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SYSTEMATIC REVIEW

Maximal Aerobic Capacity and Aging in Female Masters Athletes: A Systematic Review and Meta-analysis

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Abstract

Background Maximal aerobic capacity ($\dot{V}O_{2max}$) represents the highest rate at which the body can use oxygen during intense exercise and is a key determinant of endurance performance. Although age-related declines in $\dot{V}O_{2max}$ have been well documented in male individuals, less is known about this trajectory in female Masters athletes, defined as individuals aged 40 years or older who often engage in lifelong endurance training.

Objective We performed a systematic review and meta-analysis to quantify cross-sectional age-related differences in directly measured $\dot{V}O_{2max}$ among female Masters endurance athletes.

Methods PubMed and Web of Science were searched from database inception to 14 May, 2025 for studies reporting directly measured $\dot{V}O_{2max}$ in female Masters endurance athletes aged 40 years or older. Eligible exercise modalities included running, cycling, swimming, and large muscle-mass ergometry, with testing conducted under standard environmental conditions. Two reviewers independently screened studies, extracted data, and assessed risk of bias using a modified Joanna Briggs Institute checklist. Pooled mean $\dot{V}O_{2max}$ values were calculated for predefined age groups (40–49, 50–59, 60–69, and 70 years or older) using a random-effects meta-analysis. Meta-regression was used to estimate the relationship between age and $\dot{V}O_{2max}$.

Results Sixty-nine studies, including 1903 female Masters athletes, met the inclusion criteria. Pooled mean relative $\dot{V}O_{2max}$ was 45 $mL \cdot kg^{-1} \cdot min^{-1}$ (95% confidence interval [CI] 43.0–46.8) in athletes aged 40–49 years, 40 $mL \cdot kg^{-1} \cdot min^{-1}$ (95% CI 38.5–41.7) in those aged 50–59 years, 35 $mL \cdot kg^{-1} \cdot min^{-1}$ (95% CI 33.2–37.1) in those aged 60–69 years, and 30 $mL \cdot kg^{-1} \cdot min^{-1}$ (95% CI 27.2–31.8) in athletes aged 70 years or older. Meta-regression demonstrated that each additional year of age was associated with a 0.57 $mL \cdot kg^{-1} \cdot min^{-1}$ lower $\dot{V}O_{2max}$ (95% CI −0.70 to −0.44; $P < 0.0001$), equivalent to about 11.7% per decade. The association was consistent across testing modalities.

Conclusions This systematic review and meta-analysis demonstrates a progressive age-related decrease in directly measured $\dot{V}O_{2max}$ among female Masters endurance athletes. Maximal aerobic capacity declines at an average rate of 0.57 $mL \cdot kg^{-1} \cdot min^{-1}$ per year after age 40 years, corresponding to approximately 11.7% per decade. This decline is evident across endurance sport disciplines and appears consistent with physiological changes associated with aging despite sustained endurance training. These findings provide female-specific reference values and a quantitative framework for future studies on aerobic capacity trajectories in female athletes.

Clinical Trial Registration The protocol was registered on the Open Science Framework (OSF; https://doi.org/10.17605/OSF.IO/S2RXZ).

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Key Points

In female Masters endurance athletes aged 40 years and older, directly measured maximal aerobic capacity ($\dot{V}O_{2max}$) declines progressively with advancing age, despite sustained engagement in endurance training.

Across 69 studies including more than 1900 female athletes, a cross-sectional analysis demonstrated approximately 11–12% lower relative $\dot{V}O_2max$ per decade of age, corresponding to an average difference of 0.57 $mL \cdot kg^{-1} \cdot min^{-1}$ per year of age.

The age-related decline in $\dot{V}O_{2max}$ was consistent across endurance sport disciplines and exercise testing modalities, indicating that training and methodological differences do not explain the observed trajectory.

These findings provide contemporary female-specific reference values for maximal aerobic capacity in later adulthood and establish a quantitative framework for future studies examining aerobic fitness, aging, and training adaptations in female individuals.

1 Introduction

Maximal aerobic capacity ($\dot{V}O_{2max}$) reflects the highest rate at which oxygen can be transported and used during intense exercise and is a key determinant of endurance performance, functional capacity, and health across the lifespan [1, 2]. Although $\dot{V}O_{2max}$ is a rate and may therefore be better described as *maximal aerobic power*, the term *maximal aerobic capacity* is widely used in the literature. For consistency with this broader convention, we use maximal aerobic capacity throughout to refer to $\dot{V}O_{2max}$. In adults, $\dot{V}O_{2max}$ is a powerful prognostic indicator of health and life span [3, 4], with higher values associated with improved cardiovascular health and longevity. $\dot{V}O_{2max}$ declines progressively with advancing age in both athletic and non-athletic adults, driven by integrated changes in cardiovascular function, pulmonary capacity, skeletal muscle mass and metabolism, and habitual physical activity levels [5, 6]. Importantly, endurance exercise training can substantially increase $\dot{V}O_{2max}$ and attenuate age-related declines, even among older adults [7].

Masters athletes, typically defined as individuals aged 40 years and older who continue to engage in regular exercise training and competition, represent a unique population that could offer valuable insight into the effects of lifelong exercise training on age-related changes in aerobic capacity. Masters athletes maintain high levels of physical activity across decades and frequently demonstrate $\dot{V}O_{2max}$ values comparable to, or exceeding, those of sedentary younger adults [8, 9]. As such, Masters athletes provide valuable insight into the limits of physiological adaptation and the extent to which sustained endurance training may modify age-related changes in cardiorespiratory fitness. However, prior work suggests that although endurance training preserves higher absolute $\dot{V}O_{2max}$ with aging, the rate of decline may not be proportionally attenuated, particularly among female individuals [10, 11]. The specific physiological, behavioral, and contextual factors that shape these trajectories remain incompletely understood.

