although this does not necessarily indicate a poor cardiac capacity (Loftin et al., 2001). Therefore, this variable is unreliable for determining cardiac fitness in obese individuals (Hothi et al., 2015). This is particularly important for women because, in most countries, obesity is more common among women than men (Kantowski et al., 2024). Another factor that can influence VO_2max/BM is the height. Tall athletes have higher VO_2max values than shorter ones (Siahkouhian, 2009). Further research is required to determine the association between the effect of height on VO_2max/BM and factors such as lung capacity or movement patterns (Siahkouhian, 2009).

Using VO_2 max relative to lean mass (mL/kgLM/min) may be the most accurate technique to evaluate the metabolic lean mass function (Huth et al., 2016), as it is not affected by fat mass (Goran et al., 2000). A precise and accurate method for measuring lean mass is dual-energy X-ray absorptiometry (DXA). DXA distinguishes total bone mineral content from fat and lean body mass (Imboden et al., 2017). Besides muscles, lean mass contains nonmuscle components, such as blood and some interstitial fluid, which differs from muscle mass. Lean mass and fat-free mass (FFM) are not interchangeable when the latter includes bone mineral content (Godang et al., 2010), which does not contribute to aerobic exercise metabolism. Thus, lean mass by DXA is calculated as FFM minus bone minerals (Scafoglieri and Clarys, 2018).

Obese individuals often have low VO_2max/BM but normal values for VO_2 max relative to lean mass (VO_2max/LM) (Goran et al., 2000), therefore, this is preferred to compare individuals with different body compositions (Goran et al., 2000; Vanderburgh and Katch, 1996). As women increase body mass during menopause and aging (Hurtado et al., 2024), comparing VO_2max/LM may be useful. This measure may also be helpful for coaches and athletes who require good aerobic performance (Zhou, 2021).

Therefore, VO_2max/BM should be used to compare performance, and VO_2 max/LM should be used to compare the physiological ability of lean mass to consume oxygen (Zhou, 2021).

Physical inactivity has been linked to decreased VO_2 max (Booth et al., 2012). Conversely, physical activity, particularly aerobic training, can significantly increase VO_2max (Milanović et al., 2015). VO_2max/BM decreases with age, among endurance-trained athletes or among sedentary subjects, which is related to the deterioration of cellular organs and system structures and function, regardless of the presence of any disease (Booth et al., 2012). In addition, the rate of VO_2max /BM decline seems to be greater among endurance athletes than among sedentary people, which may be related to the athletes higher VO_2max values as young adults and/or to a greater reduction in exercise volume/intensity during aging (Fitzgerald et al., 1997; Katzel et al., 2001).

However, the degree of the aging process effects on absolute VO_2max values, VO_2max /BM, and VO_2max /LM remain unknown, both in athletes and sedentary people. Considering that absolute VO_2max values and VO_2max/BM are limited by central (cardiorespiratory) conditions and VO_2max/LM is limited by peripheral (muscular) condition and considering that aging does not affect all organs and systems equally (Catapano et al., 2022), it is possible that aging affects each of these factors differently in athletes and sedentary people.

This topic is crucial for women because they are often less active (Edwards and Sackett, 2016) and live longer lives than men (Baum et al., 2021). This situation reduces the number of years that women may live freely (https://www.who.int/data/gho/data/indicators/indicator-details/GHO/life-expectancy-at-birth-(years), n.d.). According to the World Health Organization, in Brazil in 2019, women's life expectancy at birth was 79.4 yr, and health life expectancy at birth was 67.4 yr. Therefore, women lived 12 yr (79.4–67.4) are in a non-health condition. Conversely, men have a life expectancy of 72.4 yr at birth, and their health life expectancy at birth is 63.4 yr. Therefore, men live only 9 yr (72.4–63.4) in a non-health condition (World Health Organization, 2020). Consequently, it is essential to understand the effects of aerobic exercise on cardiorespiratory and muscular aerobic capacity in women of different ages.

