Data Processing Strategies to Determine Maximum Oxygen Uptake: A Systematic Scoping Review and Experimental Comparison with Guidelines for Reporting

# Abstract

**Background** Gas exchange data from maximum oxygen uptake (V̇O2max) testing typically requires post-processing. Different processing strategies may lead to varying V̇O2max values affecting their interpretation. However, the exact processing strategies used in the literature have not been systematically investigated yet. Previous research investigated differences across methods at the group level only.

**Methods** Out of a random sample, we investigated 242 recently published articles which measured V̇O2max during ramp tests. Reported data processing methods and their rationale were extracted. We compared the most common processing strategies on a data set of 72 standardized exercise tests in trained athletes.

**Results** Half of the included studies did not report their data processing strategy and almost all articles failed to provide a rationale for the particular strategy chosen. Most studies use binned time averages to determine V̇O2max, with a minority using moving time or moving breath averages. The processing strategies found in the literature can lead to median differences in V̇O2max of more than 5% (range 0-7%) with considerable variation at the individual level.

**Conclusion** Researchers should report their data processing strategy used to determine V̇O2max. We provide a reporting checklist of seven items that can function as a template for reporting.

## Key Points

* Despite calls to use moving averages or digital filter, binned averages remain the most common data processing strategy to determine V̇O2max.
* Different processing strategies lead to varying V̇O2max values at the median as well as at the individual level.
* Researchers are advised to report their processing strategy in detail, or preferably share their raw oxygen uptake data and analysis code.

# Introduction

The maximum oxygen uptake (V̇O2max) is one of the most commonly assessed physiological parameters in sports and exercise science [1]. V̇O2max highly corresponds with endurance performance in heterogeneous groups [2–4] and can be regarded as on of the most relevant physiological predictor of endurance performance [1]. Accordingly, many training programs target V̇O2max as the performance criteria and evaluate for example the effectiveness of treatment by measuring changes in V̇O2max.

Researchers predominantly measure V̇O2max during exercise tests to exhaustion. Among the factors that influence the V̇O2max determination are the exercise test protocol [5,6,7], exercise modality [8], motivation [9], and biological variability [10]. Even the measuring method (e.g. mixing chamber, breath-by-breath) and the metabolic cart model used can influence the measured oxygen uptake — and as such the V̇O2max [11,12]. Due to its inherent variation, the collected raw data can hardly be interpreted without processing. The same oxygen uptake data generated during an exercise test may result in varying outcomes when processed differently [13], which can have serious implications in practice [14].

Whether an observed peak in oxygen uptake corresponds to the true maximum has been extensively discussed in previous research [15–19]. To identify a true maximum, researchers commonly evaluate a set of parameters measured during ramp tests — the so called ‘V̇O2max criteria’ [16]. We will not distinguish between peak and maximum oxygen uptake in this article, as the criteria for V̇O2max (e.g. the primary criterion of a plateau in oxygen uptake or the secondary criterion of the maximum respiratory quotient) do heavily rely on the data processing strategy used [13]. Thus, we speak of V̇O2max as the maximum oxygen uptake measured during an appropriate exercise test regardless of any V̇O2max criteria.

Measured gas exchange data is inherently noisy. Both the biological variability of breathing patterns and the measurement error (as well as irregular breaths such as coughs and swallowing) result in large fluctuation of raw oxygen uptake data on a breath-by-breath basis. Therefore, the raw data require some form of processing to obtain a more stable estimate. However, different data processing strategies influence measured parameters of gas exchange [13,14,20,21]. Midgley et al. [22] found differences in estimated V̇O2max values between data processing strategies. As no difference regarding the reliability of the different approaches was found, no optimal strategy exists per se. Accordingly, when comparing outcomes within and across studies obviously a consistent processing strategy should be used. Based on data in sedentary and moderately trained individuals, Martin-Rincon et al. [23] provided linear-log equations to compare mean V̇O2max values derived from processing strategies with differing averaging interval lengths. The results showed that the reliability of V̇O2max was higher in trained individuals, but not influenced by data processing. Furthermore, there is inconclusive evidence on whether the influence of different processing strategies interacts with different exercise protocols [24,25].