To the best of our knowledge, only one systematic review and meta-analysis has comprehensively evaluated $\dot{V}O_{2max}$ among endurance-trained female Masters athletes. In that seminal analysis, Fitzgerald et al. demonstrated that endurance-trained female individuals exhibit higher $\dot{V}O_{2max}$ values than their active and sedentary counterparts [11], establishing an important foundation for understanding the interactions between sex, training status, and aging. However, that work was published in 1997, and since then the scientific literature, methodological rigor of exercise testing, and participation of female individuals in competitive endurance sport have expanded substantially [12–14]. Contemporary data now include a broader range of sports, testing modalities, older age groups, and larger cumulative training exposures providing an opportunity to re-evaluate age-related patterns in aerobic capacity among well-trained female individuals. These contemporary cohorts may also have been shaped by historical shifts in access to competitive sport and opportunities for female individuals to engage in lifelong endurance training, potentially supporting more sustained participation in structured exercise into later adulthood.

Accordingly, the primary purpose of this systematic review and meta-analysis was to synthesize the existing literature on directly measured $\dot{V}O_{2max}$ in female Masters athletes aged 40 years and older. Specifically, we aimed to address two primary questions: (1) What are the reported values of maximal aerobic capacity ($\dot{V}O_{2max}$) among female Masters endurance athletes across midlife to advanced age? and (2) How does $\dot{V}O_{2max}$ change with advancing age and across sport disciplines in this population? By systematically identifying and synthesizing available data, this work seeks to provide contemporary female-specific reference values for aerobic capacity, clarify age-related trajectories in well-trained female individuals, and generate testable hypotheses

for future research focused on training, hormonal transitions, and healthy aging.

2 Methods

2.1 Protocol and Registration

This systematic review and meta-analysis was conducted in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 guidelines [15]. The study protocol was registered prospectively on the Open Science Framework (OSF; https://doi.org/10.17605/OSF.IO/S2RXZ). As this study involved secondary use of publicly available data, it was exempt from institutional review board approval and informed consent requirements in accordance with 45 CFR 46.102.

2.2 Eligibility Criteria

Eligibility criteria were defined prospectively according to the Population, Intervention/Exposure, Comparator, Outcome, and Study Design (PICOS) framework. Eligible studies enrolled healthy female Masters athletes aged 40 years or older who engaged in habitual endurance training or competitive participation in endurance sports, including running, cycling, swimming, rowing, and related endurance disciplines. Comparisons were made across chronological age groups, typically defined in 5- or 10-year increments.

The primary outcome was maximal aerobic capacity ($\dot{V}O_{2max}$) measured directly during graded or incremental exercise testing to volitional exhaustion with continuous pulmonary gas exchange. Eligible exercise testing modalities were those likely to provide an accurate representation of $\dot{V}O_{2max}$, including running, cycling, swimming, rowing, inclined walking, and large muscle-mass ergometry such as ski, kayak, or rowing ergometry. To characterize the rigor of exercise testing, we recorded the criteria used to support attainment of maximal effort, including a plateau in $\dot{V}O_2$, a respiratory exchange ratio of 1.1 or greater, a Borg rating of perceived exertion of 18 or higher, or achievement of at least 90% of the age-predicted maximal heart rate. These criteria were considered in the risk-of-bias assessment.

Testing was required to be conducted under standard environmental conditions. Studies using non-normoxic inspirates, testing conducted at altitudes meaningfully above sea level (> 1800 m), or temperatures substantially deviating from room temperature (~ 20 °C) were not eligible. Eligible study designs included cross-sectional or longitudinal observational studies reporting directly measured $\dot{V}O_{2max}$. Studies reporting estimated $\dot{V}O_{2max}$ derived from submaximal exercise tests, field tests, predictive equations, or other indirect methods were not eligible. Studies were additionally excluded if they: (1) included only male participants or did not report female data separately; (2) enrolled participants aged younger than 40 years; (3) included individuals with acute or chronic disease; or (4) did not explicitly identify participants as Masters athletes or habitual endurance athletes.

2.3 Information Sources and Search Strategy

We searched PubMed (via the PubMed interface) and the Web of Science Core Collection (via the Web of Science interface) from database inception to 21 November, 2023, with an updated search conducted on 14 May, 2025 before final analyses. In PubMed, filters were applied to limit results to human studies. No additional date or language restrictions were imposed; however, to be eligible for inclusion, full-text articles (original or translated) were required to be available in English.

Reference lists of all included studies and relevant systematic reviews were manually screened to identify additional eligible records. Search strategies combined terms related to the population (e.g., female, woman, athlete), exposure (exercise, endurance training), and outcome (oxygen consumption, oxygen uptake, $\dot{V}O_{2max}$, peak oxygen uptake). The complete search strategies for each database are provided in the Appendix in the Electronic Supplementary Material (ESM).

2.4 Study Selection and Data Abstraction

All records identified through database searches were imported into a web-based systematic review management software (Covidence, Melbourne, VIC, Australia) for deduplication and screening. Two reviewers independently screened records in two stages: initial title and abstract screening, followed by a full-text assessment of potentially eligible articles. Studies were evaluated against the predefined eligibility criteria, and disagreements were resolved through discussion or adjudication by a third reviewer. The study selection process is summarized in a PRISMA flow diagram, Fig. 1.

