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Review article

The effect of age and sex on peak oxygen uptake during upper and lower body exercise: A systematic review

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ABSTRACT

Background: Large scale population norms for peak oxygen uptake (VO_{2peak}) during cycle ergometry (CE) have been published for men and women across a wide range of ages. Although upper body functional capacity has an important role in activities of daily living far less is known regarding the effect of age and sex on upper body functional capacity (i.e. arm crank ergometry; ACE). The aim of this review was to determine the effect of age and sex on VO_{2peak} obtained during ACE and CE in the same participants.

Method: The review was pre-registered with PROSEPERO (Ref: CRD42022349566). A database search using Academic Search Complete including CINAHL complete, CINHAL Ultimate, Medline, PubMed, SPORTDiscus was undertaken.

Results: The initial search yielded 460 articles which was reduced to 243 articles following removal of duplicates. Twenty-five articles were subsequently excluded based on title resulting in 218 articles considered for retrieval. Following review of the abstracts, 78 further articles were excluded leaving 140 to be assessed for eligibility. Eighty-five articles were subsequently excluded, resulting in 55 articles being included. The decrease in VO_{2peak} with age during CE was consistent with previous studies. Decreases in VO_{2peak} during ACE with age, although paralleling those of CE, appeared to be of greater functional importance. When changes in VO_{2peak} were considered below the age of 50 years little change was observed for absolute VO_{2peak} during ACE and CE. In contrast, relative VO_{2peak} demonstrated decreases in VO_{2peak} for both ACE and CE likely reflecting increases in body mass and body fat percentage with age. After 50 years of age absolute and relative VO_{2peak} demonstrated more similar and subtle responses. Heterogeneity across studies for both absolute and relative VO_{2peak} between ACE and CE was large. Although strict inclusion criteria were applied, the inter-individual variation in sample populations was likely the main source of heterogeneity. There was a considerable lack data sets available for ages above 40 years of age.

Conclusions: These responses suggest that upper body VO_{2peak} decreases in line with that of the lower body but, due to the lower peak values achieved during ACE, decreases in VO_{2peak} may have more profound functional impact compared to that for the lower body. Using absolute and relative measures of VO_{2peak} results in different age-related profiles when considered below 50 years of age. To further our understanding of whole body ageing more data is required for participants in mid and later life. The association between VO_{2peak} and underlying physiological factors with age needs to be studied further, particularly in conjunction with activities of daily living and independent living.

1. Introduction

Arm crank ergometry (ACE) is a mode of exercise commonly used to assess the functional capacity of those individuals involved in upper body sports, such as paddlers (Tesch et al., 1982), wrestlers (Aschenbach et al., 2000) and wheelchair athletes (Nevin et al., 2018). Additionally, ACE is a relevant exercise mode for individuals who are either unable to use their legs due to spinal cord injury (Price and Campbell, 1997a) or for those with limited lower body exercise capacity, such as patients with intermittent claudication (Saxton et al., 2008) and chronic

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obstructive pulmonary disease (Carter et al., 2003). Exercise protocols involving ACE have also been used to assess the effectiveness of health interventions for the purpose of prescribing training in otherwise healthy young (Bottoms and Price, 2014) and older adults (Hill et al., 2018a) and has shown clear predictive ability for clinical outcomes in people with lower-limb disability (Chan et al., 2011). ACE therefore demonstrates clear utility across the spectrum of healthy and clinical populations.

Early studies of ACE in healthy individuals initially explored the influence of muscle mass on maximal aerobic power and lactate threshold across exercise modes (Davis et al., 1976). The resultant peak oxygen uptake (VO_{2peak}; Magel et al., 1978) during ACE is generally reported to be approximately 70 % of that achieved during cycle ergometry (CE), the lower values resulting from the use of a smaller active muscle mass, notable peripheral muscular fatigue and lower central or cardiovascular strain (Davis et al., 1976). In a recent review Larsen et al. (Larsen et al., 2016) consolidated the literature evaluating the magnitude of VO_{2peak} during ACE when compared to CE in the same participants. More specifically, the authors aimed to explore factors that may be predictive of the difference between exercise modes, potentially allowing for a direct comparison of data obtained during both tests. The pooled mean data demonstrated a difference of 12.5 ml.kg.$^{-1}$ min^{-1} between ACE and CE, in favour of CE. Interestingly, younger participants and those with greater aerobic capacity achieved a greater difference between modes. However, substantial heterogeneity was evident across studies for the difference in VO_{2peak} between exercise modes ($I^2 = 59.9$ %).

Although Larsen and colleagues noted that the systematic difference in VO_{2peak} between ACE and CE modes reduced with age, few studies had reported values for peak aerobic power for older age groups, with a similarly low number addressing values for women. Most of the studies included in the analysis reported VO_{2peak} for participants in either their 20's or 30's, with only one, two and five studies reporting values for participants in their 40's, 50's and 60's, respectively. Conversely, large scale population norms for VO_{2peak} during CE across a wide range of ages have been published for both sexes, with values peaking around 20–30 years of age and decreasing thereafter (Rapp et al., 2018). The decrease in VO_{2peak} from 30 years of age is likely due to the subsequent age-related sarcopenia and a reduction in whole body oxidative capacity (Keller and Engelhardt, 2014). As fewer studies have reported VO_{2peak} values for ACE in healthy older adults far less is known regarding the effect of age on upper body functional capacity. When considering that cardiorespiratory fitness is a strong and modifiable indicator of long-term mortality (Laukkanen et al., 2022) increasing our understanding of such age-related responses has clear importance. Furthermore, women are consistently reported to have lower all-cause mortality when compared to men (Harb et al., 2021), therefore, establishing any sex and age-related patterns in VO_{2peak} is essential, particularly considering the clinical relevance of ACE testing and the lack of data for VO_{2peak} during ACE in older women.

Typical values reported for VO_{2peak} during ACE and CE in healthy participants in their early 20's are ~24 and 39 ml.kg.$^{-1}$min.$^{-1}$, respectively (Price et al., 2014). In contrast, values of ~21 and 28 ml.kg.$^{-1}$.min.$^{-1}$ have been reported for healthy participants in their mid-60's (Hill et al., 2018a). Such results indicate that although VO_{2peak} is lower during ACE in both age groups, the rate at which VO_{2peak} decreases would appear slower for ACE, likely due to the initially lower aerobic training status of the upper body when compared to the lower body. To the authors knowledge, the effect of age on VO_{2peak} in ACE and CE in the same participants has not been reported and could reveal unique insights in relation to how upper body functional capacity changes with age. Therefore, the aim of this review was to determine the effect of age on VO_{2peak} obtained during upper and lower body ergometry. A secondary aim was to determine how age-related changes in upper and lower body functional capacity may be affected by sex; an area currently very much under-reported in the literature.

2. Method

Following institutional ethics approval (P120677) planning and conducting of the review was undertaken following the PRISMA guidelines (Page et al., 2021) and was pre-registered with PROSEPERO (Ref: CRD42022349566; August 2022).

2.1. Eligibility criteria

Criteria for studies to be included within the review were; the comparison of VO_{2peak} during incremental ACE and CE in the same participants, able-bodied or otherwise healthy participants and participants above the age of 18 years. Exclusion criteria were; studies utilising independent group designs, studies comparing ACE to exercise modes other than CE, studies utilising non-standard ACE variants (i.e. standing ACE, braced ACE, handcycling, unilateral ACE, single or double polling) or semi-recumbent cycling and studies involving participants who were trained in either the upper or lower body.

2.2. Information sources

A database search using Academic Search Complete including CINAHL complete, CINHAL Ultimate, Medline, PubMed, SPORTDiscus and both eBook collections and eBook open access Collection (EBCSO host) was undertaken between 20/06/22 and 27/06/22 for published studies up to and including July 2022. Reference lists of pertinent reviews (e.g. Larsen et al., 2016) and all articles obtained were scanned for further studies.

2.3. Search strategy

Search terms included combinations of ‘peak oxygen uptake’ or ‘maximal oxygen uptake’ as the main outcome variable in combination with, and variants of, ‘upper body exercise’ and ‘arm crank ergometry’, and ‘lower body exercise’ and ‘cycle ergometry’ as well as ‘combined arm and leg exercise’ for exercise modes and, finally, terms relating to age and older populations. It should be noted that although the term ‘elderly’ was used within searches, it is acknowledged that the term ‘older adults’ is more appropriate (Avers et al., 2011), however, we did not want to potentially omit relevant studies due to changes in terminology. More specifically, searches included:

1) “Maximal oxygen uptake” or “Peak oxygen uptake” AND “upper body exercise” or “arm crank ergometry” or “arm cranking” AND “lower body exercise” or “cycle ergometry”,
2) “Maximal oxygen uptake” or “Peak oxygen uptake” AND “upper body exercise” or “arm crank ergometry” or “arm cranking” AND “Age” or “ageing” or “older” or “elderly”,
3) “Maximal oxygen uptake” or “Peak oxygen uptake” AND “lower body exercise” or “cycle ergometry” AND “Age” or “ageing” or “older” or “elderly” and,
4) “Maximal oxygen uptake” or “Peak oxygen uptake” AND “combined upper and lower body exercise” or “arm and leg exercise” or “arm and leg ergometry”.

Only articles that were in English were selected whereas no limit was placed on publication date. Further independent searches for upper body exercise capacity (as per terms listed above) in clinical groups (e.g. hip replacement, chronic obstructive pulmonary disease, intermittent claudication, Parkinson's disease, abdominal aortic aneurysm) were also undertaken to obtain data from healthy age matched controls.

2.4. Selection process

Two independent reviewers (MP, LB) performed the initial title screening from the resultant searches using an online systematic review software package (Rayyan; https://www.rayyan.ai) to identify studies that potentially met inclusion criteria. Full text documents of selected studies were subsequently retrieved and assessed for eligibility by the primary reviewer (MP) and checked by a second reviewer (LB). Any disagreement between the independent reviewers was resolved through discussion, if agreement could not be reached a third reviewer was involved, although this was not required.

2.5. Data collection process

Data from eligible studies was extracted and entered into an Excel spreadsheet populated with specific headings of; Study (authors and date), sample size, age, physical activity status, mass (kg), stature (m), body fat percentage or BMI (kg.m^2) and absolute (l.min^{-1}) and relative (ml.kg.$^{-1}$min.$^{-1}$) VO_{2peak} (mean, standard deviation) for ACE and CE. Data was initially extracted by one reviewer (MP) and, in conjunction with methodological quality assessment ratings, was confirmed by all authors for their allocated studies. Each author worked independently. Where data was not available, a comment was provided on the spreadsheet for potential discussion of data completeness as appropriate. No automation tools were used in the data collection process.

2.6. Data items

The primary outcome measure of interest was VO_{2peak} expressed as absolute values (l.min^{-1}) and secondarily VO_{2peak} expressed relative to body mass (ml.kg.$^{-1}$min.$^{-1}$). Where only absolute values were reported but body mass was also reported relative values were calculated from group mean values. The same principle applied when only relative values were reported. Where such data could not be determined the study was excluded. Based on these data further outcome variables were assessed, namely the difference in VO_{2peak} between CE and ACE and the ratio between them (ACE:CE) following the approach utilised by Larsen et al. (Larsen et al., 2016).