Researchers have proposed a variety of calculation intervals and computational methods to process oxygen uptake data [16,26–29] and calls to standardize processing strategies are frequent [14,24,25,30]. In light of the influence on outcome variables, many articles highlighted the need to report processing strategies in research [13,14,25,30]. Midgley et al. [22] were the first to evaluate reported data processing strategies for breath-by-breath analyses in selected journals. They found that almost all studies reporting the use of binned time averaging, with only 1 in 117 using a moving time and a moving breath average, respectively. One third of the studies did not describe their processing method at all.

Robergs et al. [29] argued that to investigate the current state of data processing strategies, two possible approaches are *“(i) a summary of published research, and (ii) a survey circulated via the Internet to as many exercise physiologists as possible”*. They chose the latter approach with a total of 75 respondents, who reported a great variety in data processing strategies. Most researchers reported the use of binned time averages over 30 or 60 seconds. Surprisingly, about half of the respondents admitted that their data processing strategy was rather chosen due to subjective factors as opposed to objective criteria [29]. The present work therefore aims to investigate to what extent reporting and processing practices have followed the recommendations put forth by Midgley et al. [22] and Robergs et al. [26].

Selected data processing strategies have been extensively compared in the literature. Due to the absence of a systematic mapping of current practices, these studies however lacked the reasoning of which strategies to compare. Many studies compared different averaging intervals, but not averaging types (e.g. moving breath vs. binned time) [13,22]. Martin-Rincon et al. [23] provided formulas for comparing data processing strategies by investigating a data set of sedentary individuals and recreational athletes, using two different metabolic carts. Therefore in their work motivation and measurement devices may have interacted with the influence of processing strategies. Most comparisons only report mean differences between strategies [13,22]. No research has yet compared a variety of systematically derived strategies among a group of trained individuals using a standardized measurement set-up.

Differences in estimated V̇O2max values due to variation in data processing can have serious implications in practice. For example, the assessment of longitudinal data from athletes which participated in diagnostics using differing data processing approaches becomes problematic. The same applies to the pooling of results across studies in meta-analyses [23]. Data processing strategies directly affect the occurrence of a plateau in oxygen uptake, the primary criterion for V̇O2max [13]. Crucially, in situations where individuals are classified by their V̇O2max — for example when describing the training status of a study population [31,32] or evaluating patients for a heart transplantation [33] — differing processing strategies can lead to misclassifications [14].

This paper aims to review the usage and reporting of different data processing strategies in the scientific literature and investigates their influence on V̇O2max. The results will help to compare V̇O2max data derived from different processing methods among studies and in individuals. The review allows to assess the implementation of data processing routines and to identify problematic reporting strategies. The results build a basis for providing recommendations for the reporting of data processing strategies to determine the V̇O2max.

# Methods

The present work was preregistered before project start with the [Open Science Framework](https://osf.io/3am4s) [34], following the ‘Inclusive Systematic Review Registration Form’ [35]. Any deviations from the preregistration are indicated in a ‘Transparent Changes’ document [LINK]. Major deviations will also be explicitly stated within the methods section. All data and code of this research project can be found at [GitHub](https://www.github.com/smnnlt/vo2max-processing). All analyses were performed using R Version 4.2.0 [36] in the R Studio IDE Version 2022.2.2.485 [37].

## Systematic Scoping Review

The aim of the scoping review was to systematically map current practices of data processing for V̇O2max determination in the scientific literature. Since determining V̇O2max is a far too common procedure to perform an exhaustive search, we randomly sampled 500 articles which referred to V̇O2max or similar keywords. Data on processing strategies were extracted from all sampled articles which directly measured V̇O2max using an appropriate testing procedure in human subject. The review was performed in accordance to the PRISMA extension for Scoping reviews [38], see LINK for the CHECKLIST.

### Search & Screening

The article search was conducted on 16th March 2022 using [PubMed](https://pubmed.ncbi.nlm.nih.gov/) and [Web of Science](https://www.webofscience.com/wos/woscc/basic-search). The search included articles published from 2017 to the date of the search referring to ‘maximum oxygen uptake’ or equivalent terms in title, abstract or keywords. APPENDIX [LINK] shows the exact search terms used.