Data were extracted independently and in duplicate using a standardized data abstraction form. Abstracted variables included study characteristics (first author, year of publication, study design, sample size), participant characteristics (age, sport discipline, anthropometric measures, training

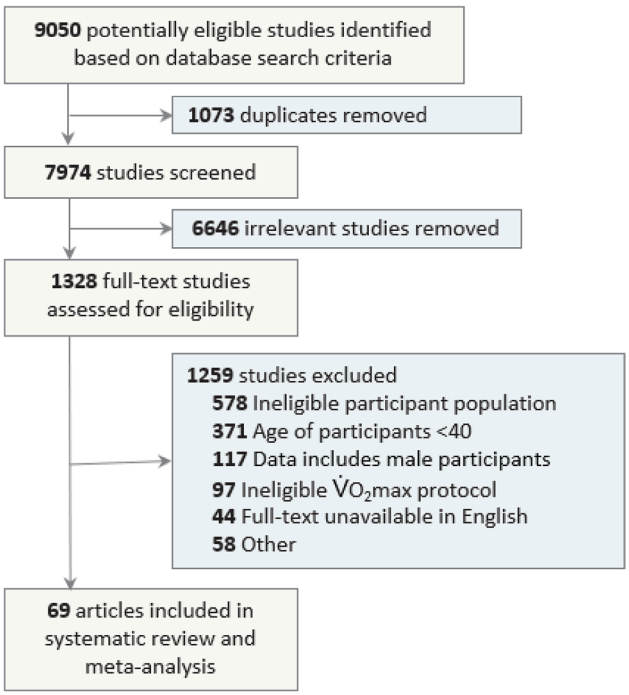


Fig. 1 Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) flow diagram. Flow diagram displaying the selection of articles through different phases of the systematic review and categorization of included articles. Sixty-nine articles, including five case studies. $\dot{V}O_{2max}$ maximal aerobic capacity

history, and menopausal status, where available), and maximal aerobic capacity (absolute [$L \cdot min^{-1}$] and relative [$mL \cdot kg^{-1} \cdot min^{-1}$] $\dot{V}O_{2max}$ values with associated estimates of error). Details of exercise testing protocols, including modality and criteria used to verify maximal effort, were also recorded. Discrepancies between reviewers were resolved through discussion or adjudication by a third reviewer.

2.5 Risk of Bias Assessment

Methodological quality and risk of bias of each included study were assessed independently and in duplicate using a modified Joanna Briggs Institute checklist adapted for observational studies of physiological outcomes (ESM). Assessment domains included clarity of participant characteristics, appropriateness of study design, adequacy of $\dot{V}O_{2max}$ testing procedures, transparency of reporting, and completeness of outcome data. The proportion of affirmative ("yes") responses was used to classify overall risk of bias, with scores of 70% or greater classified as low risk, 50–69% as moderate risk, and less than 50% as high risk. Disagreements were resolved through discussion or adjudication by a third reviewer.

2.6 Data Synthesis and Statistical Analysis

Study characteristics and $\dot{V}O_{2max}$ values were summarized descriptively and organized by age group and sport discipline. Where data permitted, meta-analyses were performed separately for absolute $\dot{V}O_{2max}$ and relative $\dot{V}O_{2max}$ using random-effects models with inverse-variance weighting. Because some studies contributed $\dot{V}O_2max$ estimates for multiple age groups, meta-regression inference was adjusted for clustering of estimates within a study using cluster-robust variance estimation, with study as the clustering unit. Statistical heterogeneity was assessed using the I^2 statistic and τ^2 estimates.

Subgroup analyses included age group and exercise testing modality. Meta-regression was used to examine the relationship between age and $\dot{V}O_{2max}$ as a continuous moderator. Results are reported with 95% confidence intervals (CIs), statistical significance was set at $\alpha = 0.05$, and all tests were two-tailed. Analyses were conducted using R and Rstudio software (R Core Team, 2023; Posit Software, PBC, 2023) with *meta* and *metafor* packages.

2.7 Handling of Missing Data

When essential $\dot{V}O_{2max}$ outcome data (means, estimates of error, or sample sizes) were not reported, corresponding authors were contacted by e-mail to request the missing information. A follow-up e-mail was sent if no response was received within 2–4 weeks. No statistical imputation methods were used to replace missing values. For studies reporting outcomes aggregated across age ranges (e.g., 40–49 years), the midpoint of the age range (e.g., 45 years) was assigned, and the standard deviation of age was set to 2.5 years.

3 Results

3.1 Study Selection

The database search identified 9050 records, of which 7974 remained after removal of 1073 duplicates. Following title and abstract screening, 1328 full-text articles were assessed for eligibility. A total of 69 studies met the inclusion criteria and were included in the review, of which 64 were eligible for quantitative synthesis [10, 16–78] (five case studies were excluded from the meta-analysis [79–83]). The study selection process is represented in the PRISMA flow diagram, Fig. 1.

Table 1 Characteristics of female Masters athletes by age group

Age group (years)	Mean	95% CI	Studies (*n*)	Participants (*N*)
Cardiorespiratory fitness				
$\dot{V}O_{2max}$ ($L \cdot min^{-1}$)				
40–49 years	2.63	2.50–2.76	19	528
50–59 years	2.34	2.26–2.42	49	865
60–69 years	2.06	1.94–2.17	28	440
70+ years	1.87	1.41–2.33	4	64
$\dot{V}O_{2max}$ ($mL \cdot kg^{-1} \cdot min^{-1}$)				
40–49 years	44.9	43.0–46.8	18	446
50–59 years	40.1	38.5–41.7	49	926
60–69 years	35.1	33.2–37.1	29	461
70+ yrs	29.5	27.2–31.8	4	64
$\dot{V}E_{max}$ ($L \cdot min^{-1}$)				
40–49 years	92	85–99	7	339
50–59 years	82	76–103	7	264
60+ years	69	63–75	10	253
HR_{max} ($beats \cdot min^{-1}$)				
40–49 years	176	172–179	9	180
50–59 years	169	165–172	17	204
60+ years	163	160–166	14	135
Anthropometrics				
Height (cm)				
40–49 years	166	164–167	15	259
50–59 years	164	163–165	38	549
60+ years	162	161–164	24	289
Weight (kg)				
40–49 years	58.8	57.2–60.4	16	269
50–59 years	58.6	57.5–59.6	47	669
60+ years	59.8	57.8–61.8	27	328
BMI ($kg \cdot m^{-2}$)				
40–49 years	22.3	21.5–23.1	4	135
50–59 years	21.3	20.7–21.8	15	235
60+ years	22.2	21.4–22.9	11	159
Body fat (%)				
40–49 years	20.3	18.1–22.6	12	221
50–59 years	23.7	22.1–25.4	38	539
60+ years	26.9	25.2–28.6	21	248
Training characteristics				
Training volume ($miles \cdot week^{-1}$)				
40–49 years	26.6	19.2–34.1	2	42
50–59 years	29.1	25.7–32.4	9	158
60+ years	27.7	21.0–34.5	2	14
Training volume ($min \cdot week^{-1}$)				
50–59 years	276	263–290	11	150
60+ years	332	228–435	7	74

3.2 Study Characteristics

The included studies were published between 1975 and 2025 and collectively enrolled 1903 female Masters athletes. Sample sizes ranged from 1 to 513 participants, and mean participant age ranged from 41 to 83 years. Studies included participants from a range of endurance sport disciplines including running, cycling, swimming, triathlon, and ultra-distance walking.