2.7. Synthesis methods

Extracted data for participant characteristics and VO_{2peak} were tabulated according to studies reporting male or female participants. Scatterplots for age against VO_{2peak} for ACE and CE for each group were initially plotted to determine the effect of age on VO_{2peak} for both exercise modes. Linear trendlines producing correlation coefficients (R) and coefficients of determination (R^2) were subsequently generated using Microsoft Excel with the gradient of each linear trend line (representing the change in VO_{2peak} per year) extrapolated to changes over a ten-year period. Where standard deviations for VO_{2peak} were reported for included studies, the pooled standard deviation was calculated, and effect size established for the difference in VO_{2peak} between ACE and CE. Data for VO_{2peak} was also grouped according to decade of life, namely; 20–29, 30–39, 40–49, 50–59, 60–69, 70–79 years of age, as well as a smaller category of <20 yrs encompassing those studies with participants under 20 years of age. To determine any meaningful differences in VO_{2peak} across age group categories weighted means and pooled standard deviations were calculated for each age category and compared using Hedges g. Following the recommendations of Deeks et al. (2022) values of g were interpreted as having small (<0.3), medium (~0.5) or large importance (>0.8). Heterogeneity (I^2) between studies was also determined according to recommendations of Deeks et al., using freely available software (Suurmond et al., 2017). Values for I^2 of between 0 and 40 %, 30–60 %, 50–90 % and 75–100 % were interpreted as likely unimportant, moderate, substantial and considerable hetereogeneity, respectively (Deeks et al., 2022). To further examine the relationship between body mass and both absolute and relative VO_{2peak} correlations between these variables were performed using Pearson's correlation.

2.8. Study risk of bias assessment

Eligible studies were assessed for methodological quality using the NIHR Quality Assessment Tool for observational cohort and cross-sectional studies (QAT) (NHLBI 2, n.d.) and the Downs and Black Quality Assessment Checklist (Downs and Black, 1998). Risk of bias per se was not assessed due to the observational and cross-sectional nature of the studies contained within the review not reflecting the design of randomised controlled trials considered by typical risk of bias tools. Equal numbers of studies were assessed for methodological quality by each author (n = ~15). The lead author confirmed ratings from a subset of assessment ratings from the three other authors, essentially moderating each author's assessment. Any disagreements between reviewers, or where a decision was difficult or could not be reached, were resolved by discussion between reviewers, with involvement of a third author where necessary. The outcomes of these assessments were subsequently integrated into the results and discussion sections of the review regarding the quality of evidence.

Methodological assessment using the QAT was utilised as this was reported by Larsen et al. (Larsen et al., 2016) when reviewing the relationship between VO_{2peak} during ACE and CE, whereas the Downs and Black checklist (Downs and Black, 1998) was utilised as this was reported by Baumgart et al. (Baumgart et al., 2018) when reviewing VO_{2peak} in Paralympic sitting sports. Thus, both tools have been applied for the same outcome variable (VO_{2peak}) and study designs as in the current review. In addition, both reviews used amended versions of the original tools as follows; Larsen et al. (Larsen et al., 2016) considered questions 1–5, 11, 12, 14 of the QAT whereas we additionally excluded question 3 ('Was the participation rate of eligible persons at least 50%?') and question 12 ('Were the outcome assessors blinded to the exposure status of participants?') as these were not appropriate for our inclusion criteria with respect to study design, resulting in a quality score out of six. Baumgart et al. considered questions 1–3, 5–7, 11, 12, 20–22, 25 of the Downs and Black checklist. In contrast to Baumgart et al. we included question 4 ('Are the interventions of interest clearly described?') rewording 'interventions' as 'methods' to cover the study as a whole, question 10 ('Have actual probability values been reported (e.g.0.035 rather than <0.05) for the main outcomes except where the probability value is less than 0.001?'), question 18 ('Were the statistical tests used to assess the main outcomes appropriate?'), question 23 ('Were study subjects randomised to intervention groups?') rewording 'intervention groups' to 'trials', and question 27 ('Did the study have sufficient power to detect a clinically important effect where the probability value for a difference being due to chance is less than 5%?'). We excluded questions 6 and 7 relating to intervention groups. Question 5 referring to confounders related to reporting and discussing of sex, age, mass, training status, differences between upper and lower body physiology. All questions scored 1 (Yes) or zero (No/unable to determine). Results from the Downs and Black checklist were reported out of a total of 15. Both scales were converted to a percentage score and considered as being of poor (<46 %), fair (54–62 %), good (65–80 %) or excellent (85–100 %) methodological quality.

3. Results

3.1. Study selection

The initial search yielded 460 articles which was reduced to 243 articles following removal of duplicates. Twenty-five articles were subsequently excluded based on title resulting in 218 articles considered for retrieval. Following review of the abstracts, 78 further articles were excluded leaving 140 to be assessed for eligibility. Of these articles, 85 were excluded, resulting in 55 articles being included (Fig. 1).

Of the 55 studies ($n = 739$) fitting the inclusion criteria, 41 provided one data set, 13 provided two data sets and one provided three data sets, resulting in a total of 70 useable data sets. Of these data sets, 56 provided

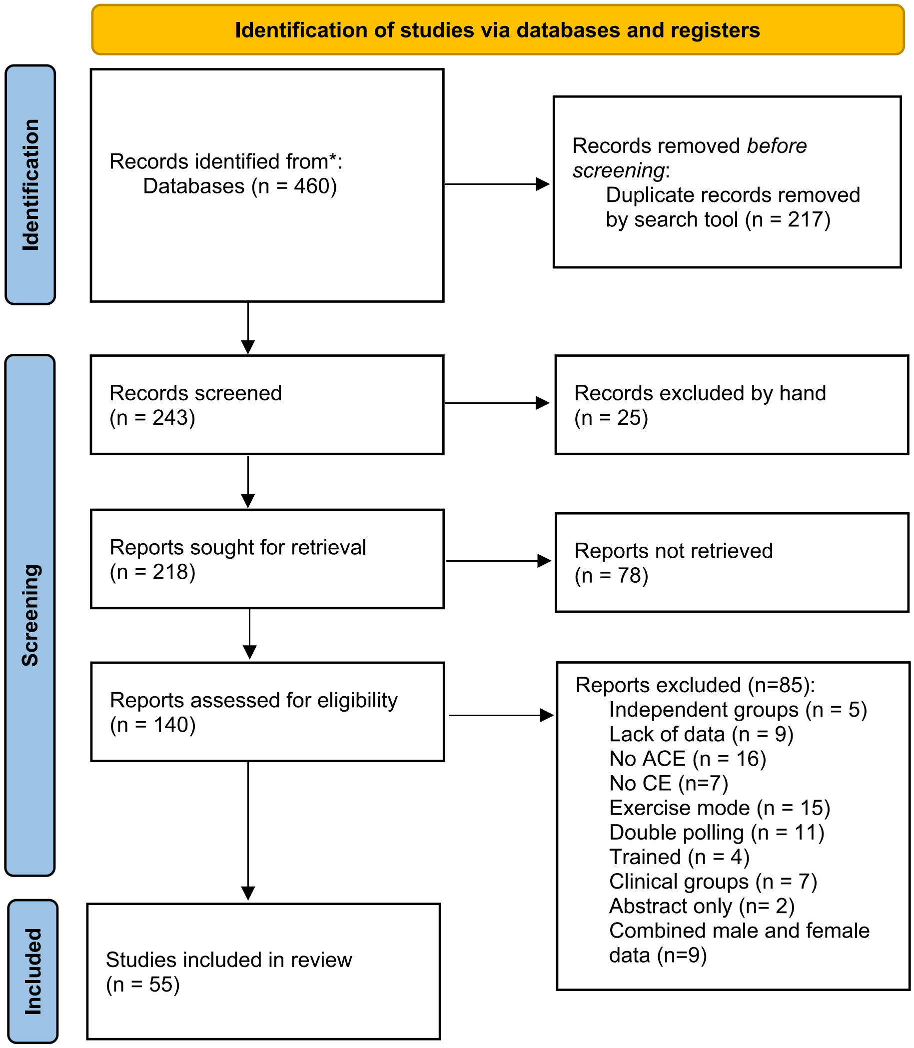

Fig. 1. PRISMA flow chart, adapted from Page et al. (2021).

peak physiological responses for ACE and CE in men and 14 in women. Specific values for the frequency of studies in each age group are shown in Table 1.

The overwhelming majority of studies recruited participants between the ages of 18–39 years. Similar percentages of studies had been undertaken for men and women between the ages of 20–29 (~68 and 71 %, respectively) and 30–39 years (~16 and 14 %, respectively). Few studies ($n = 8$) had been undertaken in older age groups (i.e. 50–79 years). Study population characteristics are shown in Table 2. Studies reporting data for men and women generated similar overall ages and mean sample size across studies. Males were generally heavier than females (Table 2), a fact that was echoed for <20, 20–29 and 30–39 yrs age categories (76.3 ± 11.4, 73.8 ± 19.1 and 78.8 ± 9.6 kg for males and 55.4 ± 7.0, 60.8 ± 8.1 and 60.2 ± 5.1 kg for females, respectively).

3.2. Study characteristics

The characteristics of each study for men and women are shown in Tables 3a, 3b and 4.

3.3. Absolute peak oxygen uptake

The relationship between absolute VO_{2peak} ($l.min^{-1}$) and age for men and women is shown in Fig. 2a and b. The accompanying summary statistics from linear fits of VO_{2peak} against age are shown in Table 5. The decrease in absolute VO_{2peak} over a ten-year period was approximately 0.2 and 0.3 $l.min^{-1}$ for ACE and CE, respectively. These values represented 7.2 and 8.3 % for men and 9.2 and 7.6 % for women when related to the 20–29 group, respectively. Fitting nonlinear curves such as polynomials did not improve the R^2 values for either data set.

Table 1
Frequency and percentage of included data sets providing peak physiological responses for arm crank ergometry and cycle ergometry in men and women.

	N	Age group (years)						
		<20	20–29	30–39	40–49	50–59	60–69	70–79
Male	56	2	37	9	1	2	4	1
Male (%)	–	3.6	66.1	16.1	1.7	3.6	7.1	1.8
Female	14	1	10	2	0	1	0	0
Female (%)	–	7.1	71.4	14.3	0.0	7.1	0.0	0.0

Table 2
Overall sample characteristics for studies providing peak physiological responses for arm crank ergometry and cycle ergometry in men and women.

	Age (years)	Mass (kg)	Stature (cm)	Group characteristics					
				Group n	Mode n	Range	Min	Max	Total n
Male	32 (13)	79 (12)	181 (5)	9 (1)	10	29	1	30	584
Female	28 (9)	61 (5)	165 (6)	10 (6)	10	26	1	27	155

The weighted means and pooled standard deviations for absolute VO_{2peak} during ACE and CE in relation to each age category for those studies reporting data for men are shown in Fig. 3a. Absolute VO_{2peak} for ACE was moderately greater in the <20 yrs age group than for the 20–29 yrs category (g = 0.564; 9.7 %) but considerably greater than all other age categories (g = 0.786 to 2.566, 17.8 to 48.7 %). Although absolute VO_{2peak} was lower for 40–49 yrs compared to <20 yrs, differences between 40 and 49 and both 20–29 and 30–39 categories were of small importance (g = 0.448, 5.0 % and g = 0.259, 2.6 %, respectively). There was a large decrease in absolute VO_{2peak} from 40 to 49 yrs to 50–59 yrs (12.2 %) onwards (g = 1.117 to 2.525). Values at 50–59 yrs were of moderate difference to 70–79 yrs (16.9 %) whereas values at 60–69 yrs were of large importance when compared to 50–59 yrs (4.9 %), demonstrating the fluctuation in absolute VO_{2peak} values. For CE, absolute values of VO_{2peak} at <20 yrs were considered similar to 20–29 yrs (g = 0.185, 2.2 %) and 40–49 yrs (g = 0.234, 3.0 %) but considered of large importance between all other age groups (g = 1.063 to 4.144, 10.0 to 47.6 %). With the exception of potentially moderate to large decreases in absolute VO_{2peak} at 30–39 yrs (3.20 $l.min^{-1}$, 11.4 %), peak values up to 40–49 yrs were generally similar (3.50 to 3.61 $l.min^{-1}$, 3.1 %). Similarly to ACE, a large decrease in absolute VO_{2peak} occurred at 50–59 yrs, with potentially larger decreases observed between both 50–59 yrs and 60–69 yrs (both 2.25 $l.min^{-1}$) compared to 70–79 yrs (1.89 $l.min^{-1}$, 10 %).