To address this gap, this study compared recreational runners and sedentary women below and at or above 50 years old in terms of absolute, VO_2max/BM, and VO_2max/LM. The study also aimed to examine the effect of aging and physical activity on VO_2max values in women. We hypothesize that aging will have a greater impact on variables limited by central (cardiorespiratory) conditions, such as VO_2max (L/min) and VO_2max/BM (mL/kg/min), than in variables limited by peripheral (muscular) conditions, such as VO_2max/LM (mL/kgLM/min).

2. Methods

2.1. Ethical approval

All experimental procedures were reviewed and approved by the Human Research Ethics Committee of the Federal University of São Paulo (approval number 0765/2023, November 19, 2023) and conformed to the principles outlined in the Declaration of Helsinki. Moreover, participants signed an informed consent form after receiving information about the study's objectives, experimental procedures, risks, and benefits, and assurances of privacy and confidentiality.

2.2. Participants

In total, 147 women (85 recreational runners and 62 sedentary controls) were recruited through running consultants, running coaches, social media outreach, and university students and staff (the medical school wherein the study was conducted had over 12,000 members). Table 1 shows the overall health characteristics of participants. For the analysis, runners and sedentary women (controls) were divided into two age groups: runners <50 yr (20–49 yr, $n = 51$), runners ≥50 yr (50–70 yr, $n = 34$), sedentary <50 yr (20–49 yr, $n = 33$), and sedentary ≥50 yr (50–70 yr, $n = 29$). Previous research indicated that VO_2 max tended to decrease beyond 50 yr of age (Baum et al., 2021). As a result, the age of 50 yr of age was used as the cutoff point for comparing age groups (younger: 20–49 yr and older: 50–70 yr). Table 2 shows the age, body mass, height, and body mass index of the participants.

The inclusion criteria for the group of runners was as follows: 1) the participants should be aged 20–70 yr and 2) the participant should have

Table 1
General health characteristics of the participants.

Variables	Runners group (n = 85)	Sedentary group (n = 62)
Life habits	Absolute number (%)	Absolute number (%)
Smoker	1 (1.2)	4 (6.45)
History of illnesses and injuries		
Chronic disease	21 (24.7)	38 (61.29)
Hypertension	5	11 (17.74)
Hypothyroidism	5	11 (17.74)
Asthma	5	–
Diabetes mellitus	3	3 (4.83)
Dyslipidemia	1	13 (20.96)
Others	2	–
Continuous medication	33 (38.8)	20 (32.25)
Menopause	31 (36.47)	26 (41.93)

participated in a running training program for at least 3 yr, three times each week. Participants in the sedentary group were classified as sedentary according to the International Physical Activity Questionnaire (IPAQ) (Craig et al., 2003) and aged 20–70 yr. Exclusion criteria include: neurological, cognitive, orthopedic, and respiratory diseases, uncontrolled cardiovascular or endocrine diseases, and, those with cardiovascular episodes or pain during the activity.

In addition, one participant from the group of runners <50 yr, one participant from the group of runners ≥50 yr, two participants from the group of sedentary women <50 yr, and nine participants from the group of sedentary women ≥50 yr were excluded from the study do to pain during cardiopulmonary exercise testing.

Moreover, all participants completed the Physical Activity Readiness Questionnaire (PAR-Q). The study comprised participants who responded “no” to all PAR-Q questions and were below 49 years old. Those aged above 50 years old who answered “yes” to at least one question, even if they were asymptomatic, were required to undergo a medical examination. These participants were included in the study only after the approval of the physician.

2.3. Study design

This cross-sectional study comprised a single morning visit to the Exercise Physiology Laboratory of UNIFESP. An anamnesis was conducted during the visit using a Google Form questionnaire that asked about general health characteristics and physical activity habits, as indicated below. Furthermore, participants had to undergo a body composition assessment and a cardiopulmonary exercise test. Participants dressed appropriately for physical activity. Stimulants such as caffeine or tea were avoided for at least 8 h before the tests. Participants were also instructed not to eat 2 h before the test and to follow their regular hydration routine. A cardiologist from the Sports Medicine Department of UNIFESP performed an electrocardiogram on all participants aged >50 yr while they were doing a maximal effort test. If an abnormal response was identified, the participant was excluded from the study and referred to a medical facility for further examination.