Most studies assessed $\dot{V}O_{2max}$ using treadmill-based protocols (37 studies; 58%), followed by cycle ergometry (18 studies; 28%). Two studies (3%) used a combination of treadmill and cycle testing, and seven studies (11%) did not report the testing modality. Key characteristics of the included studies are summarized in Table 1.

3.3 Maximal Aerobic Capacity ($\dot{V}O_{2max}$) Across Age Groups

Across all included studies, reported relative $\dot{V}O_{2max}$ values ranged from 22 to 53 $mL \cdot kg^{-1} \cdot min^{-1}$. In the

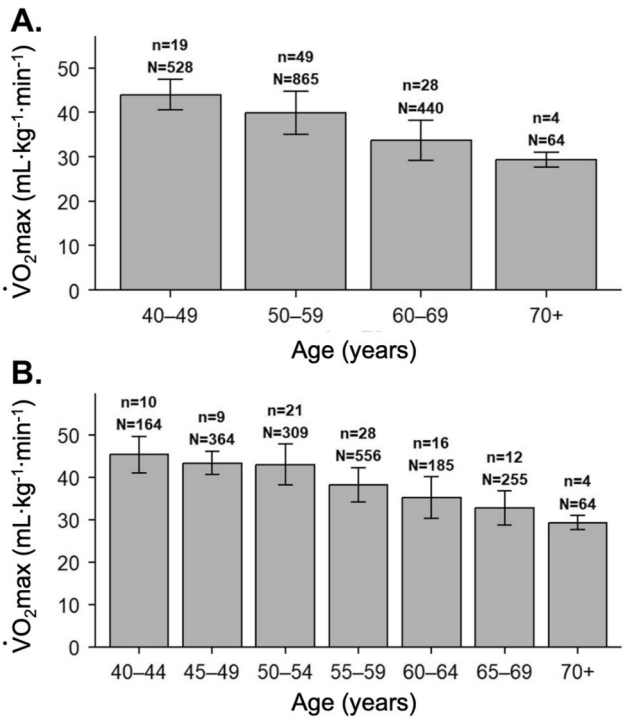


Fig. 2 Relative maximal aerobic capacity ($\dot{V}O_{2max}$) across age strata in female Masters endurance athletes. Panel **A** displays pooled mean $\dot{V}O_{2max}$ values across 10-year age bins, and Panel **B** displays pooled mean values across 5-year age bins. *Bars* represent inverse variance-weighted mean relative $\dot{V}O_{2max}$ values from a random-effects meta-analysis. Error bars indicate weighted standard deviations of the study level $\dot{V}O_{2max}$ value. Sample sizes above each bar denote the number of included studies (*n*) and the total number of participants (*N*) contributing to each age group

random-effects meta-analysis, pooled mean relative $\dot{V}O_2$max was 45 mL·kg^{-1}·min^{-1} (95% CI 43.0–46.8) in athletes aged 40–49 years, 40 mL·kg^{-1}·min^{-1} (95% CI 38.5–41.7) in athletes aged 50–59 years, 35 mL·kg^{-1}·min^{-1} (95% CI 33.2–37.1) in athletes aged 60–69 years, and 30 mL·kg^{-1}·min^{-1} (95% CI 27.2–31.8) in athletes aged 70 years or older (Fig. 2).

A similar pattern was observed for absolute $\dot{V}O_{2max}$, with pooled mean values of 2.63 L·min^{-1} (95% CI 2.50–2.76) in athletes aged 40–49 years, 2.34 L·min^{-1} (95% CI 2.26–2.42) in athletes aged 50–59 years, 2.06 L·min^{-1} (95% CI 1.94–2.17) in athletes aged 60–69 years, and 1.87 L·min^{-1} (95% CI 1.41–2.33) in athletes aged 70 years or older.

Across the age range examined, the relationship between age and relative $\dot{V}O_{2max}$ was modeled using meta-regression and was described by the equation:

$$\dot{V}O_{2\,max}\left(\text{mL}\cdot\text{kg}^{-1}\cdot\overset{-1}{\text{min}}\right) = 71.23 - 0.57 \times \text{age (years)}.$$

In this model, the intercept represents a theoretical extrapolated value at age 0 years, and the slope represents the rate of age-related decline per year. Meta-regression demonstrated a decline in relative $\dot{V}O_{2max}$ of 0.57 mL·kg^{-1}·min^{-1} per year (95% CI −0.70 to −0.44; $P < 0.0001$), corresponding to an average reduction of about 11.7% per decade (Fig. 3A). A similar age-related association was observed for absolute $\dot{V}O_{2max}$ (Fig. 3B).

Based on the random-effects pooled estimates, relative $\dot{V}O_{2max}$ declined by 10.8% (4.83 mL·kg^{-1}·min^{-1}) from 40–49 to 50–59 years, 12.3% (4.91 mL·kg^{-1}·min^{-1}) from 50–59 to 60–69 years, and 16.0% (5.62 mL·kg^{-1}·min^{-1}) from 60–69 to ≥70 years. Between-study heterogeneity for $\dot{V}O_{2max}$ was high across age groups ($I^2 = 94.8\%$, 96.7%, 94.6%, and 66.8%; $\tau^2 = 15.14$, 28.26, 23.53, and 3.11 for ages 40–49, 50–59, 60–69, and ≥70 years, respectively).