For women, no included studies reported absolute VO_{2peak} for the 40–49, 60–69 or 70–79 yrs groups. The <20 yrs group absolute VO_{2peak} values during ACE were greater than all other age groups and of a moderate to large importance (13.9 to 29.8 %). Both the 20–29 and 30–39 yrs categories demonstrated greater VO_{2peak} than those of the 50–59 yrs category being of moderate (g = 0.552, 15.9 %) to large importance (g = 0.804, 29.8 %). The VO_{2peak} during CE demonstrated the same trends.

3.4. Relative peak oxygen uptake

The relationship between relative VO_{2peak} ($ml.kg^{-1}.min^{-1}$) and age for men and women is shown in Fig. 4a and b. The accompanying summary statistics from linear fits are shown in Table 5. With the exception of the female data during CE, the potential decrease in VO_{2peak} over a ten-year period was similar across data sets for both ACE (~3.1 to 4.1 $ml.kg.^{-1}$ min^{-1} for men and women, respectively) and CE (~4.8 to 6.5 $ml.kg.^{-1}$ min^{-1}, respectively). Decreases in VO_{2peak} for ACE and CE for men represented 8.9 and 10.0 % when compared to the 20–29 group, respectively. Decreases were lower for women during ACE.

Fig. 3b shows weighted means and pooled standard deviations for relative VO_{2peak} in relation to each age category for those studies reporting data for male participants. Results for both ACE and CE demonstrated similar responses in VO_{2peak} up until 40–49 years of age. For example, Hedges g values indicated that VO_{2peak} at <20 yrs and 20–29 yrs were similar for both ACE (g = 0.387, 5.0 %) and CE (g = 0.000, 0 %) as were values between 30 and 39 yrs and 40–49 yrs for ACE (g = 0.148, 0 %) and CE (g = 0.000, 0 %). However, the decrease in VO_{2peak} from 20 to 29 yrs to 30–39 yrs was large for ACE (g = 0.775, 12.1 %) but only medium for CE (g = 0.583, 8.3 %). After this point there was a large decrease in VO_{2peak} from 40 to 49 years to 50–59 yrs for both ACE (g = 2.169, 34.4 %) and CE (g = 2.274, 38.6 %). Subsequent decreases in VO_{2peak} from 50 to 59 yrs to 70–79 yrs groups were again considered medium for ACE (g = 0.632, 10.5 %, respectively) but low for CE (g = 0.283, 11.1 %, respectively).

For females ACE and CE values were also similar between 20 and 29 and 30–39 age categories (g = 0.146, 7.4 % to 0.343, 5.0 %) with large decreases occurring up to the 50–59 yrs category (40.7 and 48.1 %, respectively). However, values for the <20 yrs age group were considered greater and large when compared to all other age groups (g = 1.236 to 5.394).

Although the above figures (Figs. 2, 4) have shown general decreases in absolute and relative VO_{2peak} for ACE and CE from 19 to 75 years of age, more subtle differences between measures were observed when decreases in VO_{2peak} were considered above and below the age of 50 yrs (Fig. 5). For absolute VO_{2peak} there was little change from <20 to 40–49 years for CE (0.04 $l.min^{-1}$ per decade, 0.10 %) or ACE (0.12 $l.min^{-1}$ per decade, 4.5 %). Similarly, there was little change from 50-59 to 70–79 years for CE (0.11 $l.min^{-1}$ per decade, 3.0 % compared to <20 yrs, 4.9 % compared to 50–59 yrs) or ACE (0.04 $l.min^{-1}$ per decade, 1.5 % compared to <20, 2.5 % compared to 50–59 yrs). In contrast, relative VO_{2peak} values from <20 to 40–49 years for both CE and ACE decreased by 3.4 (7.1 % relative to <20 yrs) and 3.8 $ml.kg.^{-1}min.^{-1}$ per decade (10.9 % relative to <20 yrs), respectively. However, there was little change in values for CE (0.2 $ml.kg.^{-1}min.^{-1}$ per decade, 0.4 % relative to <20 yrs, 0.7 % relative to 50–59 yrs) or ACE from 50 to 59 to 70–79 yrs (0.8 $ml.kg.^{-1}min.^{-1}$ per decade, 2.3 % relative to <20 yrs, 4.2 % relative to 50–59 yrs).

There was no relationship between body mass and age (R = 0.175, R^2 = 0.030, P = 0.228) or body mass and absolute VO_{2peak} for ACE (R = 0.052, R^2 = 0.003, P = 0.716) or CE (R = 0.022, R^2 = 0.001, P = 0.875). Significant relationships were observed between body mass and relative VO_{2peak} during ACE (R = 0.333, R^2 = 0.111, P = 0.019) and CE (R = 0.328, R^2 = 0.107, P = 0.021).

3.5. Effect sizes and heterogeneity

Mean ES for absolute VO_{2peak} for men and women were large (2.4 ± 1.5 and 1.8 ± 1.3, respectively) as were values for relative VO_{2peak} (2.3 ± 1.0 and 2.7 ± 2.0, respectively). Heterogeneity (I^2) values for absolute VO_{2peak} for men and women were both 87 %. Values for relative VO_{2peak} were 84 and 85 %, respectively.

3.6. Ratio between VO_{2peak} during ACE and CE and age

The ratio of VO_{2peak} between ACE and CE (i.e. ACE: CE) is shown in Fig. 6. Responses were similar for ACE:CE whether VO_{2peak} had been expressed as absolute or relative values. The ACE:CE was greatest for the youngest age category (<20 yrs) and gradually decreased to 30–39 yrs, remaining similar at 40–49 yrs. Ratios then increased from this point until 60–69 yrs.

3.7. Methodological quality

The results of the methodological quality assessments indicated mean scores of 69 % (29 to 100 %) and 73 % (44 to 100 %) for the QAT and Downs and Black tools, respectively. The QAT resulted in a lower number of studies in the good (34 %) and excellent (26 %) categories when compared to Downs and Black (52 and 35 %, respectively). For most questions posed, over 87 % of studies fulfilled the specific criteria

Table 3a

Characteristics of included studies for men of mean age between 20 and 29 years undertaking both arm crank ergometry (ACE) and cycle ergometry (CE) graded exercise protocols to exhaustion ($n = 37$). NST = non-specifically trained; PA = physically active; Untr = untrained; Uni Std = university standard; PE = physical education; Rec = recreational; NS = not stated; MA = moderately active; NCS = no competitive Sport; min·d^{-1} = minutes per day; Sed = sedentary; ES = effect size; D&B = Downs and Black quality rating; QAT = NIHR quality rating.

Authors	N	Training status	Age (yrs)		Mass (kg)		Stature (cm)		Relative VO_{2peak} (ml·kg^{-1}·min^{-1})					Absolute VO_{2peak} (l·min^{-1})					Quality rating	
			Mean	SD	Mean	SD	Mean	SD	ACE		CE		ES	ACE		CE		ES	QAT (%)	D&B (%)
									Mean	SD	Mean	SD		Mean	SD	Mean	SD			
20–29 yrs																				
Lewis et al. (1980)	5	Healthy	20.0	3.0	73.0	12.0	175	2	22	–	37	–	–	1.64	0.22	2.69	0.40	3.3	43	56
Koppo et al. (2002)	10	PA	21.3	0.8	73.9	5.3	180	6	37	5	58	6	3.9	2.74	–	4.31	–	–	43	69
Schneider et al. (2002)	10	Untr	21.6	1.3	80.7	3.1	180	1	26	2	39	2	6.8	2.08	0.11	3.10	0.14	8.1	71	69
Hill et al. (2018b)	10	PA, MST	21.7	3.4	73.6	8.7	181	5	37	5	43	4	1.6	2.68	0.34	3.17	0.46	1.2	100	100
Dekerle et al. (2002)	20	PE students	22.0	2.2	73.5	5.3	180	6	27	4	38	6	2.3	2.74	0.35	3.81	0.57	2.3	86	81
Lewis et al. (1980)	5	Healthy	22.0	2.0	79.0	13.0	186	10	25	–	39	–	–	1.97	0.32	3.09	0.41	3.0	43	56
Pimental et al. (1984)	9	Healthy	22.0	3.0	71.4	6.9	172	8	35	6	49	7	2.2	2.49	–	3.48	–	–	33	53
Sawka et al. (1984)	9	Healthy	22.0	3.0	71.4	7.0	–	–	34	6	48	7	2.1	2.46	0.42	3.44	0.52	2.1	83	76
Toner et al. (1984)	8	Healthy	22.4	3.6	70.9	6.2	171	5	36	5	47	7	2.0	2.54	0.40	3.34	0.53	1.7	50	59
Davis et al. (1976)	30	No end tr for 4 mo	22.5	2.5	75.5	9.0	180	7	31	4	49	5	3.7	2.34	0.39	3.68	0.41	3.3	67	59
Warren et al. (1990)	10	Untr	22.6	5.1	74.4	9.5	175	6	30	5	47	5	3.8	2.17	0.27	3.43	0.26	4.8	71	81
Nag (1984)	5	Motivated	22.7	3.4	48.9	0.9	160	2	37	–	45	–	–	1.81	0.36	2.20	0.38	1.1	43	56
Swensen et al. (1993)	5	Untr	22.8	–	73.0	–	–	–	28	–	40	–	–	2.02	0.20	2.94	0.20	4.6	57	75
Turner et al. (1997)	6	Rec, NST	23.0	1.0	75.0	2.0	179	1	34	1	49	2	9.5	2.55	–	3.68	–	–	29	44
Ogata and Yano (2005)	8	Healthy	23.4	2.7	67.7	4.4	173	5	29	–	37	–	–	1.98	0.23	2.53	0.31	2.0	57	69
Bohnert et al. (1998)	6	Healthy	23.8	0.7	71.0	5.6	178	8	33	7	50	10	2.0	2.23	0.51	3.51	0.71	2.1	57	69
Sharp et al. (1988)	18	NS	23.9	3.7	75.9	8.8	177	9	34	–	48	–	–	2.57	0.46	3.63	0.56	2.1	43	44
Helge et al. (2011)	10	Healthy	24.0	1.0	77.6	2.1	179	3	31	5	50	6	3.5	2.36	0.42	3.80	0.38	3.6	43	44
Tiller et al. (2019)	8	Rec	24.0	5.0	74.0	11.0	179	7	31	6	41	10	1.2	2.36	0.54	3.12	0.72	1.2	71	88
Hill et al. (2014)	9	Healthy, Untr	24.1	4.8	75.6	13.9	177	5	35	7	45	8	1.3	2.62	0.34	3.23	0.52	1.4	100	100
Hill et al. (2020)	12	MA, 2–3 wk	24.6	5.3	83.1	8.4	181	7	31	4	40	6	2.0	2.52	0.27	3.27	0.33	2.5	86	94
Hill et al. (2019)	13	PA, 2–3 wk	24.7	5.0	74.1	9.4	177	8	34	6	44	7	1.5	2.62	0.62	3.27	0.61	1.1	86	94
Yasuda et al. (2006)	12	Rec, mild intensity	24.7	6.0	73.0	12.0	178	8	33	5	59	7	4.0	2.41	0.39	4.25	0.68	3.3	57	69
Kang et al. (1998)	10	Healthy, NCS	25.0	4.0	84.0	16.0	176	4	32	–	41	–	–	2.66	0.45	3.45	0.58	1.5	86	88
Reybrouck et al. (1975)	1	Not regularly active	25.0	–	68.0	–	–	–	32	–	39	–	–	2.19	–	2.67	–	–	67	73
Yasuda et al. (2008)	9	Rec, mild intensity	25.0	6.9	74.2	12.8	178	7	34	5	60	6	4.9	2.39	0.43	4.21	0.64	3.3	71	81
Bhambhani et al. (1998)	15	University students, Rec	25.2	5.3	72.8	8.5	176	8	38	7	55	13	1.6	2.77	0.69	4.04	1.16	1.3	86	81
Lyons et al. (2007)	10	PA, MA 30 min.d-1	25.7	5.8	104.9	18.7	184	7	21	–	30	–	–	2.20	0.25	3.10	0.38	2.8	73	67
Sporer et al. (2007)	8	Non cyclist, NST	26.0	5.0	82.8	8.1	185	7	30	5	44	4	3.2	2.52	–	3.56	–	–	71	81
Maresh et al. (2006)	8	Healthy, Untr, Rec	26.4	3.5	76.6	10.2	179	6	32	3	47	5	3.4	2.48	–	3.59	–	–	57	69
Marterer et al. (2020)	9	up to 3/wk, NST	27.5	5.0	–	–	185	7	40	6	52	6	2.1	3.12	0.66	4.18	0.90	1.3	71	81
Franklin et al. (1983)	10	Healthy	28.0	2.4	69.3	7.1	171	8	37	–	46	–	–	2.54	0.45	3.17	0.53	1.3	86	81
Miles et al. (1983)	9	NS	28.0	6.0	78.0	12.0	–	–	29	–	42	–	–	2.30	–	3.30	–	–	67	71
Sawka et al. (1983)	9	Healthy	28.0	6.0	78.0	12.0	–	–	29	–	42	–	–	2.27	0.30	3.31	0.53	2.4	57	69
Jensen-Urstad et al. (1993)	7	PA, NCS	28.3	1.4	75.3	1.3	183	3	35	2	56	4	7.1	2.65	0.14	4.22	0.11	12.5	86	88
Pivarnik et al. (1988)	8	Healthy	28.4	3.6	72.3	5.5	182	3	36	–	56	–	–	2.60	0.44	4.07	0.52	3.1	83	71
Aminoff et al. (1999)	3	Kitchen workers	28.8	–	75.2	–	179	–	26	3	52	2	9.9	1.98	0.39	3.87	0.43	4.6	83	71