The search results from both data bases were merged and checked for the presence of a Digital Object Identifier (DOI). Entries without DOI were excluded to allow for automated removal of duplicates by DOI matching in the next step. This was followed by an automated title scanning to exclude results that were likely no original research articles. All titles that contained one of the following words were excluded: *‘review’, ‘correction’, ‘meta-analysis’, ‘comment’, ‘retraction’, ‘editorial’, ‘erratum’, ‘reply’.*

In accordance with the preregistration we drew a random sample from the search results. The goal of this process was to give an unbiased estimate of the current state of scientific V̇O2max testing. Based on the procedure described in the preregistration, the sample included a total of 500 articles.

The abstracts from the articles included in the random sample were blinded for scanning, by removing any authors identities and journal information. Two of the authors (SN and OJQ) independently scanned the blinded abstracts to filter those that matched one of the exclusion criteria shown in **?@tbl-exclusion**. When the screeners disagreed in their assessment, they resolved the conflict by discussion.

After the abstract screening we retrieved the full-texts for the remaining articles. The full-texts were again independently scanned by two authors (SN and OJQ) to include only those articles that measured V̇O2max using an appropriate testing procedure in humans (see **?@tbl-exclusion** for the detailed full-text exclusion criteria[LINK]). Conflicts were resolved by discussion between the two examiners.

### Data Extraction

We retrieved data from all articles remaining after the abstract and full-text screening. Extraction included the following data:

* metabolic cart used
* measurement type (breath-by-breath, mixing chamber)
* type of outcome for V̇O2max (primary, secondary, other)
* data preprocessing (e.g., filtering)
* data processing software
* interpolation procedure
* data processing/determination of V̇O2max:
  + type (time average, breath average, digital filtering, …)
  + alignment (moving, binned, …)
  + interval (in seconds or breaths, parameters for filtering)
* rationale for the used data processing strategy (e.g. a reference)

The criteria ‘type of outcome’ and ‘rationale’ were added to the extraction list after the abstracts had been scanned, thus they were not stated in the preregistration.

### Data Synthesis

The extracted data is presented in a purely descriptive way. We calculated the relative and absolute frequency for the reporting of the extracted items. Similarly, we counted the use of different strategies for processing data in all articles that reportedly measured breath-by-breath. Total interval duration of averaging procedures were derived from the reported parameters.

## Experimental Comparison

To determine the influence of the most common data processing strategies on the determination of V̇O2max, we compared them on a set of already collected gas exchange data from ramp tests in running.

### Data Source

A total of N = 72 exercise tests were analyzed for this study. Due to a miscalculation, the preregistration had incorrectly stated a number of 76 tests. The data were from previous research on the metabolic profile of endurance runners [39,40]. The tested individuals were experienced distance runners (15 female, 54 male; three of the males participated in both studies). The V̇O2max tests were conducted in March to September 2019 [39] and March to October 2021 [40], respectively, while using identical exercise protocols and test equipment. Participants run on a treadmill (saturn 300/100, h/p/cosmos sports & medical 127 GmbH, Nussdorf-Traunstein, Germany) with 1% inclination for 8 minutes at a velocity of 2.8 m·s-1 as a warm-up. After preparing the gas exchange measures, they started a ramp protocol with an initial speed of 2.8 m·s-1 for two minutes and subsequently increased velocity by 0.15 m·s-1 every 30 seconds. The researchers provided verbal encouragement and terminated the exercise when the participants reached subjective exhaustion.

Gas exchange data were recorded using a ZAN 600 USB device (nSpire Health, Inc., Longmont, CO, United States of America). The device was calibrated with a 3l-syringe pump (nSpire Health, Inc., Longmont, CO, 143 United States of America) and a reference gas (15% O2, 6% CO2) before each measurement. The measured breath-by-breath data is available on [GitHub](https://github.com/smnnlt/vo2max-processing/tree/master/data/ramptests).