2.4. Questionnaires

The questionnaires used included the PAR-Q and the IPAQ. Furthermore, runner participants responded to the following questions: 1)How long have you been running? 2)How many running training sessions do you undertake in a regular training week? 3)How many kilometers do you work out every session in a regular training week? 4) How many strengthening training sessions do you do in a regular training week? 5)How long does each strengthening session last in a regular training week? 6)How long will it take you today to run 10 km? 7)Are you a smoker? 8)Do you have any chronic diseases? 9)If yes, which one? 10)Do you continually use drugs? 11)Are you experiencing menopause? 12)When was your last period? Menopause was defined as the permanent cessation of menstrual periods, which was frequently confirmed after 12 months of amenorrhea (https://www.who.int/data/gho/data/indicators/indicator-details/GHO/life-expectancy-at-birth-(years), n.d.).

2.5. Cardiopulmonary exercise testing

The cardiopulmonary exercise test (CEPT) was conducted on a treadmill (Imbrasport, ATL, Brazil), and the results were used to determine VO_2max. Physiological responses to exercise were measured during the test using a metabolic system (Quark PFT; Cosmed®, Rome, Italy), which included a respiratory airflow sensor and rapid-response O_2 and CO_2 gas analyzers that are heat-adjusted and compensated for variations in barometric pressure, temperature, and relative humidity. This method is valid, accurate, and reliable for calculating VO_2max (Nieman et al., 2013). The calibration procedure was performed in accordance with the manufacturer’s instructions before each test.

All evaluations began with a 1-min break. This duration would be prolonged if the participant showed any signs of hyperventilation, which indicated anxiety and/or discomfort. The warm-up period then begins at 3 min of constant speed. The incremental protocol began immediately following the warm-up, with an increase of 1 km/h per minute, and the inclination remained constant at 1 % during the incremental test (Bentley et al., 2007). The respiratory data were collected for each breath and averaged every 20s for analysis.

Participants were instructed to do maximum progressive activity until volitional exhaustion. The Borg scale was used to assess effort perception at the end of each stage (Borg, 1990). Cardiovascular and respiratory variables were examined for 2 min after the test ended.

The VO_2 max was determined using the plateau in the VO_2 curve (increased by <150 mL·min^{-1}) despite increasing exercise intensity (ATS/ACCP Statement on cardiopulmonary exercise testing, 2003). To determine VO_2 max without a plateau, the following criteria had to be

Table 2
Characteristics of the participants.

	Age group (yr)	Runners group (n = 85)	Sedentary group (n = 62)	ANOVA	F	p value	Effect size	Power
Age (yr)	<50	35.8 ± 7.0	41.1 ± 6.1	Age group	365.7	<0.001	0.719	1.00
	≥50	60.7 ± 7.2	57.6 ± 4.2	Physical activity group	1.12	0.292	0.008	0.183
				Interaction	14.8	<0.001	0.094	0.969
Body mass (kg)	<50	60.3 ± 6.5	81.5 ± 13.4	Age group	0.000	0.988	0.00	0.05
	≥50	59.1 ± 9.7	82.8 ± 9.9	Physical activity group	183.4	<0.001	0.562	1.00
				Interaction	0.563	0.454	0.004	0.116
Body height (m)	<50	163.5 ± 5.4	160.8 ± 6.5	Age group	13.4	<0.00	0.086	0.953
	≥50	157.6 ± 5.9	159.6 ± 4.6	Physical activity group	0.136	0.713	0.001	0.065
				Interaction	6.09	0.015	0.041	0.689
BMI	<50	22.6 ± 2.1	31.5 ± 4.4	Age group	3.6	0.058	0.025	0.475
	≥50	23.8 ± 4.1	32.5 ± 4.1	Physical activity group	203.8	<0.001	0.588	1.00
				Interaction	0.026	0.872	0.000	0.53

Note. ANOVA, two-way analysis of variance; BMI, body mass index; effect size, η^2p; power, $1 - \beta$. Data are presented as mean ± standard deviation.

met: a respiratory exchange ratio of ≥1.10, a maximum heart rate predicted by age, and a Borg's perceived exertion scale of 20 (Borg, 1990). VO_2 max was measured as absolute value (L/min). The total body mass adjusted VO_2max (mL/kg/min) and lean mass adjusted VO_2 max (mL/kgLM/min) were calculated.