Table 3b
Characteristics of included studies for men of mean age between <20 years and between 30 and 79 years undertaking both arm crank ergometry (ACE) and cycle ergometry (CE) graded exercise protocols to exhaustion (*n* = 19). NST = non-specifically trained; PA = physically active; Untr = untrained; Uni Std = university standard; PE = physical education; Rec = recreational; ns = not stated; MA = moderately active; NCS = no competitive Sport; min·d^{-1} = minutes per day; Sed = sedentary; ES = effect size; D&B = Downs and Black quality rating; QAT = NIHR quality rating.

Authors	N	Training status	Age (yrs)		Mass (kg)		Stature (cm)		Relative VO_{2peak} (ml·kg^{-1}·min^{-1})					Absolute VO_{2peak} (l·min^{-1})					Quality rating	
			Mean	SD	Mean	SD	Mean	SD	ACE		CE		ES	ACE		CE		ES	D&B (%)	QAT (%)
									Mean	SD	Mean	SD		Mean	SD	Mean	SD			
<20 yrs																				
Price et al. (2022)	13	Healthy, NST	19.3	0.5	78.1	9.1	–	–	36	7	48	5	2.0	2.73	0.64	3.62	0.46	1.6	86	88
Price et al. (2014)	8	PA, Uni Std, team sports	19.8	0.7	79.1	14.6	181	5	34	6	48	11	1.6	2.61	0.29	3.60	0.29	3.4	83	82
30-39 yrs																				
Davies et al. (1974)	12	Healthy	30.5	6.0	75.1	10.1	178	5	21	–	47	–	–	1.60	0.28	3.50	0.37	5.8	57	50
Rösler et al. (1985)	10	Healthy, Rec	30.5	–	70.8	–	178	–	38	–	52	–	–	2.72	0.13	3.66	0.12	7.5	86	81
Sargeant and Davies (1973)	6	Healthy	30.7	5.5	79.1	11.7	180	6	22	2	44	6	5.4	1.71	0.30	3.49	0.33	5.6	57	69
Ara et al. (2011)	10	Control group	31.2	1.5	91.0	4.2	184	3	28	–	40	–	–	2.50	1.20	3.60	0.10	1.3	57	69
Barstow et al. (1993)	3	Untr	31.3	7.6	78.3	11.6	–	–	26	8	35	11	1	1.96	0.47	2.65	0.44	1.5	57	63
Shiomi et al. (2000)	7	No regular exercise	32.1	–	64.1	–	170	–	29	2	46	5	4.1	1.87	–	2.92	–	–	57	69
Louhevaara et al. (1990)	21	Healthy, Untr	33.3	5.9	78.3	12.7	178	7	32	–	41	–	–	2.52	0.32	3.24	0.44	1.9	57	63
Bhambhani (1995)	25	Rec	35.0	7.3	82.9	9.1	178	7	30	7	44	6	2.1	2.49	0.51	3.61	0.51	2.2	57	69
Bhambhani et al. (1991)	8	NST	35.2	6.6	85.0	–	176	7	32	6	45	6	2.1	2.72	0.20	3.77	0.46	3.0	86	75
40–49 yrs																				
Bhambhani et al. (1991)	8	NST	41.0	4.7	80.4	11	178	5	29	5	44	6	2.7	2.29	–	3.47	–	–	86	75
50–59 yrs																				
Keteyian et al. (1994)	10	Healthy, Rec	51.0	5.0	80.4	15.6	–	–	19	–	28	–	–	1.50	0.12	2.28	0.16	5.5	43	69
Mitropoulos et al. (2017)	6	Sed, no training history	51.7	4.7	85.0	12.4	176	8	19	4	26	10	0.9	1.80	0.50	2.20	0.70	0.7	100	82
60–69 yrs																				
McKeough et al. (2003)	7	Healthy, no regular training	62.0	2.0	–	–	–	–	16	4	23	8	1.1	–	–	–	–	–	93	83
Protas et al. (1996)	7	Majority sedentary, 2 = MA	65.0	–	–	–	–	–	16	–	25	–	–	–	–	–	–	–	71	86
Pogliaghi et al. (2006)	6	Sed, <20 min 3/wk	66.0	5.0	76.0	11.0	169	6	24	4	29	5	1.0	1.62	0.24	2.31	0.37	2.2	86	81
Pogliaghi et al. (2006)	6	Sed, <20 min 3/wk	68.0	4.0	74.0	6.0	172	4	22	3	31	5	2.5	1.84	0.30	2.18	0.28	1.2	86	81
70–79 yrs																				
Pogliaghi et al. (2006)	6	Sed, <20 min 3/wk	73.0	4.0	80.0	8.0	173	8	17	2	24	3	2.7	1.37	0.25	1.89	0.42	1.5	86	81

Table 4
Characteristics of included studies for women undertaking both arm crank ergometry (ACE) and cycle ergometry (CE) graded exercise protocols to exhaustion (n=16). NST = non-specifically trained; PA = physically active; Untr = untrained; Uni Std = university standard; PE = physical education; Rec = recreational; ns = not stated; MA = moderately active; NCS = no competitive sport; min·d^{-1} = minutes per day; Sed = sedentary; ES = effect size; D&B = Downs and Black quality rating; QAT = NIHR quality rating.

Authors	N	Training status	Age (yrs)		Mass (kg)		Stature (cm)		Relative VO_{2peak} (ml·kg^{-1}·min^{-1})					Absolute VO_{2peak} (l·min^{-1})					Quality rating	
			Mean	SD	Mean	SD	Mean	SD	ACE		CE		ES	ACE		CE		ES	D&B (%)	QAT (%)
									Mean	SD	Mean	SD		Mean	SD	Mean	SD			
< 20 yrs																				
Muraki et al. (2004)	27	Healthy, some were PA	19.9	0.56	55.4	7.0	162	6	30.9	6.5	44.4	5.9	2.2	1.74	0.52	2.47	0.52	1.4	57	56
20–29 yrs																				
Bhambhani et al. (1998)	10	Uni students, Rec	21.3	4.9	64.5	5.4	166	4	27.3	5.4	38.9	10.4	1.4	1.77	0.41	2.53	0.82	1.2	86	81
Orr et al. (2013)	15	Not MA or trained cyclists	23.4	3.7	60.6	7.8	167	5	24.9	4.0	39.8	7.2	2.6	1.51	–	2.41	–	–	71	81
Yasuda et al. (2008)	9	Rec, mild intensity	23.4	3.6	63.6	5.5	167	8	25.9	7.8	50.9	5.7	3.7	1.62	0.37	3.13	0.3	4.2	71	81
Barstow et al. (1993)	1	Untr	24.0	–	59.0	–	–	–	17.8	–	31.0	–	–	1.05	–	1.85	–	–	57	63
Helge et al. (2011)	6	Healthy	24.0	1.0	64.2	5.6	169	2	27.5	1.5	45.4	6.2	4.0	1.62	0.14	2.85	0.27	5.7	43	44
Marterer et al. (2020)	11	PA up to 3/wk, NST	24.3	3.0	–	–	167	9	26.4	3.3	39.5	4.8	3.2	1.55	0.31	2.33	0.53	1.8	71	81
Yasuda et al. (2006)	10	Rec, mild intensity	25.0	3.4	62.5	6.2	166	7	25.7	7.3	49.1	6.1	3.5	1.59	0.36	3.06	0.40	3.9	57	69
Warren et al. (1990)	10	Untrained	25.1	7.8	54.3	7.1	161	4	25.4	7.4	36.6	8.6	1.4	1.34	0.29	1.95	0.27	2.2	71	81
Kang et al. (1998)	7	Healthy, NCS	27.0	8.0	65.0	20.0	166	4	21.2	–	34.0	–	–	1.38	0.70	2.21	0.82	1.1	86	88
30–39 yrs																				
Bhambhani (1995)	12	Rec	32.1	7.7	–	–	–	–	25.1	4.9	36.6	7.1	1.9	1.48	0.25	2.16	0.37	2.2	71	75
Aminoff et al. (1999)	6	Kitchen workers	32.4	–	63.0	–	172	–	22.0	5.0	36.0	7.0	2.3	1.39	0.27	2.15	0.36	2.4	83	71
Javierre et al. (2007)	15	Healthy, Sed	35.6	–	57.5	5.1	159	5	17.9	4.8	23.4	6.1	1.0	1.04	0.25	1.36	0.38	1.0	43	69
50–59 yrs																				
Mitropoulos et al. (2017)	6	Sed, no training history	58.5	2.4	73.6	13.4	160	7	13.8	2.5	20.4	4.0	2.0	1.06	0.24	1.48	0.24	1.8	100	92