### Data Processing

The spiro package version 0.0.4 for R [41] processed the raw gas exchange data. The software includes various algorithms to calculate V̇O2max with user-defined parameters. Moving time-based averages were calculated by first linearly interpolating the breath-by-breath data to full seconds. Subsequently a (center aligned) moving average was calculated over the defined timespan.

For binned time-averages, the breath-by-breath data were initially interpolated to full seconds and then binned into consecutive intervals of constant lengths. The average of each interval was aligned to its center. Incomplete intervals (i.e. the last seconds of measurement) were not considered in the analysis. Note that some authors use a different procedure for determining their bins, starting by the end point of the measurement. However, defining bins beginning by the start of the measurement is a common output option for many gas exchange data analysis software (e.g. Cosmed Omnia). Breath based moving averages were calculated on the raw data.

### Comparison of Methods

To compare different processing methods within and between individuals, we chose to express the V̇O2max normalized to a reference procedure. The reference procedure was the most commonly applied one in current literature as determined by our scoping review. Individual V̇O2max values were expressed in reference to this procedure, where a value of 1 means that the processing method yields exactly the same V̇O2max value as the reference method. We calculated the data for all integer parameter values within the range of the calculation intervals found in the literature during the review. On a group level, we calculated the median and 10%- and 90%-quantiles of each processing strategy.

# Results

## Systematic Scoping Review

Initial search yielded 7529 results of which 4364 remained after automated filtering and removal of duplicates (see flow diagram in [Figure 1](#fig-flow)). Out of the random sample (n = 500), 242 articles were included in the final analysis.

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| Figure 1: Flow diagram for the systematic scoping review in accordance with the PRISMA 2020 Statement [42] |

Reporting practices of the methodology of gas exchange measures differed widely across the literature (see [Table 1](#tbl-reporting)). Almost half (44.2%) of the articles did not report any information regarding their data processing strategy. About one in twenty articles (5.8%) provided a rationale for their used strategy. Only a single article [43] reported information regarding all the investigated criteria.

Table 1: Percentage of studies that provided details on the different characteristics of oxygen uptake data processing.

| Metabolic cart | Preprocessing | Software | Processing Strategy | Rationale |
| --- | --- | --- | --- | --- |
| 88.0% | 5.6%\* | 15.0%\* | 55.8% | 5.8% |
| \*only examined within the subgroup of studies using breath-by-breath measurements |  |  |  |  |

Out of the authors that provided information and collected breath-by-breath measurements, most (79.5%) utilized binned averages to determine V̇O2max. Moving time averages, or breath-based averages were uncommon (see [Table 2](#tbl-strategies)). No study used digital filtering methods to determine V̇O2max.

Table 2: Strategies for processing breath-by-breath data in the reviewed literature (n = 88)

| Processing Strategy | Usage |
| --- | --- |
| Binned Time | 79.5% |
| Moving Time | 6.8% |
| Moving Breath | 5.7% |
| Multiple Binned Time | 5.7% |
| Binned Breath | 2.3% |

For preprocessing, some authors reported the use of a (linear) interpolation for the breath-by-breath data to seconds (n = 7; 4.3%). Few studies reported the use of data filtering strategies to remove outliers. This included the use of initial data smoothing by a short moving average (3 seconds, n = 1; 5 breaths, n = 3), the manual detection and removal of outliers (n = 2) or an automated removal of outliers (n = 5). For the automated outlier detection authors removed single data points differing from a not further defined local mean by a varying number of standard deviations (2, 3 or 4) or being outside of a 95% confidence interval. When reported, the software used for data processing varied among studies showing a total of more than 15 reported programs (for 30 studies that reported this parameter).

The calculation intervals for time-based averages of mixing chamber and breath-by-breath devices ranged from 5 to 60 seconds (see [Table 3](#tbl-duration)). 30-second intervals were most common to define V̇O2max, while some authors also often employed shorter (10-20 s) and longer (60 s) periods.

Table 3: Total durations of the calculation interval of V̇O2max in the reviewed studies.

| Interval duration (s) | Count |
| --- | --- |
| 5 | 1 |
| 10 | 12 |
| 15 | 29 |
| 20 | 12 |
| 30 | 49 |
| 40 | 1 |
| 45 | 1 |
| 60 | 22 |

## Experimental Comparison

The average V̇O2max as determined by a binned 30-second average was 62.2 ± 6.3 ml·min-1·kg-1 (mean ± standard deviation). Applying different data processing strategies for V̇O2max determination lead to different outcome values (see [Figure 2](#fig-comparison)).