2.6. Assessment of body composition

Participant's body height and total body mass were measured using a calibrated wall stadiometer and a balance (Filizola®, São Paulo, Brazil), respectively. Measurements were recorded to the nearest 0.1 cm and 0.1 kg.

The body composition (fat mass % and lean mass) was assessed using a dual-emission X-ray absorptiometry system (DXA, software version 12.3, Lunar DPX, Wisconsin, USA). This approach is reliable for assessing body composition with minimal radiation exposure (<10 microSieverts) (Colyer et al., 2016; Shepherd et al., 2017). Moreover, DXA provides accuracy across a wide range of body sizes and types, which is crucial for the purpose of this study (Shepherd et al., 2017). Lean mass was expressed as absolute values (kg), with absolute values adjusted for VO_2 max (mL/kgLM/min).

2.7. Statistical analysis

Descriptive data were presented as mean, standard deviation, and effect size. The sample size was calculated using a significant effect size of 0.30, indicating a medium effect (Cohen, 1962), a significance level of 0.05, and a power of 0.80. The G*Power program (version 3.1.9.7; Heinrich-Heine-Universität Düsseldorf, Düsseldorf, Germany) was used to determine the test power level. According to the calculations, a total sample size of 90 participants (approximately 23 in each group) was required. The Shapiro–Wilk test revealed that all data presented a normal distribution, while Levene's test confirmed homogenous variances.

Physical activity group (sedentary vs. runners), age group (<50 yr vs. ≥50 yr), and interaction effects on general characteristics and VO_2 max were confirmed using two-way analysis of variance (ANOVA, physical activity level × age). The Sidak post hoc test was used in addition to the ANOVA when the significance level was met.

Differences in training characteristics between the two age groups of runners were identified using the Welch's *t*-test, which performs better than the Student's *t*-test when sample sizes differ (Delacre et al., 2017). The effect size measurements for group differences were calculated by dividing the mean difference between the two groups by the pooled standard deviation. The magnitude of any change was determined using the following criteria: $d < 0.2$ was considered to have no effect, $0.2 \leq d < 0.5$ was considered to have a small effect size, $0.5 \leq d < 0.8$ was considered to have a medium effect size, $0.8 \leq d < 1.3$ was considered to have a significant effect size, and $d \geq 1.3$ was considered to have a substantial effect size (Cohen, 1962). We used multiple regression models to calculate participant's VO_2max (mL/min), VO_2max (mL/kg/min), and VO_2max (mL/kgLM/min). The regression model formula is $x = \alpha + \beta \cdot y + E$, where x is the dependent variable (VO_2max), y is the independent variable (age and physical activity group), α is the intercept, β is the slope, and E is the residual. The assumption of residual variance homogeneity (homoscedasticity) was graphically tested using a quantile–quantile plot test. The Durbin–Watson test was used for autocorrelation, and for multicollinearity, the tolerance and variance inflation factor (VIF) was determined. A Durbin–Watson statistic between 1.5 and 2.0 is considered adequate. VIFs <4.0 and a tolerance of >0.50 were considered to indicate the absence of multicollinearity. The significance level was set at 0.05. All statistical analyses were performed using SPSS version 26.0 (SPSS, Inc., Chicago, Illinois).

3. Results

There was no statistically significant difference in age between the runners and sedentary groups ($p = 0.292$). Similarly, there was no statistically significant difference in women's height between groups ($p = 0.713$). The sedentary group had significantly higher total body mass than the runner group ($p < 0.001$). The sedentary group had a higher body mass index than the runner group ($p < 0.001$, Table 2).

Considering the training characteristics of the runners, the group that was aged <50 yr had less experience in years of training ($p < 0.001$) compared with the group that was aged ≥50 yr and had a shorter referred time in 10 km ($p < 0.001$). There was no statistically significant difference between age groups in terms of running volume or strengthening volume expended during a regular training week (Table 3).