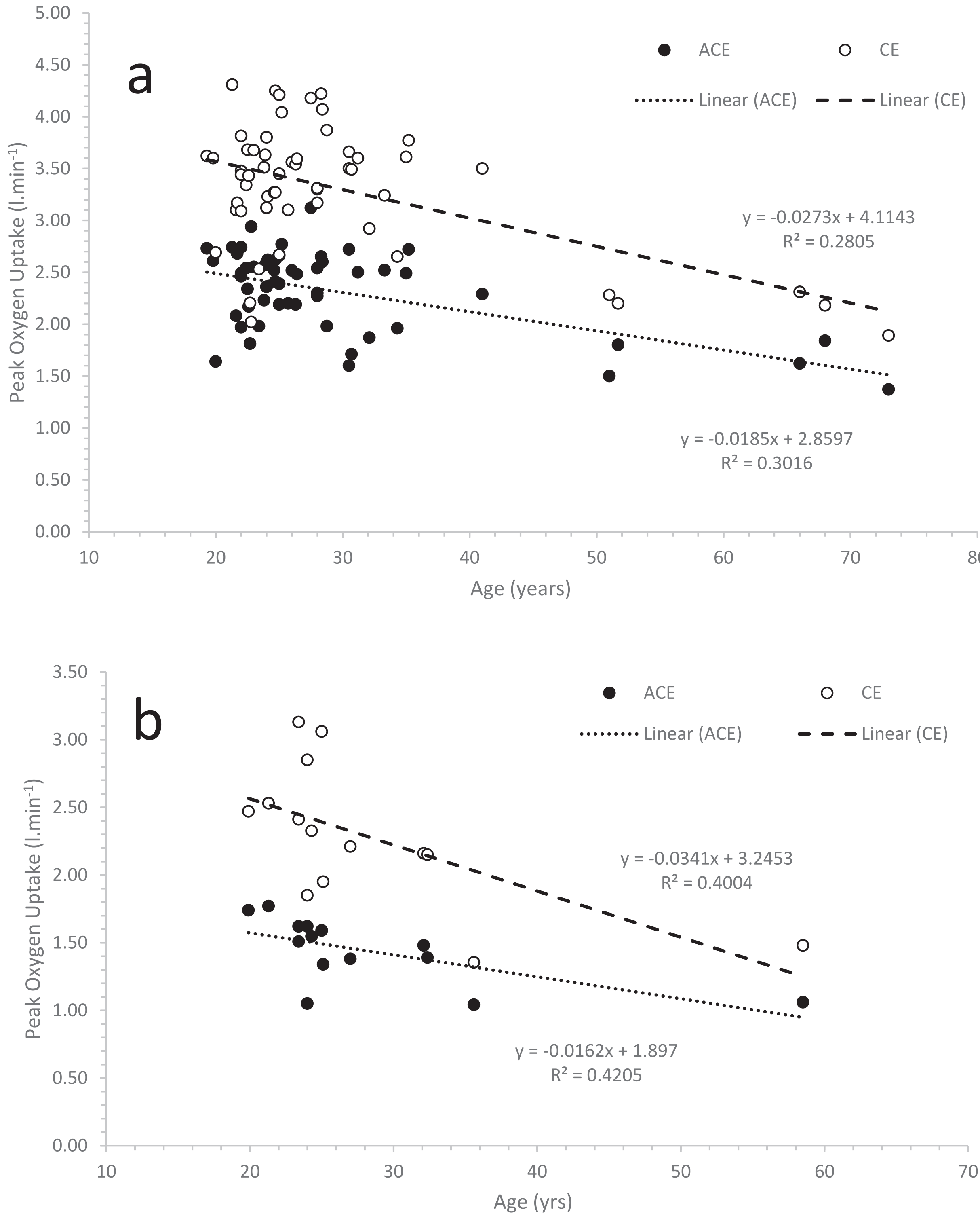

Fig. 2. The relationship between absolute VO_{2peak} ($l{\cdot}min^{-1}$) and age in men (a) and women (b).

asked. This return was lower for questions regarding discussion of confounders (50 %), including specific inclusion and exclusion criteria (56 %) and randomisation of trials (66 %). The aspects least well reported were the justification of sample size (13 %) and the reporting of actual *P* values (32 %).

4. Discussion

This is the first systematic review to consider VO_{2peak} during ACE and CE in the same participants specifically in relation to age and sex. The key findings were that; (1) when considered across the whole age range, absolute and relative VO_{2peak} decreased at similar rates for both exercise modes for men and women, (2) however, when considered above and below 50 years of age VO_{2peak} demonstrated different age related responses for absolute and relative values, (3) where meaningful decreases in VO_{2peak} were observed between age categories these tended to be greater for ACE than for CE, (4) Variability in VO_{2peak} across studies was greater for the younger age groups (20–29 and 30–39 yrs) likely due to

Table 5
Summary of linear fit statistics for absolute (above) and relative VO_{2peak} (below) against age for included studies of men and women.

		M	C	R	R^2	Equivalent decrease per 10 years
Absolute VO_{2peak}						($l \cdot min^{-1}$)
Male	ACE	−0.0190	2.8855	0.552	0.305	0.19
	CE	−0.0276	4.1294	0.534	0.285	0.28
Female	ACE	−0.0162	1.8970	0.649	0.420	0.16
	CE	−0.0341	3.2543	0.633	0.400	0.34
Relative VO_{2peak}						($ml \cdot kg^{-1} \cdot min^{-1}$)
Male	ACE	−0.3130	37.606	0.652	0.425	3.1
	CE	−0.4882	55.764	0.670	0.449	4.8
Female	ACE	−0.4121	36.263	0.864	0.747	4.1
	CE	−0.6529	55.834	0.735	0.540	6.5

the existence of more studies in this population and (5) there was a lack of studies providing data for participants from 40 years of age, particularly between 40 and 59 years of age.

4.1. Peak oxygen uptake in relation to age

4.1.1. Cycle ergometry in males

The current review indicated decreases in VO_{2peak} for men during CE of 9–10 % per decade for absolute (0.3 $l.min^{-1}$) and relative VO_{2peak} (4.5 $ml.kg.^{-1}min.^{-1}$). Previous studies of cross-sectional data have indicated decreases in VO_{2peak} during CE of ~4.2 $ml.kg.^{-1}min.^{-1}$ per decade (Herdy and Uhlendorf, 2011) with longitudinal data for absolute VO_{2peak} during CE over 20 years indicating decreases equivalent to ~20 % (Astrand et al., 1973). Although the latter is greater than the ~16 % in the current review for a similar age range, this is potentially due to use of longitudinal rather the cross-sectional data (Fleg et al., 1995). Conversely, Rapp et al. (Rapp et al., 2018), produced norms from a large population study (n = 10,090; men n = 6462) suggesting a decrease of 3.3 $ml.kg^{-1}.min^{-1}$ per decade between 25 and 69 yrs. Although, norms for VO_{2peak} produced by Rapp et al. from 50 years onwards were consistently ~3 $ml.kg^{-1}.min^{-1}$ per decade greater than in the present study, the rate of decrease was similar between 50 and 69 years of age. Therefore, the decrease in VO_{2peak} for men over similar age ranges is consistent with previous research.

4.1.2. Arm crank ergometry in males

The overall decrease in VO_{2peak} during ACE per decade for men was lower than that for CE, amounting to a reduction of 0.2 compared to 0.3 $l.min^{-1}$ (3.1 and 4.5 $ml.kg.^{-1}min.^{-1}$) respectively. However, the overall decreases in VO_{2peak} for both exercise modes between 20–29 yrs were similar (9.4 and 9.8 % for ACE and CE, respectively) which closely approximates previous projections of a 10 % decrease in VO_{2peak} per decade (Shephard, 2009). Furthermore, decreases in VO_{2peak} during ACE occurred within the same age categories as for CE but to a greater extent. Large changes were observed from 20–29 to 30–39 yrs for ACE compared to moderate changes for CE, and medium changes between 50–59 and both 60–69 and 70–79 for ACE compared to small changes for CE. These responses suggest that upper body VO_{2peak} decreases in line with that of the lower body, but, due to the lower peak values achieved during ACE, decreases in VO_{2peak} may have more profound functional impact compared to that for the lower body.

4.1.3. Decreases in peak oxygen uptake before and after 50 years of age

Scatter plots of absolute and relative VO_{2peak} for ACE and CE against age across all studies suggested good linear fits. However, the figures presenting weighted means for VO_{2peak} during ACE and CE for each decade indicate different phases and rates of decrease with age for both exercise modes. Specifically, moderate to large changes were evident from 20–29 to 30–39 yrs and small to moderate changes were evident between 50–59 and both 60–69 and 70–79 yrs for ACE and CE, respectively. This trend was observed for men and women and for both relative and absolute values of VO_{2peak}. Indeed, Fleg et al. (Fleg et al., 1995) observed that the decrease in VO_{2peak} during treadmill exercise was non-linear over the lifespan.

Although the non-linear decrease in VO_{2peak} with age appears consistent with previous studies (Hansen et al., 2019), the regression equations generated for VO_{2peak} and age above and below 50 years of age indicated different responses, particularly for VO_{2peak} expressed as absolute and relative values. For example, below the age of 50 yrs, there was a clear decrease in relative VO_{2peak} with age for ACE and CE (7.8, 11.1 %, respectively), but little or no change in absolute VO_{2peak} (4.5, 0.1 %, respectively). Similar values for absolute VO_{2peak} across ages but decreasing values for relative VO_{2peak} most likely represents an increase in body mass with age, with such changes likely resulting in a concomitant increase in proportions of fat mass. Although there was no significant correlation between age and body mass per se across the included studies, those reporting body fat percentage did indicate a rise from ~16 to ~25 % body fat from the 20–29 and 30–39 yrs age categories. Furthermore, relative VO_{2peak} was correlated with body mass, likely due to inclusion of body mass in its calculation, whereas absolute VO_{2peak} was not correlated. However, without specific body composition data for each study no further insight can be readily gained. It should be noted though, that using absolute and relative measures of VO_{2peak} results in different age-related profiles when considered below 50 years of age.

Changes in VO_{2peak} after 50 years of age were similar between ACE and CE no matter whether expressed as absolute or relative VO_{2peak}. Furthermore, there were no differences when potential changes in VO_{2peak} at 70–79 yrs were expressed relative to the youngest age group considered in the analysis (i.e. <20 yrs; 1.5 to 3.0 %) or the youngest group from 50 yrs onwards (i.e. 50–59 yrs; 2.5 to 5.0 %). More importantly, both the absolute and relative VO_{2peak} relationships with age above 50 years were relatively flat. Fleg et al. (Fleg et al., 1995) noted how healthy active volunteers may have genetic and lifestyle differences to participants recruited in younger age groups, who may not survive to old age. As a result, each consecutive decade presents a more highly selected group than its predecessor (Fleg et al., 1995). Such a factor may explain the similarity of values across the later decades of life observed in the current analysis. This information holds the potential to identify threshold values associated with preserved aerobic function and an acceptable quality of life, as previously reported for treadmill exercise (~18 and 15 $ml.kg.^{-1}min.^{-1}$ for men and women, respectively; Paterson et al., 1999). Data for older age groups in the current analysis were often derived from control groups of studies examining clinical groups, few studies purposively recruited and reported values for otherwise healthy older groups per se. Thus, there is a need for greater exploration of upper and lower body functional capacity in otherwise healthy individuals to better understand the effects of ageing.