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| Figure 2: V̇O2max varies by data processing strategy. Values are expressed relative to the V̇O2max from a 30-second binned average — the most common strategy as determined by the review. Solid lines display the median, the shaded areas mark the interval between 10th and 90th percentile. Using moving average leads to systematically higher V̇O2max values compared to binned time averages. Changing the averaging interval (in seconds or breaths) can lead to median changes in V̇O2max as large as 5%. |

Binned time averages systematically generated lower V̇O2max values compared to moving averages. Decreasing the calculation interval to 5 seconds lead to a 3-4% median increase of V̇O2max values. Notably at the individual level these increases may be lower (~2%) or much higher (>10%) than the median value.

Moving time and moving breath averages yield nearly identical values for V̇O2max over all calculation intervals, as most of the trained athletes reached respiratory rates around 60 min-1 in the final minutes of the exercise test (see SUPPL FIG LINK).

# Discussion

We aimed to review current practices of data processing strategies to determine V̇O2max and to compare them on experimental data. Our results show, that current research uses a variety of processing strategies to determine V̇O2max, which directly influences the values obtained. Identical raw breath-by-breath data can result in different V̇O2max values when processed differently. Many articles provide only incomplete reports about their chosen methods, which hinders reproducibility of V̇O2max measurement.

## Current State of Data Processing

Despite calls to use moving averages or digital filters [26,29], binned time averages remain the most common data processing strategy to determine V̇O2max in the reviewed literature (see [Table 2](#tbl-strategies)). The present findings are generally in agreement with the findings of the non-systematic search by Midgley et al. [22] and the survey by Robergs et al. [29]. It is somewhat surprising, that practices have not changed in recent years despite the publication of recommendations discouraging researchers from using binned averages [29]. Using binned time averages leads to systematically lower V̇O2max values as compared to moving averages (see [Figure 2](#fig-comparison)). The peak in oxygen uptake may be attained between two averaging intervals, resulting in an underestimation of V̇O2max. Binned time averages undermine the most important argument in favor of measuring breath-by-breath: the high temporal resolution of data. Despite these arguments speaking against the use of binned time averages, the present review demonstrates that they remain extremely common in the scientific literature.

Breath-based averages seem to be more common (~8%) than reported previously (<1%) [22], but less common than assessed in self-reporting (~17%) [29]. The increasing proportion of breath-based averages may be explained by publications in the recent years advocating for their use [26,29]. The length of the calculation interval for averaging is highly diverse within the literature (see [Table 3](#tbl-duration)). This may reflect contradictory recommendations [16,26]. There is no consensus on using shorter or longer calculation intervals, and it is unclear whether an optimal interval duration even exists. As different interval durations influence V̇O2max by more than 5% with respect to median levels (see [Figure 2](#fig-comparison)), the exact reporting of the data processing strategy remains essential for interpretation.

One possible reason for the prevalence of binned averages data processing approaches may be due to limitations in analysis software used. The results show that most researchers use the vendor software of the metabolic cart’s manufacturer. These software products may by default output binned time averages instead of raw breath-by-breath data. Moreover, further processing (e.g., interpolation, moving averages) may require the use of additional software. This may also explain why digital filtering has — despite recommended by Robergs et al. [29] — not been used in a single study reviewed here: standard distributions of common data analysis software (e.g., Microsoft Excel) lack the capability to perform such operations. The common practices of data processing are likely to be attributed to both: a lack of awareness and adequate software solutions.