The two-way ANOVA showed that age group of participants [<50 and ≥50 yr; $F(2,131) = 32.79$, $p < 0.001$] and physical activity group [runners or sedentary; $F(2,131) = 55.64$, $p < 0.001$] had a significant impact on VO_2max (mL/min). The interaction between the age group and physical activity group significantly impacted VO_2max (mL/min) [$F(2,131) = 4.43$, $p < 0.001$; Table 4 and Fig. 1]. Age, physical activity, and interaction affected VO_2max (mL/kg/min; Fig. 2) and VO_2max (mL/kgLM/min; Fig. 3 and Table 4). For all three dependent variables examined, younger women had higher values than older women, runners had higher values than sedentary women, and the difference between age groups was higher for runners than sedentary women.

Multiple linear regression models were fitted to validate the impact of age and physical activity levels on VO_2max values. The analyses resulted in the statistical models shown in Table 5.

The multiple regression model for predicting VO_2max (mL/min), predicts that the age group ($\beta = -0.520$, $t = -8.756$, $p < 0.001$) and physical activity group ($\beta = -0.485$, $t = -8.166$, $p < 0.001$) may explain 53.9 % of the dependent variable.

The multiple regression model for predicting VO_2max (mL/kg/min), predicts that the age group ($\beta = -0.335$, $t = -7.841$, $p < 0.001$), and physical activity group ($\beta = -0.784$, $t = -18.351$, $p < 0.001$) may explain 76.2 % of the dependent variable.

Finally, the multiple regression model for predicting VO_2max (mL/kgLM/min), predicts that the age group ($\beta = -0.451$, $t = -8.362$, $p < 0.001$), and physical activity group ($\beta = -0.618$, $t = -11.472$, $p < 0.001$) may explain 62.1 % of the dependent variable (Table 5).

4. Discussion

This study compared the absolute, total body mass adjusted, and lean mass adjusted VO_2max across two age groups of runners and sedentary women. Initially, we hypothesized that aging impacted female runners more than sedentary women. We confirmed this hypothesis. Conversely, we hypothesized that, as previously demonstrated by male runners (Seffrin et al., 2023), variables limited by central conditions, such as VO_2max (mL/min) and VO_2max (mL/kg/min), would be more affected by aging than variables limited by peripheral conditions, such as VO_2max (mL/kgLM/min) (Seffrin et al., 2023). However this hypothesis was not confirmed, as all VO_2max values were similarly affected by aging.

VO_2max is a critical variable, because it has a significant predictive value for CVD (Booth et al., 2012) and risk of mortality from all causes (González-Gross and Meléndez, 2013). Total body mass adjusted VO_2 max is a more accurate predictor of endurance performance (Puccinelli et al., 2020; Barbosa et al., 2023) and functional capacity compared with absolute values for VO_2 max (L/min), which does not account for body size differences.

The study results revealed that female runners had higher absolute and total body mass adjusted VO_2max values than sedentary women of both age groups. This is well known because aerobic exercise increases maximal systolic volume and, hence, maximal cardiac output (Ramos et al., 2015). In 2021, WHO reviewed physical activity

Table 3
Training characteristics of the runner group.

	< 50 yr (*n* = 51)	≥ 50 yr (*n* = 34)	*p* value	Effect size	Power
Experience in running (yr)	8.3 ± 5.8	13.9 ± 8.5	0.001	0.77	0.98
Weekly running volume (km)	41.5 ± 19.7	35.9 ± 27.0	0.276	0.24	0.30
Weekly strengthening volume (min)	161 ± 67	185 ± 120	0.260	0.24	0.29
Time referred to in the 10 km (min)	51.4 ± 12.4	64.4 ± 14.4	<0.001	0.96	0.99

Note. Data are presented as mean ± standard deviation.

Table 4
Mean and standard deviation values for VO_2max (mL/min), VO_2max (mL/kg/min), and VO_2max (mL/kgLM/min) presented by age group and physical activity group.