3.4 Subgroup Analyses

Subgroup analyses revealed no differences in $\dot{V}O_{2max}$ based on the primary sporting discipline. All but two studies assessed $\dot{V}O_{2max}$ using an exercise test modality consistent with the participants' primary sport (e.g., treadmill testing for runners and cycle ergometry for cyclists). There were no differences in $\dot{V}O_{2max}$ values obtained using treadmill testing compared with cycle ergometry (Fig. 4).

3.5 Risk of Bias Assessment

Using the modified Joanna Briggs Institute checklist, 63 studies were classified as low risk of bias, four studies as moderate risk, and two studies as high risk (ESM). Common methodological limitations included incomplete reporting of criteria used to verify maximal effort and limited detail regarding participant training histories.

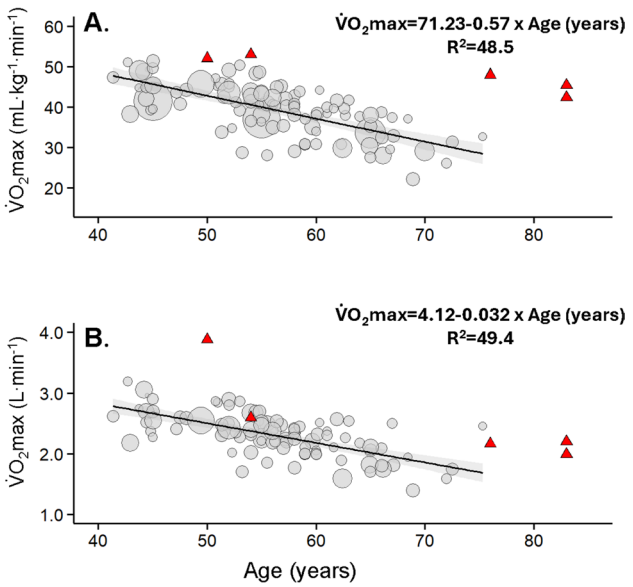


Fig. 3 Meta-regression of relative maximal aerobic capacity ($\dot{V}O_{2max}$) with age in female Masters athletes. Data are derived from 64 studies for relative $\dot{V}O_{2max}$ (**A**) and 60 studies for absolute $\dot{V}O_{2max}$ (**B**). Each bubble represents an age-group estimate from a single study, with bubble size proportional to the number of participants contributing to that estimate. The solid line represents the random-effects meta-regression relating age (years) to relative $\dot{V}O_{2max}$, and the *shaded band* indicates the 95% confidence interval. The regression equation and coefficient of determination are displayed. Case studies, which were excluded from the quantitative synthesis, are depicted as red triangles

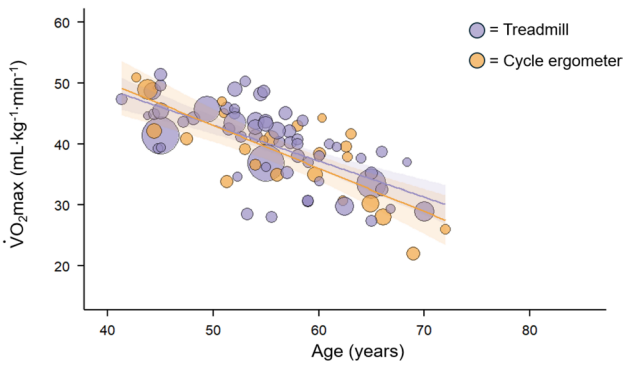


Fig. 4 Meta-regression of relative maximal aerobic capacity ($\dot{V}O_{2max}$) with age stratified by exercise testing modality in female Masters athletes. Data are derived from 55 studies. Each bubble represents an age-group estimate from a single study, with bubble size proportional to the number of participants contributing to that estimate. Purple circles indicate treadmill-based testing (37 studies), and orange circles indicate cycle ergometer testing (18 studies). Nine additional studies that used alternative testing modalities or mixed protocols are not displayed. The solid lines indicate random-effects meta-regressions for each testing modality, with shaded bands indicating the 95% confidence intervals

4 Discussion

In this systematic review and meta-analysis, we synthesized evidence from 69 studies including 1903 female Masters endurance athletes aged 40 years and older to characterize cross-sectional age-related changes in maximal aerobic capacity. Two principal findings emerged. First, directly measured $\dot{V}O_{2max}$ declined progressively with advancing age, with pooled mean relative values of 45, 40, 35, and 30 mL·kg^{-1}·min^{-1} in the fifth, sixth, seventh, and eighth decades of life and beyond, respectively. Second, the magnitude and trajectory of decline were consistent across endurance sport disciplines and exercise testing modalities, indicating that training and methodological differences do not explain the observed age-related pattern.

4.1 Declines in Maximal Aerobic Capacity with Age

The cross-sectional age-related decline in $\dot{V}O_{2max}$ observed in the present analysis is consistent with prior work in endurance-trained female athletes [11]. Fitzgerald et al. reported a decline of about 11.3% per decade (6.2 mL·kg^{-1}·min^{-1} per decade) among trained endurance female individuals, closely aligning with the 11.7% per decade (5.7 mL·kg^{-1}·min^{-1} per decade) decline observed in the current meta-analysis. Together, these findings suggest a reproducible trajectory of age-related decline in $\dot{V}O_{2max}$ among female individuals who maintain high levels of endurance training across adulthood.

When viewed alongside previously published data from sedentary or non-athletic female cohorts, the trajectory of $\dot{V}O_{2max}$ decline in female Masters athletes appears steeper in relative terms. For example, Fitzgerald et al. reported a smaller relative decline of about 10.5% per decade (3.5 mL·kg^{-1}·min^{-1} per decade) among sedentary female individuals. Broader population-based cohorts, such as the HUNT study [5], have demonstrated more modest age-related declines of 8.7% per decade across mid-to-late adulthood (Fig. 5). To further contextualize these values relative to the general population, we present age-matched $\dot{V}O_2$max data from the FRIEND registry [84], the largest population-based reference dataset and one commonly used in clinical settings, which highlights the substantial aerobic capacity of female Masters athletes (Table 2). Juxtaposing these trajectories provides a useful perspective on patterns of age-related change in aerobic capacity in the context of sustained endurance training, while recognizing that these external cohorts are not direct control groups. Importantly, despite the steeper age-related decline, absolute $\dot{V}O_{2max}$ values in female Masters athletes remained exceptionally high across all age groups.