## Impact of Different Data Processing Strategies

The different data processing strategies found in the literature directly bias the V̇O2max determination (see [Figure 2](#fig-comparison)), and as such influence the classification of individuals, the evaluation of training success, and the assessment of V̇O2max attainment. In accordance with previous findings [13,14,21] longer calculation intervals lead to lower V̇O2max values (see [Figure 2](#fig-comparison)). The analyzed data shows median differences up to 5-7% between processing strategies, which is in accordance with previous research [23]. Some studies reported even higher mean differences of up to 20% [30], but only when including raw breath-by-breath data in the comparison. The evaluation of unprocessed raw data for its maximum is highly erroneous and as such is not performed in research (see [Table 3](#tbl-duration)); so there is no reason to compare it to other strategies. While previous research was often conducted in sedentary or recreationally trained individuals, we now present evidence that a similar effect of data processing strategies on V̇O2max exists in trained athletes.

Since training interventions in trained athletes typically show improvements in V̇O2max in the range of 0-6% [44,45], variation caused by differing data processing strategies is in the same range and can bias the evaluation of their success. Together with biological [10] and technical [11] variability, data processing is just one of several sources of variation in the process of V̇O2max determination, but it is one that can easily be controlled without the need for multiple testing.

Binned time averages lead to systematically lower V̇O2max values compared with moving averages, for the reasons explained above. While this general trend has been acknowledged previously [23], it has not been quantified. The present data suggest a ~1% lower median V̇O2max when using binned averages compared with moving averages of the same calculation interval length. This difference is well within the measurement error of most if not all metabolic carts, but it is systematic and as such may bias the evaluation in scenarios where small changes in V̇O2max are important (e.g. in elite sports).

Moving time and moving breath averages lead to almost identical V̇O2max values with respect to median values ([Figure 2](#fig-comparison)). This seems natural in that the athletes in this study reached respiratory rates around 60 min-1 (see SUPPL LINK), resulting in equivalent time- and breath-based interval lengths. For an athletic population, V̇O2max values obtained by moving time and moving breath averages can approximately be used interchangeably. Given that less trained individuals display lower respiratory rates during exercise tests to exhaustion [46], this finding will likely not translate to sedentary populations.

The exact impact of data processing strategies on the V̇O2max is highly individual. Most research did present only comparisons of mean values, with results in accordance with those found here [23]. Data processing strategies may impact V̇O2max values with varying magnitudes at the individual level. For example, for 10% of the investigated athletes a binned time average of 5 seconds leads to a V̇O2max <3% higher than by a 30-second average, while for another 10% of the investigated athletes the V̇O2max was >6% higher (see [Figure 2](#fig-comparison)). Current values reported and equation derived compare strategies on a group level [23], which improves comparison of group results for meta-analyses or group classifications. However, at the individual level these equations can only be applied with a large margin of error. Changes in the impact of different data processing strategies on V̇O2max range from 1-2% in some individuals to more than 10% in others. Hence when evaluating V̇O2max data from different tests in a single individual obtained by using different processing methods, there is no way to accurately compare these values even when the processing strategies are reported. While the comparison of V̇O2max from different processing strategies require their reporting for a sufficient analysis on a group level, the raw data from each test is required on the individual level.

## Guidelines for Reporting

To compare and evaluate V̇O2max values from different studies, knowledge of the underlying data processing strategies is crucial. Our review demonstrates that almost half of the studies measuring V̇O2max did not describe their processing strategy. Other aspects of the data processing, such as outlier filtering or the rationale for the chosen procedure were only in rare instances reported (see [Table 1](#tbl-reporting)). [Table 4](#tbl-recommendation) lists seven items that should be reported to provide sufficient information on the data processing strategy used to determine V̇O2max. These items may be reported in form of a checklist, as an in-text enumeration or in sentence form. An example paragraph containing all the relevant information for the original data presented in this paper [39,40] would be:

*“We measured breath-by-breath data during the ramp tests with a ZAN 600 USB device (nSpire Health, Inc., Longmont, CO, United States of America). The raw data was analyzed without any previous filtering by using a low-pass forward-backward Butterworth filter (each filter: 3rd order, 0.04 Hz cut-off) implemented in the spiro package for R version 0.0.4 [41]. This strategy produces similar results as that recommended by Robergs et al. [29], but does not include a time lag.”*

Note that the correct reporting of an exercise test to determine V̇O2max requires more information than those on data processing. Further aspects to be reported include, but are not limited to: the study population, exercise protocol, device calibration, and criteria to terminate the test. In cases where journals endorse word limits on articles, this reporting — including the reporting on data processing strategies — may be included in supplementary files. The correct and detailed reporting of data processing strategies, as well as other test characteristics, is crucial for interpreting presented V̇O2max values.