Variables	Age group (yr)	Runner group (*n* = 83)	Sedentary group (*n* = 51)	ANOVA	*F*	*p* value	Effect size	Power
VO_2max (mL/min)	< 50	2823.1 ± 398.4	2148.8 ± 327.1	Age group	32.79	<0.001	0.201	1.000
	≥ 50	2270.9 ± 431.3	1893.6 ± 366.5	Physical activity group	55.64	<0.001	0.300	1.000
				Interaction	4.43	0.037	0.033	0.552
VO_2max (mL/kg/min)	< 50	47.0 ± 6.8	26.0 ± 4.4	Age group	25.47	<0.001	0.164	0.999
	≥ 50	38.9 ± 7.1	23.1 ± 3.3	Physical activity group	283.5	<0.001	0.686	1.000
				Interaction	5.4	0.022	0.040	0.636
VO_2max (mL/kgLM/min)	< 50	71.5 ± 9.0	53.2 ± 7.1	Age group	29.6	<0.001	0.186	1.00
	≥ 50	60.5 ± 7.8	48.5 ± 6.1	Physical activity group	109.8	<0.001	0.458	1.00
				Interaction	5.00	0.027	0.037	0.603

Note. ANOVA, two-way analysis of variance; Effect size, η^2p; power, $1 - \beta$. Data are presented as mean ± standard deviation.

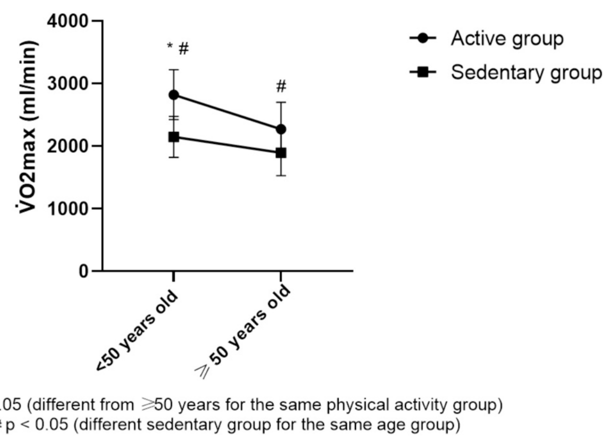

Fig. 1. VO_2max (mL/min) values for runner and sedentary groups for both age groups.

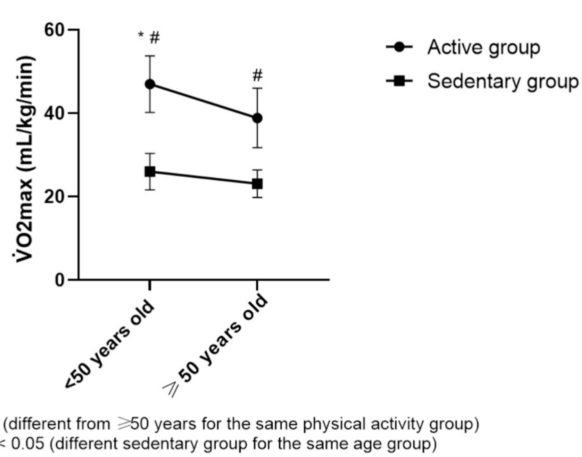

Fig. 2. VO_2max (mL/kg/min) values for runner and sedentary groups for both age groups.

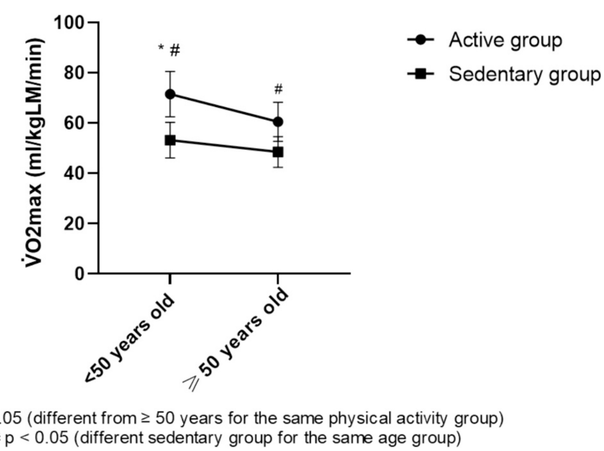

Fig. 3. VO_2max (mL/kgLM/min) values for runner and sedentary groups for both age groups.

recommendations based on evidence supporting the importance of total body mass adjusted VO_2 max for maintaining health and life independence (Booth et al., 2012), including the potential to prevent and treat coronavirus diseases 2019 (Barbosa et al., 2023). Aside from limiting sedentary behavior, current recommendations for persons aged 18–64 yr include 150–300 min/week of moderate aerobic physical activity or 75–150 min/week of vigorous aerobic physical activity (Bull et al., 2020).