Several factors may contribute to the magnitude of decline observed in female Masters athletes. One consideration is baseline aerobic power. Because Masters athletes typically begin in later adulthood with relatively high $\dot{V}O_{2max}$ values, a given relative decline translates

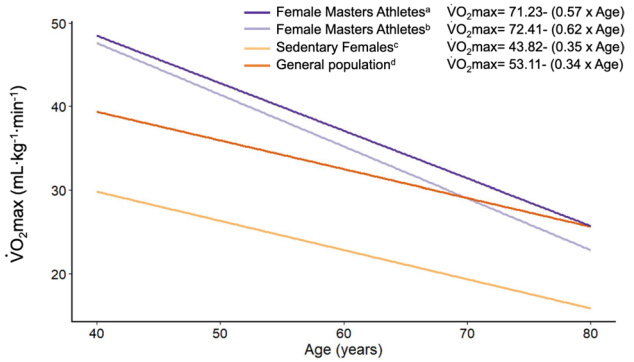


Fig. 5 Comparison of age-related changes in relative maximal aerobic capacity ($\dot{V}O_{2max}$) across female Masters athletes and previously published reference equations. Lines depict linear equations describing the relationship between age (years) and relative $\dot{V}O_{2max}$ derived from the current meta-analysis and from previously published cohorts. The dark purple line (a) represents the meta-regression from the present study of female Masters endurance athletes. The light purple line (b) represents endurance-trained female athletes from Fitzgerald et al. The light orange line (c) represents sedentary female individuals from Fitzgerald et al. The dark orange line (d) represents female individuals from the population-based HUNT study. Corresponding regression equations are shown in the figure

Table 2 Comparison of $\dot{V}O_{2max}$ in female Masters endurance athletes and similarly aged female individuals from the FRIEND Registry

	Female Masters athletes	FRIEND Registry 50th percentile	FRIEND Registry 95th percentile
$\dot{V}O_{2max}$ (L·min^{-1})			
40–49 years	2.7 ± 0.3	1.56 ± 0.3	
50–59 years	2.2 ± 0.1	1.42 ± 0.3	
60–69 years	2.0 ± 0.3	1.25 ± 0.2	
70+ years	1.8 ± 0.1	1.05 ± 0.2	
$\dot{V}O_{2max}$ (mL·kg^{-1}·min^{-1})			
40–49 years	45.2 ± 4.4	20.1 ± 5.1	41.7
50–59 years	42.0 ± 0.9	18.0 ± 4.1	35.9
60–69 years	34.3 ± 3.8	16.6 ± 3.3	29.4
70+ yrs	29.7 ± 1.5	15.0 ± 2.5	24.1

Values are presented as mean ± standard deviation (where available) for female Masters athletes derived from the present meta-analysis and age-matched reference data for the 50th and 95th percentiles from cycle ergometry testing in a large population-based cohort (FRIEND Registry; [84, 96])

$\dot{V}O_{2max}$ maximal aerobic capacity

into a larger absolute decrease in aerobic capacity compared with more sedentary individuals. In addition, reductions in training volume or intensity with advancing age have been documented in Masters athletes and contribute to accelerated declines in aerobic capacity In the present synthesis, however, weekly training duration was reported in only 13 studies, and pooled estimates did not demonstrate a clear age-related decline. Training volume was 276 min·week^{-1} (95% CI 263–290) in athletes aged 50–59 years and 332 min·week^{-1} (95% CI 228–435) in those aged ≥60 years (Table 1). The wide CI in the older group highlights substantial variability in reported training exposure. Even modest reductions in the training stimulus may meaningfully influence long-term $\dot{V}O_{2max}$ trajectories.

Importantly, age-related changes in body size and composition likely influence observed declines in both relative and absolute $\dot{V}O_{2max}$. Across included studies, body mass was relatively stable, with pooled means of 58.8 kg (95% CI 57.2–60.4) in female Masters athletes aged 40–49 years and 59.8 kg (95% CI 57.8–61.8) in those aged ≥ 60 years. In contrast, body fat percentage increased from 20.3% (95% CI 18.1–22.6) to 26.9% (95% CI 25.2–28.6) across these age groups (Table 1). Because relative $\dot{V}O_{2max}$ is normalized to total body mass, greater adiposity may contribute to lower relative $\dot{V}O_{2max}$ even when body mass remains relatively stable. The combination of stable body mass and greater adiposity is also consistent with lower fat-free mass at older ages including less metabolically active lean tissue, which may contribute to reductions in absolute $\dot{V}O_{2max}$. These quantitative trends highlight the importance of considering body size and composition when interpreting age-related changes in aerobic fitness among female Masters athletes [85].

When examined by decade, the relative decline in $\dot{V}O_{2max}$ increased progressively with advancing age, declining 10.8% (4.83 mL·kg^{-1}·min^{-1}) from the fifth to sixth decade, 12.3% (4.91 mL·kg^{-1}·min^{-1}) from the sixth to seventh decade, and 16.0% (5.62 mL·kg^{-1}·min^{-1}) from the seventh to eighth decade (Fig. 2). Fitzgerald et al. similarly reported greater decade-specific declines at older ages, although the magnitude of decline in the present analysis was somewhat smaller, suggesting that reductions in training volume with age are unlikely to fully explain age-related decreases in $\dot{V}O_{2max}$ among female Masters athletes. This pattern may likely reflect historical shifts in access to competitive sport, social norms, and opportunities for female individuals to engage in lifelong endurance training [86], potentially enabling more sustained engagement in structured exercise into later adulthood and a comparatively smaller age-related decline in $\dot{V}O_{2max}$ in contemporary cohorts. Importantly, 48 of the studies included in this analysis were published after 1997, reflecting a predominantly contemporary cohort of female Masters athletes.