The large decrease in VO_{2peak} for both exercise modes between the decades of 40–49 and 50–59 yrs warrant further consideration. There were fewer studies found reporting VO_{2peak} for ACE and CE in the same participants for ages above 40 yrs when compared to below 40 yrs (i.e. 8/56 data sets for males and 9/70 data sets from all studies), with only one study included specifically within the 40–49 yrs category for men

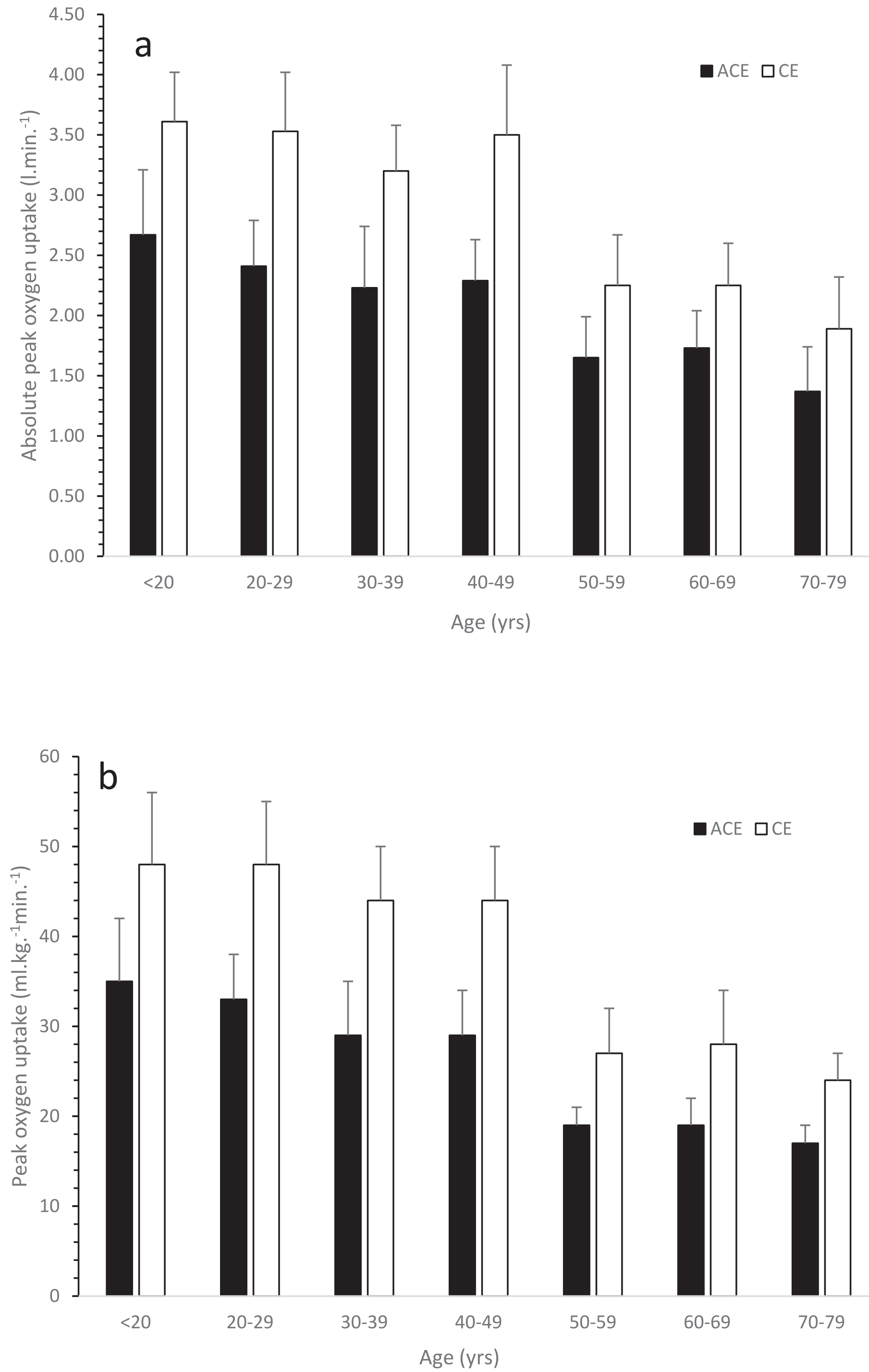

Fig. 3. Weighted means and pooled standard deviations for absolute (a) and relative (b) peak oxygen uptake in men.

(Bhambhani et al., 1991). The mean age of participants within this particular study was 41.0 ± 4.7 years, indicating that participants were likely physiologically closer to those in the 30–39 yrs group than those in the 50–59 yrs group, which is consistent with similar VO_{2peak} values for both modes in these age categories. Therefore, when considering the available data, VO_{2peak} for ACE and CE for 30–39 yrs and 40–49 yrs appear similar. Nevertheless, a considerable gap in knowledge exists regarding typical values of VO_{2peak} for participants of 40 years of age and above. Such a gap in the literature requires attention as the importance of midlife cardiorespiratory fitness on longevity and reduced individual health care costs has recently been highlighted (Hansen et al., 2019). It is important though to note that the large decrease in VO_{2peak} for ACE and CE between 40–49 and 50–59 yrs more likely reflects a lack of available data rather than anything physiological in nature.

4.2. *Sex differences*

There were considerably fewer studies reporting VO_{2peak} during both ACE and CE for women ($n = 14$) when compared to men ($n = 56$); but with a similar proportion of those within the 20–29 yrs age category (~70 %) for both sexes. The estimated decreases in VO_{2peak} per decade during ACE for women were similar to those for men (i.e. 0.16 and 0.19 $l.min^{-1}$; 3.5 and 3.1 $ml.kg^{-1}.min^{-1}$, respectively), whereas the decreases in VO_{2peak} for CE in women were greater than for men (i.e. 0.34

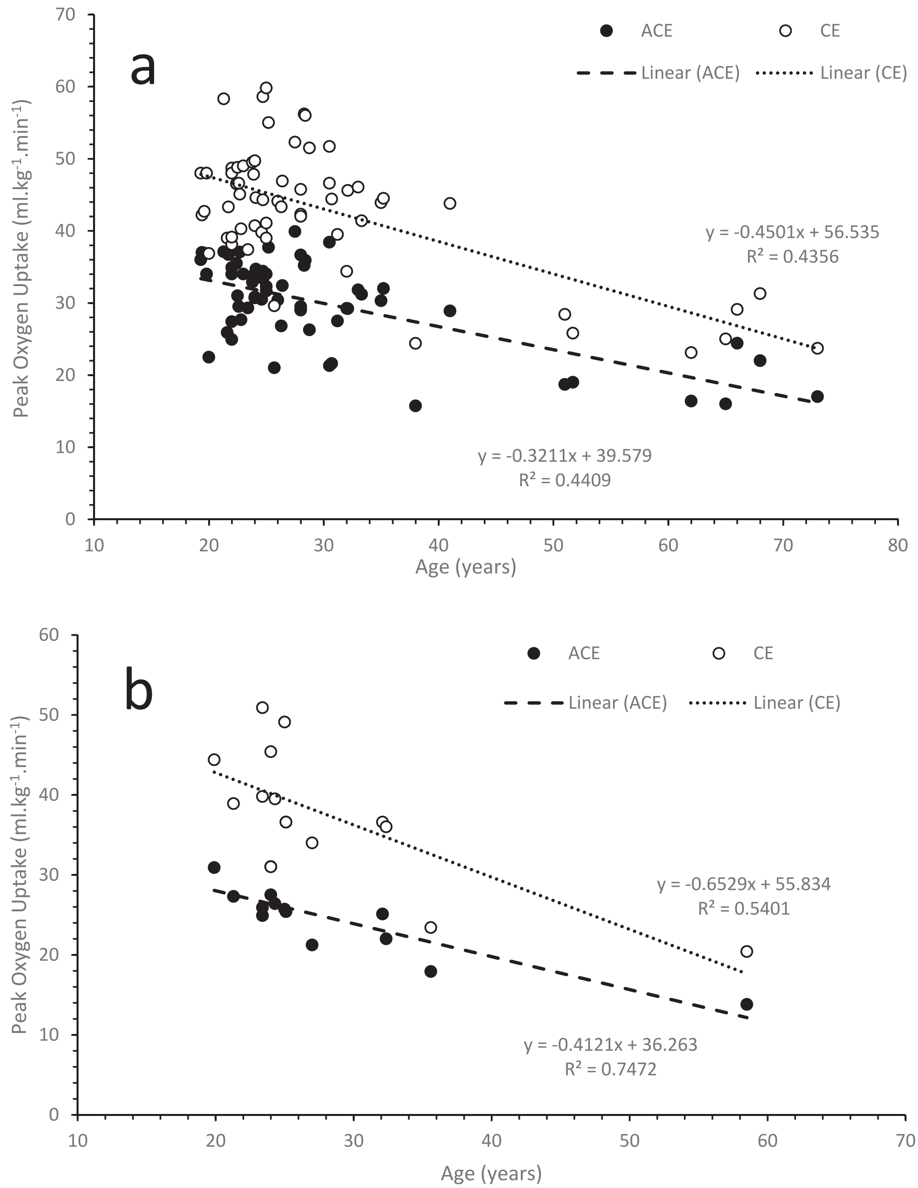

Fig. 4. The relationship between relative VO_{2peak} (ml·kg^{-1}·min^{-1}) and age for men (a) and women (b).

and 0.28 l.min^{-1}; 6.5 and 4.8 ml.kg^{-1}.min^{-1}, respectively). Furthermore, when the decrease in VO_{2peak} per decade for women was considered in relation to values at 20–29 yrs, the decreases observed for CE (absolute; 16.4 %, relative 16.3 %) were greater than for ACE (absolute; 10.7 %, relative; 13.4 %). The lesser decrease in VO_{2peak} during ACE with age for women may represent a relatively lower training status of the upper body compared to the lower body in comparison to men. However, decreases in VO_{2peak} for both modes of exercise for women were of a greater magnitude than for men (Absolute VO_{2peak} ~ 8 %, relative VO_{2peak} ~ 10 %). These data therefore suggest that not only is the decrease in VO_{2peak} for females generally greater than for males for both exercise modes, but difference also exist between modes for females.

Only one study was obtained for women within the <20 yrs age group (Muraki et al., 2004). In this study, the relative value for VO_{2peak} (31 ml.kg.$^{-1}$ min^{-1}) was greater than any of the studies contributing to the 20–29 yrs age category (range: 18–28 ml.kg.$^{-1}$min.$^{-1}$) and the absolute value for VO_{2peak} (1.74 l.min^{-1}) was similar to the largest values in the category (range: 1.05 to 1.77 l.min^{-1}). The corresponding VO_{2peak} for CE was also relatively high at 44 ml.kg.$^{-1}$min.$^{-1}$ and similar to values for the equivalent male age group, likely reflecting that some of the population were 'physically active' (Muraki et al., 2004). Nevertheless, although these VO_{2peak} values suggest a greater training status than that reported by the other authors, the ACE value was still 70 % of CE, and likely representative of values for non-specifically trained, but physically active females.