The study discovered that runners and sedentary women had higher absolute and total body mass adjusted VO_2max in the participants aged <50 yr compared with the those aged ≥50 yr. These findings are consistent with previous literature data for female and male participants (Seffrin et al., 2023), suggesting that while physical activity positively affects VO_2max, adverse effects of aging overlaps.

Considering the magnitude of the aging effect on absolute and total body mass adjusted VO_2max in female runners and sedentary women, the present study revealed that aging has a significantly higher negative impact on VO_2max in runners than sedentary women. Although there was no significant difference in weekly training volume between people aged < or > 50 yr (Table 2), the physical activity intensity may reduce more among the runners than among the sedentary women during the aging. Therefore, the greater rate of decline in VO_2max in runner groups

Table 5
Multiple regression models for calculating participant VO_2max (mL/min), VO_2max (mL/kg/min), and VO_2max (mL/kgLM/min).

Split	r^2	z	df	p	Tolerance	VIF	Durbin−Watson statistic
VO_2max (mL/min)	VO_2max (mL/min) = 4096.4–21.32(age) – 518.65 (physical activity group)						
	0.539	76.65	2, 131	< 0.001	0.996	1.004	2.162
VO_2max (mL/kg/min)	VO_2max (mL/kg/min) = 76.0–0.302 (age) – 18.43 (physical activity group)						
	0.762	209.37	2, 131	< 0.001	0.996	1.004	2.217
VO_2max (mL/kgLM/min)	VO_2max (mL/kg/min) = 101.45–0.421 (age) – 15.1 (physical activity group)						
	0.621	107.47	2131	<0.001	0.996	1.004	1.905

Note. df, degrees of freedom.

may be associated with a greater reduction in habitual physical activity during aging (Katzel et al., 2001). In addition, the greater rate of decline in VO_2max presented by the runner's group may also be related to their much higher values at the young group, as it has been suggested that individuals with the highest levels of VO_2max as young adults should demonstrate the greatest rates of decline with advancing age (Kusy and Zieliński, 2014). Similar findings were observed comparing the VO_2max decline in men and in women (Ekblom-Bak et al., 2019). Men presented higher VO_2max values than the women, and rate of decline in VO_2max also is higher among the men (Ekblom-Bak et al., 2019). Furthermore, aging affects the human body (inevitable deterioration of the cellular structure and function) (Booth et al., 2012), reduces the maximal cardiac output (Luisada et al., n.d.; Rivera-Brown and Frontera, 2012), mainly due to the lower maximal heart rate (Carrick-Ranson et al., 2013) and, consequently, VO max. However, it is worth highlighting that although runners have a higher rate of decline in VO_2max than sedentary women, runners also show significantly higher VO_2max even at older ages.

Another interesting option for normalizing VO_2max is adjusting absolute values for lean mass. The study discovered that female runners have higher lean mass adjusted VO_2max than sedentary women of both age groups. The difference between groups was higher for total body mass adjusted VO_2max than for lean mass adjusted VO_2max, indicating that running has a greater impact on women's central conditions (cardiac output) than on their peripheral conditions. In terms of aging effect, the present results revealed a more evident worsening in runner group compared with that in the sedentary group, indicating that aging affects central and peripheral conditions in female runners and sedentary women. This is one of the most interesting outcomes of the study because it contradicts our initial hypothesis. A previous study reported that, unlike total body mass adjusted VO_2max, lean mass adjusted VO_2 max is unaffected by aging in a group of well-trained male runners (Seffrin et al., 2023). According to the authors, aging has a greater impact on men's central condition (cardiac output) than on their peripheral condition. However, our results indicate that aging affects these variables similarly in women. Therefore, it appears that men and women experience aging differently. The presence of intramuscular adipose tissue may impact VO_2 max, which is then adjusted for muscle mass.