Collectively, these observations suggest that while endurance-trained female individuals maintain substantially higher absolute levels of aerobic capacity than sedentary peers, aging is nonetheless associated with a meaningful and progressive decline in $\dot{V}O_{2max}$. The comparison of trained and non-trained trajectories highlights the need for future studies to directly examine how baseline fitness, training exposure, body composition, and aging interact to shape long-term changes in cardiorespiratory fitness in female individuals. The majority of the studies included in the present analysis were cross-sectional, limiting inference regarding within-individual $\dot{V}O_{2max}$ trajectories. Available longitudinal studies in female endurance athletes have broadly reported similar age-related declines while also substantially inter-individual variability [36, 87]. Because longitudinal studies spanning multiple decades are rarely practical, shorter-term follow-up studies remain important for determining how changes in training exposure and physiology contribute to a within-individual $\dot{V}O_{2max}$ decline with aging.

4.2 Exercise Testing Modality

We observed no difference in $\dot{V}O_{2max}$ values based on exercise testing modality, despite longstanding concerns that cycle ergometry may underestimate maximal aerobic capacity relative to treadmill testing. In nearly all included studies, the testing modality aligned with the athletes' primary training discipline (e.g., runners assessed on a treadmill and cyclists on a cycle ergometer), which likely minimized modality-specific limitations. Accordingly, the exercise testing modality did not appear to introduce systematic methodological bias in the included literature (Fig. 4).

These findings suggest that, in female Masters athletes, treadmill and cycle ergometry provide comparable assessments of $\dot{V}O_{2max}$ when maximal effort is achieved and testing reflects habitual exercise patterns. This contrasts with population-based reference data, such as the FRIEND registry [84], in which treadmill-derived $\dot{V}O_{2max}$ values exceed those obtained during cycle testing. Such modality-dependent differences may be more relevant in untrained or recreationally active populations than in trained Masters athletes accustomed to discipline-specific exercise.

When compared with the Cardiopulmonary Health and Endurance Exercise Registry (CHEER), an athlete-specific cardiopulmonary exercise testing reference dataset that provides modality-specific prediction equations [88], the age-related $\dot{V}O_{2max}$ values observed in the present meta-analysis were generally consistent with contemporary

endurance-athlete reference standards. Predicted values derived from the CHEER equations were similar to the pooled $\dot{V}O_{2max}$ estimates across age groups and testing modalities, with differences remaining within the reported prediction error of the CHEER models. These observations support the external validity of our findings and suggest that the age-related trajectory of aerobic capacity observed in female Masters athletes is consistent with endurance-athlete normative data.

4.3 Other Physiological Considerations and Potential Nonlinearity

Most prior studies, including the present meta-analysis, have assumed a linear decline in $\dot{V}O_{2max}$ with age. The aggregated data from the included studies suggested a greater decline in $\dot{V}O_{2max}$ at older ages. The apparent greater decline emerged descriptively from the age-group estimates and was therefore treated as hypothesis generating. The decline became more pronounced after approximately 50–54 years of age (Fig. 2B), a period that often coincides with the menopausal transition. This pattern raises the possibility that factors beyond chronological aging alone may contribute to midlife changes in aerobic capacity among female Masters athletes. Interpretation of this pattern is limited by inconsistent reporting of menopausal status and use of menopausal hormone therapy across studies, precluding formal subgroup or moderator analyses.

Across the included literature, reporting of menopausal status was heterogenous. Two studies exclusively enrolled premenopausal subjects [44, 65], whereas 22 studies included only post-menopausal subjects [25, 26, 28, 31, 32, 38, 42, 44, 47, 48, 55–57, 59, 61, 65, 68, 70, 76, 80–82]. The remaining studies either grouped premenopausal and postmenopausal female individuals together or menopausal status was not reported. Based on the available data, there was no clear difference in $\dot{V}O_{2max}$ between postmenopausal female Masters athletes and the remaining study participants, which comprised a combination of premenopausal female individuals and female individuals with unknown menopause status. Reporting of menopausal hormone therapy use was even less frequent and could not be incorporated into secondary analyses. These limitations highlight the challenges of evaluating menopause-related effects within the existing literature.

Nonetheless, menopause- and age-related hormonal changes remain a biologically plausible contributor to non-linear declines in $\dot{V}O_{2max}$ across midlife. Estrogen has well-described effects on vascular function, erythropoiesis, and mitochondrial efficiency [89–92], all of which affect oxygen delivery and utilization during exercise. Reductions in endogenous estrogen may therefore affect multiple components of the oxygen transport cascade, including both central and peripheral determinants of $\dot{V}O_{2max}$. In addition, testosterone (although present at lower concentrations in female than male individuals) contributes to the regulation of skeletal and cardiac muscle mass, erythropoesis, and muscle capillary density [93]. Age-related declines in testosterone levels and bioavailability in female individuals may therefore also influence multiple physiological components of $\dot{V}O_{2max}$ [94]. Consequently, an apparent acceleration in $\dot{V}O_{2max}$ decline during midlife may reflect endocrine transitions in addition to aging. Future longitudinal studies spanning the menopausal transition, with explicit characterization of endocrine status and hormone use, will be essential to clarify these relationships.

Because $\dot{V}O_{2max}$ reflects the integrated function of the oxygen transport cascade, age-related changes in pulmonary and respiratory function may also contribute to reductions in aerobic capacity. Across 15 studies including 856 female Masters athletes, maximal exercise ventilation declined by approximately 1.15 $L \cdot min^{-1}$ per year, which was steeper than estimates derived from population-based female reference data from the HUNT Study (~0.7 $L \cdot min^{-1}$ per year). These findings suggest that maximal exercise ventilation, like $\dot{V}O_{2max}$, remains susceptible to an age-related decline despite sustained endurance training. Importantly, maximal exercise ventilation is not influenced only by pulmonary function, but also by respiratory muscle function, chest wall mechanics, and lung elastic recoil. Age-related changes across these physiological systems may therefore contribute to reductions in maximal ventilation and potentially influence the decline in aerobic capacity observed in female Masters athletes.