4.3. Heterogeneity

4.3.1. Between studies

Assessment of heterogeneity is an important component of systematic reviews and meta-analyses (Page et al., 2022). The I^2 values reported here indicate a substantial amount of heterogeneity across studies, and much greater than previously reported (~60 %) (Larsen et al., 2016). Greater variation may be expected due to differences in training status across samples, even when the included studies participants were reported or recruited as 'non-specifically trained'. Both ACE and CE yielded overall coefficients of variation for VO_{2peak} of ~14 % (e.g. for men), indicating similar variation for both exercise modes. Although studies of trained individuals were excluded, there was still a

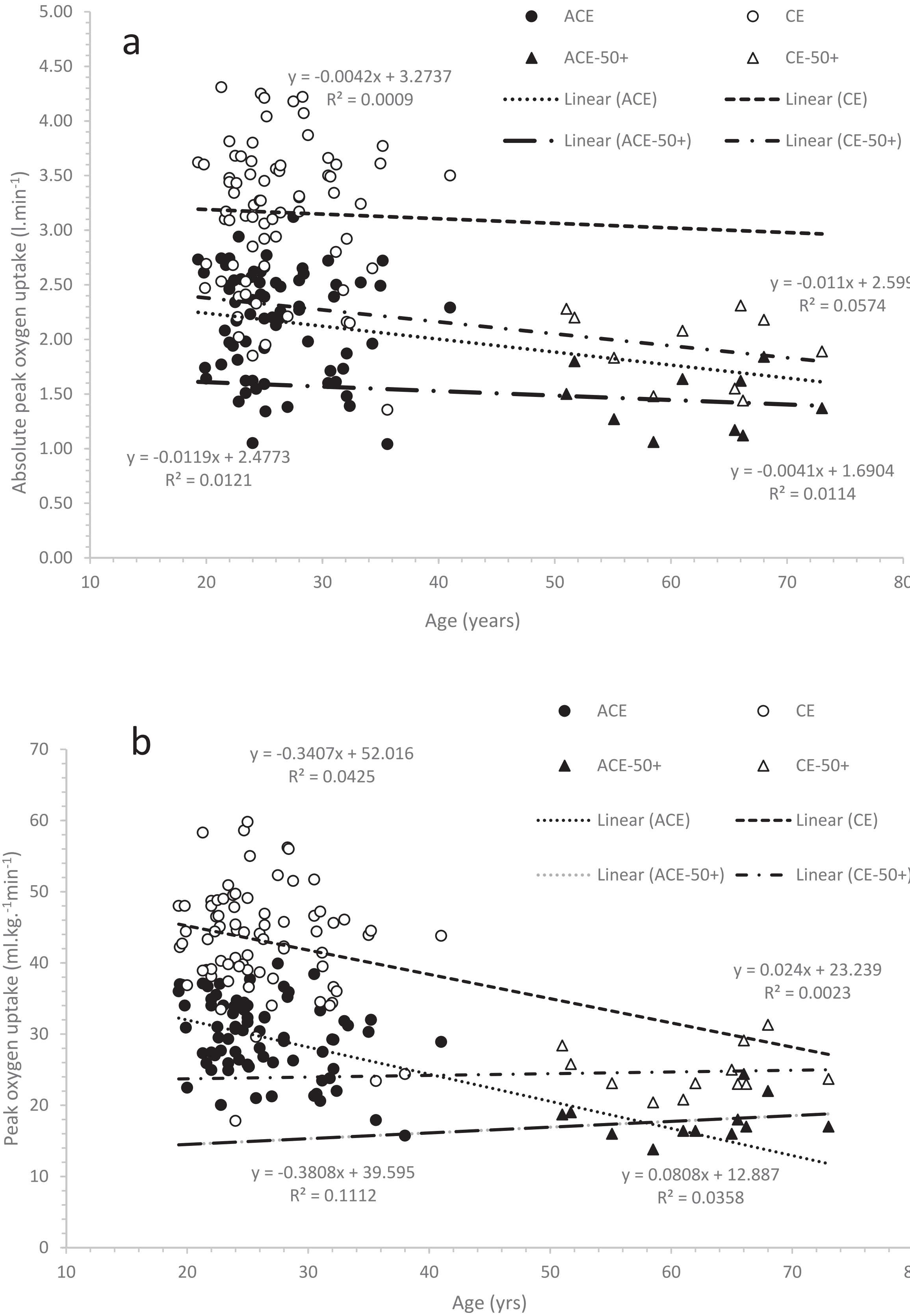

Fig. 5. The relationship between absolute VO_{2peak} ($l \cdot min^{-1}$) (above) and relative VO_{2peak} ($ml \cdot kg^{-1} \cdot min^{-1}$) (below) against age for men above and below the age of 50 yrs.

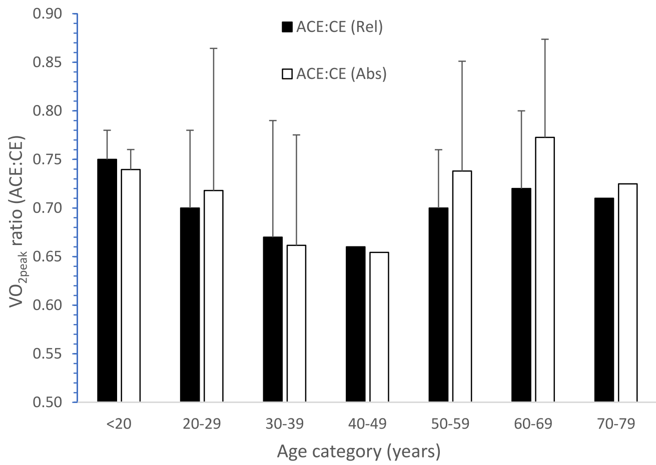

Fig. 6. Ratio between VO_{2peak} during arm crank ergometry (ACE) and cycle ergometry (CE) in men.

considerable range of values for VO_{2peak}, especially for men where more studies fitted the review inclusion criteria. For example, for the 20–29 yrs age category the range of relative VO_{2peak} values for ACE was 21–40 ml.kg.$^{-1}$min.$^{-1}$ and greater than for women (i.e. 21–31 ml. kg.$^{-1}$min.$^{-1}$). The data for men was normally distributed with 66 % of VO_{2peak} values for ACE within one standard deviation of the mean (i.e. relative VO_{2peak}: 28 to 36 ml.kg.$^{-1}$min.$^{-1}$, absolute VO_{2peak}: 2.1 to 2.7 l. min^{-1}). Values for absolute VO_{2peak} during ACE for trained individuals, such as elite paddlers (Tesch, 1983) are much greater than in the present study (4.30 and 2.42 l.min.$^{-1}$, respectively) as indeed are values for unskilled paddlers or those with a range of skill levels (Pendergast et al., 1979) (2.90 and 2.82 l.min^{-1}; respectively). Furthermore, even with 6 to 8 weeks ACE endurance training in previously untrained participants resulting in significant improvements in VO_{2peak} during ACE in young (27 yrs; 27 to 32 ml.kg.$^{-1}$ min^{-1}) (Bottoms and Price, 2014) and older participants (65 yrs; 17 to 22 ml.kg.$^{-1}$ min^{-1}) (Hill et al., 2018a), VO_{2peak} values are still within the range of values reported in the current study. In addition, the overall mean VO_{2peak} for CE was 46 ml. kg.$^{-1}$min.$^{-1}$ but with its distribution skewed towards the lesser trained values at 40–44 ml.kg.$^{-1}$min.$^{-1}$ and only eight values above 50 ml.kg.$^{-1}$ min^{-1}. Thus, we are confident that the range of VO_{2peak} values within the data analysed are indeed representative of the desired inclusion criteria, but likely represents a source of heterogeneity across studies. Variation between studies decreased in the older age categories, most likely in part due to the smaller number of available studies.

The most likely factors affecting heterogeneity between studies, other than differences in the actual sample populations, could relate to the exercise protocols undertaken to elicit VO_{2peak}. Within ACE protocols the most likely differences between studies relate to crank rate and continuous or discontinuous protocol design. Little difference has generally been reported for VO_{2peak} values during ACE achieved using continuous and discontinuous protocols (Sawka et al., 1983) whereas significant effects have been consistently observed for crank rate. Although differences in VO_{2peak} during ACE are evident between protocols utilising 60 and 70 rev.min^{-1} (e.g. 0.2 l.min^{-1}, 3 ml.kg.$^{-1}$min.$^{-1}$) (Price and Campbell, 1997b) they are not as great as those between 50 and 70 rev.min^{-1} (e.g. 0.37 l.min^{-1}; 5 ml.kg.$^{-1}$min.$^{-1}$) (Price et al., 2007). However, many of the studies reviewed often reported faster cadences for ACE than CE protocols (i.e. 60 or 70 rev.min^{-1}) so, although differences may exist between studies due to crank rate these are still likely less than or similar to those considered as small based on Hedges g analysis (e.g. 35 vs 32 ml.kg.$^{-1}$min.$^{-1}$, g = 0.39) and certainly less than those considered of 'medium' or 'large' importance between age categories.

4.3.2. Within studies

The variation in VO_{2peak} within studies relates to variability of the sample and thus variability of participants undertaking the same exercise protocol. Key contributors to variability include diurnal as well as day to day variation (i.e. reliability or repeatability of VO_{2peak} values) and training status. Studies evaluating the reliability of VO_{2peak} during ACE have shown similar variability for ACE protocols of 2–3 % utilising cadences of 50 (Bar-Or and Zwiren, 1975) and 60 rev.min^{-1} (Price and Campbell, 1997b). Thus, for typical VO_{2peak} values during ACE for the 20–29 and 60–69 yrs age groups (i.e. 33 and 20 ml.kg.$^{-1}$min.$^{-1}$, respectively) a 3 % difference represents ~1 and < 1 ml.kg.$^{-1}$min.$^{-1}$, respectively, and is within the expected and acceptable measurement error for VO_{2peak} during ACE (Smith and Price, 2007). Similarly, variability for CE using similar protocols to those in the included studies is ~4 % (Dideriksen and Mikkelsen, 2017), representing 2 and 1 ml. kg.$^{-1}$min.$^{-1}$ for the equivalent age categories above. Furthermore, circadian variation for maximal oxygen uptake is not generally observed (Deschenes et al., 1998) and in agreement with a reduced circadian effect in greater intensities of exercise (Reilly, 2007). When combined such variability components may thus be considered relatively small and not the major contributor to heterogeneity.

4.4. Ratio between peak oxygen uptake during ACE and CE

When considering the ratio between ACE:CE for VO_{2peak} the mean value across all ages was 0.70, with a difference in VO_{2peak} between ACE and CE of 13 ml.kg.$^{-1}$min.$^{-1}$ (0.93 l.min^{-1}) both values being similar to those reported by Larsen et al. (Larsen et al., 2016), i.e. 0.70 and 12.5 ml.kg.$^{-1}$.min.$^{-1}$, respectively. However, when considered with respect to the different age categories, the ACE:CE for VO_{2peak} was greatest (0.73) for the youngest age category (<20 yrs) decreasing steadily by 20–29 years (0.70) to 40–49 yrs (0.66). Thereafter, the ratio increased at 50–59 yrs (0.70) before stabilising in the two oldest groups (0.72). A greater ratio for ACE:CE suggests that VO_{2peak} from ACE represents a greater proportion of the CE value. Thus, VO_{2peak} values during CE were similar between <20 yrs to 30–39 groups (48 vs. 46 ml.kg.$^{-1}$min.$^{-1}$), whereas VO_{2peak} during ACE was greatest for the <20 yrs group implying that upper body functional capacity is relatively greater at this age. From this point onwards however, VO_{2peak} during ACE decreased steadily until 30-39 yrs (36 to 28 ml.kg.$^{-1}$min.$^{-1}$, respectively) and to a greater extent than CE. Therefore, ACE is likely a valuable and effective exercise mode to aid in the development of cardiovascular fitness in younger ages which may enable retention of whole-body functional capacity in later years.

Larsen et al. (Larsen et al., 2016) observed that the difference between VO_{2peak} during ACE and CE was associated with both age and aerobic capacity. More specifically, the difference between modes was reduced with age and increased with better aerobic capacity. Indeed, our data suggest that the ratio decreases with age up to 40–49 yrs, before increasing at 50–59 and 60–69 before plateauing. As noted earlier, this latter plateau likely represents the older participants who volunteered to take part in the studies representing fitter members of the population (Fleg et al., 1995). Furthermore, two further data sets were identified for the <20 years category but involved standing ACE, so were excluded (Stamford et al., 1978). These groups consequently elicited greater VO_{2peak} during ACE and thus a greater ACE:CE of ~0.87, supporting the sensitivity of the ratio to greater VO_{2peak} during ACE. Thus, the current data give more specific age-related insight into the relationship between age and VO_{2peak} during ACE and CE.

