Systematic Review

Analysis and stratification of internal and external loads in rowers of different categories, age groups, and sex: a systematic review and meta-analysis

Álvaro Huerta Ojeda[1], Miguel Riquelme Guerra[2], Guillermo Barahona-Fuentes[1,3], María-Mercedes Yeomans-Cabrera[4], Darío Martínez-García[5]

[1]Universidad de Las Américas, Núcleo de Investigación en Salud, Actividad Física y Deporte, Viña del Mar, Chile; [2]Universidad Santo Tomás, Facultad de Salud, Escuela de Kinesiología, Viña del Mar, Chile; [3]Universidad Andres Bello, Faculty of Education and Social Sciences, Viña del Mar, Chile; [4]Universidad de Las Américas, Facultad de Salud y Ciencias Sociales, Escuela de Psicología, Viña del Mar, Chile; [5]University of Granada, Faculty of Sports Sciences, Department of Physical Education and Sports, Strength & Conditioning Laboratory, CTS-642 Research Group, Granada, Spain.

Associate Editor: Marcela de Castro Ferracioli Gama, Universidade Federal do Ceará, Fortaleza, CE, Brazil. E-mail: marcelaferracioli@gmail.com.

Abstract - Background Competitive rowing has also been on the Olympic program since the first Modern Olympic Games. However, there are no reports that normalize physical performance in the different tests. **Aim:** The purpose of the study was to analyze and present standardized values of physical performance in rowers of different categories, age groups, and sex. **Methods:** The search was structured under the PRISMA® guidelines for systematic reviews and meta-analysis. The search was performed in Web of Science, Scopus, SPORTDiscus, PubMed, and MedLine with no time limit until September 2023. Variables analyzed were maximal oxygen consumption (VO_{2max}), heart rate, aerobic power, anaerobic power, and critical rowing speeds. **Results:** Most studies focus on VO_{2max}. The highest VO_{2max} was in the "elite" men category (5.46 $LO_2 \cdot min^{-1}$), while the lowest value was in the "novice" women category (2.88 $LO_2 \cdot min^{-1}$). The most frequently used test to evaluate VO_{2max} was the 2,000-meter (m) rowing ergometer. **Conclusion:** The internal load most evaluated in rowers of all categories, age groups, and sex is VO_{2max}. In most cases, VO_{2max} is evaluated through the 2,000 m rowing ergometer test. However, this test has low reliability in lower-level athletes. In the latter case, exploring tests with a shorter duration (6-min on the rowing ergometer) is suggested.

Keywords: rowing, physical tests, functional tests, physical performance.

Introduction

Competitive rowing is one of the sports with the longest historical records; an example of this is that since the 13th century and up to the present day, the term "regatta" has been used to refer to rowing competitions[1]. The sport has also been on the Olympic program since the first Modern Olympic Games[2]. Rowing requires a high physical and technical demand. Its optimal execution is conditioned by three variables: a) working with a machine, b) working on aquatic supports, which generates constant instability, and c) most boats are configured for teamwork. The latter requires a great effort to synchronize the members of the boat[3] physically[2] and mentally.

From a physiological and metabolic point of view, rowing is one of the most demanding disciplines[4]. It has a high aerobic contribution and a lower - but equally important - anaerobic contribution[5-7]. In this sense, research has calculated that the contribution of aerobic metabolism ranges between 70%[5,7] to 88%[6]. Moreover, the contribution of anaerobic metabolism fluctuates between 12%[6] to 30%[5,7]. In addition to this, it has been proven that small changes in the rowing technique significantly influence strength production[8]. Indeed, evidence shows that sports performance in rowing is associated with the continuous increase of both technique and energy metabolism[7].

Nowadays, training in rowing is specific, individualized, and highly complex[2]. In this sense, the training load is the primary variable to obtain the desired responses and organic adaptations[9]. These training loads are divided into external and internal loads[9-11]. External loads correspond to the physical work prescribed in the training plan and are expressed as external resistance, distance covered, accelerations, or metabolic power[12,13]. At the same time, internal loads correspond to the psychophysiological responses initiated by the body itself, which are activated to cope with the demands caused by the external load[9-11]. In this context, the most frequently evaluated internal loads are maximal oxygen uptake (VO_{2max}), maximum heart rate (HR max), and rating of perceived exertion (RPE)[9-11].

Among other conditions, competitive rowing requires a high level of oxygen consumption (VO_2)[5]. During a competition, this component can increase from a resting value of ~0.25 to 0.5 L of oxygen per minute ($LO_2 \cdot min^{-1}$) to individual maximum values[14]. This can exceed 6 ($LO_2 \cdot min^{-1}$)[5]. In this sense, the first evaluations of VO_{2max} through gas analysis on a rowing ergometer were performed in 6 min in elite rowers[5,15]. This test is considered the gold standard[16] for elite rowers because it yields measurement errors of less than 5%[17,18]. However, Klusiewickz et al.[19] reported that the total error rate for estimating VO_{2max} in rowers was smaller when the capacity was higher[19]. Indeed, rowers would have to go below 6-min over 2,000 m on the rowing ergometer to achieve a high degree of reliability[20]. Therefore, if it is considered that rowers in the “novice” category take more than 7-min to complete the 2,000 m on the rowing ergometer, the estimated consumption would be inaccurate[21,22]. Currently, there is evidence of the behavior of VO_2 kinetics in the 6-min test in amateur rowers[23,24]. Indeed, a high correlation between VO_2 and power output during the 6-min test has been observed[23]. Furthermore, the 6-min test is a reliable tool for training prescription. Despite this, scientists and coaches’ importance to VO_{2max} on rowing performance is so high that they have also created equations based on critical speeds[4]. Sometimes, with a high anaerobic component[25,26], estimating VO_{2max} demonstrates, indirectly, that this variable is the best predictor of performance in this sport[18].