Intramuscular adipose tissue is an adipose depot that was initially classified as "muscle fat infiltration" associated with aging and is more common in women (Yoshiko et al., 2024; Goodpaster et al., 2023; Delmonico et al., 2009). This is referred to as a muscle quality marker; excess intramuscular adipose tissue causes insulin resistance and a reduced ability to produce force per unit of muscle mass (Yoshiko et al., 2024; Avesani et al., 2023). The intramuscular adipose tissue may impact muscle oxidative capacity similarly as it affects muscle force. Despite their recent findings, Yoshiko et al. (Yoshiko et al., 2024) investigated this relationship. The authors found no significant relationship between skeletal muscle oxidative capacity and intramuscular adipose tissue. The sample size of their study was very small (six men and seven women). The authors recommend that this result be interpreted cautiously because the lack of significant differences could be due to a type II error (Luisada et al., n.d.; Yoshiko et al., 2024). Further research is needed to evaluate the impact of fat infiltration on muscle mass across sexes and ages and its impact on VO_2 max adjusted for lean mass, using a larger sample size.

Using multiple regression models to predict VO_2max values yields interesting results. Age and physical activity level can account for >75 % of body mass adjusted VO_2max (mL/kg/min), highlighting their importance functional capacity. Although the aging process has a negative significant effect on VO_2max, the lower physical activity level has a greater negative effect on VO_2max values than the aging process. These results have important clinical implications. Although it is impossible to avoid the adverse effects of aging, understanding the magnitude of the impact of physical activity is crucial, and it may even be used to improve general awareness of the importance of physical activity.

5. Limitations

The present study has some limitations that should be noted. It used a cross-sectional design. Therefore, although the same individual was examined several times, the aging effect was investigated by comparing individuals of different ages. Moreover, the participants self-reported their training habits throughout their lifetimes, which might lead to recall bias. Furthermore, although we have provided data on women's weekly running training volume, we lacked data on training intensity. Finally, although road running is considered a low-cost and accessible sport and the study was conducted in parks and clubs frequented by people from various socioeconomic backgrounds, participants were not asked about their socioeconomic status, which could be considered a study bias.

6. Practical applications

This study provides valuable insights into the impact of aging and physical activity on women's VO_2max. As variables limited by central conditions (cardiorespiratory), such as VO_2max (L/min) and VO_2max/BM (mL/kg/min), and variables limited by peripheral conditions (muscular), such as VO_2max/LM (mL/kgLM/min), exhibit comparable age-related alterations, it is imperative for coaches to tailor training regimens to address both sets of conditions throughout the aging process. In addition, although aging negatively impacts VO_2max adjusted to weight and to lean mass, regression models show that the effect of physical activity status on VO_2max is greater than age, highlighting the importance of engaging in aerobic physical activity during the entire life.

7. Conclusions

The findings indicate that the negative effect of aging on VO_2max is more evident in physically active women; however, physically active women had higher VO_2max at any age. In addition, the findings suggest that aging has a negative effect on both variables measured, which are limited by the central condition (absolute VO_2max and total body mass adjusted VO_2max) or peripheral condition (lower limbs lean mass adjusted VO_2max). Finally, the findings could provide valuable insights for understanding the effects of aging on women's functional capacities. In order to address unanswered questions stemming from the limitations of the current study's experimental design, the authors advocate for further research utilizing longitudinal methodologies. Such studies would facilitate the tracking of women's aging trajectories across various decades of life, thereby enabling the assessment of the decay curve associated with different manifestations of VO2max. This line of inquiry is particularly pertinent given the rising life expectancy, the growing involvement of elderly individuals in sports, and the increasing participation of women in athletic pursuits.

CRediT authorship contribution statement

Vinícius Ribeiro dos Anjos Souza: Conceptualization. **Lavínia Vivan:** Conceptualization. **Aldo Seffrin:** Formal analysis. **Lucca Vallini:** Writing – original draft. **Fabio de Paula Domingos:** Writing – original draft. **Claudio Andre Barbosa de Lira:** Writing – review & editing. **Rodrigo Luiz Vancini:** Writing – review & editing. **Katja Weiss:** Writing – review & editing. **Thomas Rosemann:** Writing – review & editing. **Beat Knechtle:** Writing – review & editing. **Marilia Santos Andrade:** Conceptualization.

Declaration of competing interest

No potential conflict of interest was reported by the authors.

Data availability

We will make available the data upon request to Marilia S Andrade (marilia1707@gmail.com).

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