4.5. Excluded studies

4.5.1. Abstract only studies

Two studies were excluded due to being abstract only (Hernandez-Murua et al., 2017; Shakespeare and Parr, 2020). More specifically, Hernandez-Murua et al. (Hernandez-Murua et al., 2017) was the only study initially sourced within the 40–49 years of age category for women and its omission strengthens the finding of little or no data within that age group for women. Although the values for VO_{2peak} from this study did not directly lie on the regression equations their omission did not affect the relationships obtained. A second abstract (Shakespeare and Parr, 2020) provided mean values for oxygen consumption at anaerobic threshold and as a percentage of relative VO_{2peak} for both exercise modes in a combined group of men and women. Firstly, the data could not be separated based on sex alone, and although mean values could be estimated, standard deviations could not, and therefore these results could not be incorporated into the weighted mean and standard deviation calculations. Omission of these studies however, is unlikely to affect the overall conclusions of the current review.

4.5.2. Combined data sets

Of the studies potentially included within the review 14 (representing 15 data sets) presented results either as; specific samples of men and women as well as these participants combined as a whole sample, or one combined group of men and women whose data could not be separated based on sex. Five of these studies (Kang et al., 1998; Marterer et al., 2020; Aminoff et al., 1999; Barstow et al., 1993; Mitropoulos et al., 2017) reflected the former and were included in the separate data analyses for men and women. Of the remaining nine studies, one did not identify the sex of participants (Charbonnier et al., 1975) and eight presented data that could not be divided into separate data sets for men or women (Hill et al., 2018a; McKeough et al., 2003; Sedlock, 1991; Keyser et al., 1989; Alison et al., 1998; Castro et al., 2011; Loughney et al., 2014; Franssen et al., 2002) and were thus excluded. Where such data sets were combined these tended to be older (39 ± 4 yrs) with slightly larger sample sizes ($n = 12$) with a distribution of ~52 % men to 48 % women. Importantly most studies were within the 20–29 or 60–69 yrs age groups which still represents a lack of data for middle aged participants. Future studies presenting combined data for men and women should do so to enable separate analysis where possible.

4.5.3. Exercise mode

A small number of studies were excluded due to comparing VO_{2peak} during ACE with treadmill running (Helgerud et al., 2019). Although VO_{2peak} during ACE was similar in excluded studies to those reported in the current review for similar ages (i.e. 31 ml.kg.$^{-1}$min.$^{-1}$) treadmill-based VO_{2peak}, as expected, was greater than for CE (51 ml. kg.$^{-1}$min.$^{-1}$) due to a greater active muscle mass. Corresponding ACE: TM ratios were thus lower than for ACE:CE at ~0.61, but slightly greater for upper body trained individuals (i.e. 0.66–0.71 for boxers and gymnasts; Venckunas et al., 2022). Similarly, studies involving standing ACE were also excluded due to potentially increasing the active muscle mass associated with ACE. For example, both Stamford et al. (Stamford et al., 1978) and Nag et al. (Nag, 1984) observed greater ACE:CE with standing ACE (0.86 and 0.77, respectively) than for the overall mean reported in the current review. Standing and seated ACE protocols though do represent a range of vocational postures and should therefore be evaluated more fully.

4.5.4. Training status

Only one study was initially identified that directly compared VO_{2peak} during ACE and CE across age groups (males aged 26 and 57 years of age) (Aminoff et al., 1999). Values for VO_{2peak} for ACE and CE in the younger group were similar to the current study (ACE: 27 and 29 ml. kg.$^{-1}$ min^{-1}, CE: both 43 ml.kg.$^{-1}$ min^{-1}, respectively) and with lower values for CE in the older group (36 ml.kg.$^{-1}$ min^{-1}). Values for ACE though were similar for both younger and older participants (i.e. 27 and 25 ml.kg.$^{-1}$ min^{-1}, respectively) as a result of arm muscle mass being similar across groups. In addition, the CE values for the older participants were larger than expected for the equivalent age category in the current study (36 vs. 28 ml.kg.$^{-1}$ min^{-1}, respectively) further suggesting a greater overall aerobic fitness status. As the older participant group was therefore likely more upper and lower body trained than may be expected for that age group, this study was excluded from the current review (in addition to using semi-upright cycling). The importance of this study, however, should be noted as physical performance with small muscle groups did not necessarily decrease with age where muscle mass was retained. The importance and relevance of maintaining upper body muscle mass for healthy ageing is further emphasized in the current study.

4.5.5. ACE only

Two studies were identified that compared VO_{2peak} across age groups but only during ACE (Balady et al., 1996; Groslambert et al., 2006). Balady et al. (Balady et al., 1996) compared men and women of 20–29, 30–39 and 40–59 years of age observing similar VO_{2peak} across ages for males (~20–21 ml.kg.$^{-1}$min.$^{-1}$) and females (~15–16 ml.kg.$^{-1}$min.$^{-1}$) indicating no differences in aerobic fitness across age groups for either sex. As the VO_{2peak} values for the two younger groups are considerably lower than expected from the current review, differences in aerobic fitness could be presumed. Gross Lambert et al. (Groslambert et al., 2006) reported VO_{2peak} during ACE for females with mean ages of 23 and 75 years to be 24 and 11 ml.kg.$^{-1}$min.$^{-1}$, respectively. The current study obtained a VO_{2peak} value of 26 ml.kg.$^{-1}$ min^{-1} during ACE for the younger group, which is in agreement with that of Gross Lambert et al. Although no data was available for females of 60+ years the linear regression equation generated for age and VO_{2peak} during ACE in the current study predicts a value of 9 ml.kg.$^{-1}$min.$^{-1}$ for an equivalent older age, potentially validating our equation. Although these two studies were excluded, the data demonstrates consistency with the current study.

4.6. Methodological quality

The mean scores for the methodological quality assessment indicated ‘good’ overall quality of reporting. Although there was a wide range of scores observed this has been reported previously, albeit in a different discipline (Desmeules et al., 2012). When quality scores for those studies common to both the current review and that of Larsen et al. (Larsen et al., 2016) were compared, we obtained similar overall scores (4.1 and 4.5, Larsen et al. and current study, respectively), evidencing consistency between studies. When considering the full range of methodological questions posed, 87 % of studies or above indicated that the specific criteria were fulfilled, which is encouraging. However, only one half to two thirds of studies clearly discussed confounders, stated specific inclusion and exclusion criteria or randomisation of trials. The two least reported criteria related to justification of sample size and reporting actual P values. Justification of sample size has also been noted to be poorly reported in both medical and dentistry studies (Tripathi et al., 2020) whereas reporting of exact P values is a relatively recent development in sport and exercise science. Although these are important factors, the key methodological aspect underpinning the validity and reliability of protocols and methods utilised in the included studies were generally well reported across studies. Thus, the quality of the data presented in each study included in the current review is likely to be of a high standard.

4.7. Limitations

One potential limitation of the current review is examining changes in VO_{2peak} in relation to ten-year age categories. For example, Rapp et al. (Rapp et al., 2018) noted that individuals at the younger and older ages of such categories can differ appreciably in their VO_{2peak} values, particularly in older categories (e.g. VO_{2peak} at 30 and 39 yrs; 34 and 30 ml.kg.$^{-1}$ min^{-1}, respectively, ~12 %; VO_{2peak} at 50 and 59 yrs; 28 and 26 ml.kg.$^{-1}$ min^{-1}, respectively, ~7 %). Furthermore, there is no one specific age where functional capacity decreases in all individuals, which appears to be a predominantly individual phenomenon (Lazarus et al., 2019). Thus, examining upper and lower body VO_{2peak} responses in relation to underpinning physiological variables and behavioural factors known to interact with functional capacity is essential to better understand the cause and implications of whole-body ageing. The limitation of the literature regarding the lack of data for midlife age groups should also be acknowledged here.

A second limitation of the current study is that a specific meta-regression was not undertaken. However, several key factors were considered to effectively answer the research question. Firstly, the magnitude of effect between weighted means for each age group were assessed for each exercise mode using Hedges g, thus addressing the effect of age. Secondly, studies incorporating data sets for men and women were considered separately, thus addressing the influence of sex. Thirdly, the study utilised stringent inclusion and exclusion criteria, thus improving consistency across studies with respect to training status and exercise mode. We are therefore confident that this approach has provided novel insights into the effect of age and sex on upper and lower body VO_{2peak}.

4.8. Future work

Although there were a substantial number of studies reporting VO_{2peak} during both ACE and CE in younger participants, there is a clear lack of data from the age of 40 years onwards for both males and females. Thus, one clear avenue for future work is to bridge this gap to allow for a clearer understanding of how upper body and lower body function changes with middle age. Such studies should ensure reporting both absolute and relative VO_{2peak} alongside body composition and more specific estimates of upper and lower limb muscle mass to clearly understand changes in VO_{2peak} with age. We strongly encourage development of a repository for individual data from such studies to be compiled facilitating larger studies which include and compare a wider range of ages.

Future studies should further consider how the gross measures of functional capacity considered in this review (i.e. VO_{2peak}) are associated with activities of daily living. To our knowledge, only one study has examined how ACE and CE training regimes impact upon activities of daily living and measures of balance (Hill et al., 2018a). Here, both ACE and CE training elicited positive adaptations, but for different functional components. For example, ACE elicited improvements in forward reach and the control of medio-lateral body sway during upright stance whereas CE elicited improvements in lower body reach distance (star-excursion balance test) and control of antero-posterior body sway. The possibility of developing combined arm and leg ergometry training regimes could thus be considered to maximise adaptations and maintain a wider range of daily living activities.

Threshold values for lower body VO_{2peak} in relation to maintaining independent living of 18 ml.kg.$^{-1}$min.$^{-1}$ for men and 15 ml.kg.$^{-1}$min.$^{-1}$ for women at 80–85 years have been reported (Paterson et al., 1999). The current review established VO_{2peak} values during ACE of 19, 19, 17 ml.kg.$^{-1}$min.$^{-1}$ for men at ages of between 50–59, 60–69 and 70–79 yrs, but with equivalent values for CE of 27, 28, 24 ml.kg.$^{-1}$min.$^{-1}$. Although the CE values from healthy individuals are greater than the suggested 'threshold' values for treadmill exercise no such functional capacity thresholds exist for ACE. Considering VO_{2peak} values during ACE are much lower for clinical populations (e.g. Chronic fatigue syndrome 10 ml.kg.$^{-1}$.min^{-1} (Javierre et al., 2007), peripheral arterial disease 13 ml.kg.$^{-1}$min.$^{-1}$ (Zwierska et al., 2006), Parkinson's disease 15 ml.kg.$^{-1}$min.$^{-1}$ (Protas et al., 1996)) and that VO_{2peak} during ACE has diagnostic worth (Ilias et al., 2009) greater information regarding pre-surgery values for ACE, in populations unable to exercise their lower body effectively, would certainly be of practical importance.

5. Conclusions

This is the first review to consider changes in VO_{2peak} during ACE and CE in the same participants in relation to both age and sex. Although the decrease in VO_{2peak} during CE was consistent with other studies of age-related changes in lower body VO_{2peak}, age-related decreases in VO_{2peak} during ACE demonstrated a different pattern of responses and of a greater proportion of functional capacity. Importantly, examining absolute and relative measures of VO_{2peak} for both exercise modes resulted in different age-related profiles when considered below 50 years of age, likely due to increases in body mass and changes in body composition. To further our understanding of whole body ageing more data is required for participants in mid and later life. The association between VO_{2peak} and underlying physiological factors with age needs to be studied further, particularly in conjunction with activities of daily living and independent living.

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CRediT authorship contribution statement

M.J. Price: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **P.M. Smith:** Validation, Investigation, Writing - Review & Editing. **L.M. Bottoms:** Validation, Investigation, Writing - Review & Editing. **M.W. Hill:** Writing – review & editing, Visualization, Formal analysis, Data curation.

Declaration of competing interest

MP, PS, LB and MH declare that they have no conflict of interest.

Data availability

All data generated or analysed during this study are included in this published article.

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