The results of the present work suggest that comprehensive reporting facilitates approximate comparisons of V̇O2max data on a group level derived using different data processing strategies. However, on an individual level and for a precise comparison, reporting may not be sufficient, as differences between data processing strategies vary between individuals and are potentially influenced by training status. Sharing of the raw gas exchange data can solve this challenge, as it allows any researcher to recalculate the V̇O2max using their preferred data processing strategy. Most raw gas exchange data files are structured in a simple way, which allows to easily remove any personal information (if this had not been done in the metabolic cart’s system before). In terms of reproducibility of V̇O2max determination, sharing the raw data as well as the data analysis code seems to be an even superior way. This requires the data analysis to take place in a programming (or at least code generating) environment. Such programs for the purpose of analyzing gas exchange data exist as free open-source software [41,47].

Table 4: Recommendations for reporting data processing strategies to determine the maximum oxygen uptake.

| Reporting Item | Description |
| --- | --- |
| Metabolic Cart | State the exact device model and manufacturer. |
| Measurement Mode | State the measurement mode (e.g., mixing chamber, breath-by-breath,…). |
| Software | State the name and version of the software used for data analysis. |
| Preprocessing | State if and how data underwent any initial modification (e.g., filtering of outliers, interpolation) before analysis. |
| Processing Strategy | State the exact data processing strategy used to determine the VO2max (e.g., binned time averages). |
| Processing Parameters | State the parameters used for the processing strategy (e.g., length of averaging interval). |
| Rationale | State the rationale for using the processing strategy (e.g., reference to recommendations). |

## Limitations

Due to the sheer quantity of the publications investigating V̇O2max, it was not possible to perform an exhaustive review of all articles. The scoping review therefore relies on a random sample which not necessarily captures exact trends of the literature. However, efforts were made — such as random sampling and systematic article exclusions — to ensure the sample to be representative. Notable, almost half of the studies did not report their data processing strategy at all. The data processing strategies used in the literature could only be investigated when studies reported them.

Ambiguities in the reporting of the investigated studies may impact analysis results. For example some studies using long binned averages (e.g. 60 seconds) may have in fact been using multiple binned averages of shorter duration (e.g. 4×15 second), without describing this correctly. Moreover, the exact definitions for building binned averages vary within the literature. While most studies define the binning periods from the beginning of the exercise, some may define them from the endpoint. Additionally some of the included studies did not define the maximum bin, but a pre-set binned average period as their V̇O2max (for example the last bin, regardless of its value). In situations where the maximum in oxygen uptake is reached considerably before exhaustion (i.e., a long plateau in oxygen uptake exists) this may lead to different results than a traditional binned average processing. We did not separately consider such sub-categories of data processing strategies, as they may not be very common and are often hard to investigate precisely due to ambiguities in their reporting.

This work treated each breath as the single data processing unit of cardiopulmonary exercise testing. However, metabolic carts sample gas fraction and gas flow data at a much higher frequency (e.g., 50 Hz). The data for each breath is subsequently calculated from these raw signals by the means of an algorithm. Different algorithms to generate the breath-by-breath data can lead to different outcomes [48], and as such may also influence the V̇O2max. Hence documenting and reporting of the breath-by-breath algorithm is advisable. Yet many metabolic carts do not describe their default algorithm and limit access to the raw data signal.

The experimental comparison of different data processing strategies was conducted on a standardized data set of exercise tests. This standardization in terms of training status, exercise protocol, and measurement device helps to highlight the impact of different data processing even in a relatively homogeneous data set. However the results may only partly transfer to different settings, such as individuals with less training background.

# Summary

Despite calls for standardization, researchers use a variety of data processing strategies to determine the V̇O2max from raw gas exchange data. Based on current reporting practices we developed a checklist that can serve as a guideline for reporting data processing methods for V̇O2max determination. We advise authors to follow the reporting guidelines and ideally share anonymized raw data to improve the reproducibility of research in exercise physiology.

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