4.4 Lessons from Case Studies

Case studies and single-participant extractions provide valuable complementary insight into the upper boundaries of aerobic capacity in female Masters athletes. Although excluded from quantitative synthesis, these cases offer illustrative examples of what may be physiologically attainable with sustained engagement in endurance exercise across the lifespan.

Across five identified cases, spanning ages 50–83 years, reported $\dot{V}O_{2max}$ values ranged from 42.3 to 52 $mL \cdot kg^{-1} \cdot min^{-1}$ (Fig. 3), values that are notably high for advanced age. These included a 50-year-old individual with a $\dot{V}O_{2max}$ of 52 $mL \cdot kg^{-1} \cdot min^{-1}$ [83], a 54-year-old individual with a $\dot{V}O_{2max}$ of 49.3 $mL \cdot kg^{-1} \cdot min^{-1}$ [79], and a 76-year-old runner completing high weekly mileage (70–110 km per week) with a $\dot{V}O_{2max}$ of 47.9 $mL \cdot kg^{-1} \cdot min^{-1}$ [82]. Two additional cases described 83-year-old individuals with $\dot{V}O_{2max}$ values of 42.3 and 45.3 $mL \cdot kg^{-1} \cdot min^{-1}$, achieved through differing training modalities including walking, running, and

track-and-field competition [80, 81]. These cases highlight the considerable heterogeneity in aerobic capacity among female Masters athletes and highlight that exceptionally high levels of cardiorespiratory fitness can be maintained into later life through diverse training backgrounds and sports disciplines. While such cases are not representative of the broader population of female Masters athletes, they provide useful reference points for the upper limits of aerobic performance and reinforce the potential for sustained endurance training to preserve high levels of $\dot{V}O_{2max}$ well beyond midlife.

4.5 Limitations and Defining a Masters Athlete

A key limitation of this synthesis is the absence of a universally accepted definition of a "Masters athlete." Although most definitions emphasize continued participation in structured training or competition beyond the age of 35 or 40 years [95], studies varied in how participants were described and classified. To maximize inclusion while preserving physiological relevance, we included studies of healthy female individuals aged 40 years or older who engaged in regular endurance training or competition. This inclusive approach increases heterogeneity and may modestly underestimate characteristics of highly trained Masters athletes, but it reflects the diversity of training backgrounds represented in the literature. Some caution is also warranted when interpreting values in athletes aged ≥70 years, as this age group only had 64 participants from four contributing studies. As participation of female individuals in endurance sports continues to expand across the lifespan, greater representation of athletes at more advanced ages will be important for refining the estimate of aerobic capacity in this population.

Additional limitations should be acknowledged. First, most included studies were cross-sectional in design, limiting inference regarding within-individual trajectories of a $\dot{V}O_{2max}$ decline with aging. While studies that span a decade or more may not show a difference in trajectories, longitudinal studies are warranted to better understand the factors that shape $\dot{V}O_{2max}$ trajectories. Second, training exposure (including volume, intensity, and lifetime training history) was inconsistently reported, precluding formal evaluation of the training dose as a moderator of age-related changes in $\dot{V}O_{2max}$. Third, information on menopausal status and hormone therapy use was sparsely reported, limiting the ability to evaluate endocrine influences on aerobic capacity across midlife. Fourth, Masters athletes represent a self-selected population of individuals who maintain higher levels of physical activity into older age, and survivorship or selection bias may limit generalizability to broader populations of aging female individuals. Despite these limitations, the consistency of findings across sport disciplines and testing modalities supports the robustness of the observed age-related trajectory of $\dot{V}O_{2max}$ in female Masters endurance athletes.

5 Conclusions

This systematic review and meta-analysis demonstrates a consistent inverse relationship between age and directly measured $\dot{V}O_{2max}$ in female Masters endurance athletes. $\dot{V}O_{2max}$ declines at an average rate of about 0.6 $mL \cdot kg^{-1} \cdot min^{-1}$ per year after age 40 years, corresponding to about 11.7% per decade. This decline is evident across exercise testing modalities and appears consistent with physiological changes associated with aging despite sustained endurance training. These findings provide contemporary female-specific reference values and establish a quantitative framework for future research, including testable hypotheses on the influence of training history, menopausal status, and other factors on aerobic capacity trajectories in aging female individuals. Improved reporting of menopausal and hormonal characteristics will be essential for clarifying female-specific factors that may influence the trajectory of age-related changes in aerobic capacity.

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Declarations

Conflict of Interest Shalaya Kipp, Kathryn F. Larson, Diana B. Collantes, Ashley M. Michael, Tiffany L. Brazile, Benjamin D. Levine, Wyatt W. Pruter, Michael J. Joyner, and Jonathon W. Senefeld have no conflicts of interest that are directly relevant to the content of this article.

Ethics Approval Not applicable.

Consent to Participate Not applicable.

Consent for Publication Not applicable.

Availability of Data and Material Data are available upon reasonable request from the corresponding author.

Code Availability The code used for the analysis in this study is available upon reasonable request from the corresponding author.

Author Contributions SK, KFL, JWS, and MJJ conceived and designed the study. JWS and MJJ supervised the study. SK, KFL, DBC, AMM, WWP, and JWS implemented the search strategy, conducted abstract screening, applied inclusion and exclusion criteria, and performed data extraction and quality assessment. SK performed the meta-analysis and conducted the quantitative synthesis. SK, KFL, and JWS interpreted the data. SK, KFL, JWS, and MJJ contributed to manuscript drafting. TLB and BDL contributed previously collected data and provided critical intellectual input regarding study context and interpretation.

All authors critically reviewed and approved the final version of the manuscript.

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