According to the background presented, tests that analyze ventilatory parameters play an important role in defining the performance profile in rowers[4,19]. These tests usually include internal loads such as VO_{2max}[5,16] and HR[2,27], and external loads such as maximal aerobic power (MAP) evaluated in watts (W)[28,29]. Tests that analyze anaerobic parameters on the rowing ergometer also allow the construction of the performance profile of the rowers[28,30,31]. These tests include internal loads such as HR[27,32] and external loads such as anaerobic power (AP)[33,34] evaluated in W. However, no studies analyze and stratify both internal and external loads in rowers of different categories, age groups, and sex to the best of our knowledge. Consequently, the main objective of this systematic review and meta-analysis was to analyze and present standardized values of physical performance in rowers of different categories, age groups, and sex. At the same time, the secondary objective was to determine the recurrent tests used to evaluate VO_{2max} in rowers of different categories, age groups, and sex.

Methods

This systematic review and meta-analysis followed the preferred reporting items for systematic reviews and meta-analyses (PRISMA) guidelines[35] and the Cochrane Collaboration guidelines to evaluate the risk of studies bias. The protocol of this review was registered in PROSPERO (CRD42021276783).

Eligibility criteria

Articles were eligible if published in peer-reviewed, full-text journals in English, Spanish, Portuguese, French, and German. The search range was not limited to the start date but was limited to the end date (September 2023). The relevance of each study was assessed according to population, intervention, comparators, and outcomes (PICO). These were established as follows: a) healthy rowers; b) studies that performed physical performance testing and reported results with internal and external loads; c) physical performance testing supervised by one or more experts; d) sufficient data to calculate the mean and standard deviation of primary and secondary outcomes.

Two independent reviewers (AHO and MRG) examined the title/summary of the articles found in the databases. After the initial selection, they analyzed each study with the inclusion criteria. Each criterion was evaluated as yes/no. If discrepancies existed between the authors, the ratings of the articles were shared and discussed until consensus. The authors were familiar with the existing literature and did not have a different bias with the studies selected for inclusion in the review.

Information sources and search

Studies were identified through searching in five electronic databases: Web of Science (WoS), Scopus, SPORTDiscus, PubMed, and MedLine. The bibliographic search was carried out by combining the different Medical Subject Headings (MeSH) terms with the following keywords: “[(“rowing” OR “rowers” OR “oarsmen”) AND (“functional test” OR “physical test” OR “Physical evaluation” OR “exercise test”)]. These search terms were combined with two Boolean operators (AND/OR). Also, the bibliographies of other previous related reviews and the selected studies were examined to search for new studies.

Data extraction process

Two independent authors extracted data according to a previously established protocol. A third reviewer would discuss the study data if differences or inconsistencies were found until an agreement was made. The following information was collected: a) author's name and year of publication; b) sample size and gender of participants; c) origin of the sample (e.g., sports club or school); d) subjects' age; e) physical performance tests that reported results with internal (VO_{2max}[26] or HR[2]) and external loads (MAP[28,29] or AP[25] or critical rowing speed[4]); f) participants' sport experience; g) limitations, suggestions, applications, and conclusions described in the studies.

Quality assessment

Two reviewers independently assessed the risk of bias according to the Cochrane Collaboration Handbook recommendations[36]. The included studies were assessed using the Cochrane Collaboration tool for assessing the risk of bias. This tool assesses the risk of bias according to six domains: bias arising from the randomization process, bias due to deviations from intended interventions, the bias due to missing outcome data, the bias in the measurement of the outcome, the bias in the selection of the reported result, and overall bias. A response to a question was considered for each item; when the question was answered with "Yes," it indicated a low risk of bias, "No" indicated a high risk of bias, and "Unclear" indicated a lack of information or uncertainty about possible bias.

Data analysis

A meta-analysis was conducted to provide average reference values and explore the impact of sex and categories on performance outcomes to integrate the results of a set of studies about performance tests in rowers. The first analysis performed was the risk of bias through the Cochrane Collaboration Handbook recommendations[36]. All statistical analyses were carried out using the comprehensive software meta-analysis package for the R metaphor 1.9-8[37]. The outcome variable in each meta-analysis was the raw mean of the performance outcomes, and the explanatory variable was expressed by the athletes' sex and expertise reported by the included studies. Random effects were specified for the dataset, and the resulting model was fit using Restricted Maximum Likelihood Estimation[38]. Therefore, the tests on individual coefficients and the confidence intervals relied on the distributions with k-1 degrees of freedom, where k is the number of studies. Heterogeneity was assessed with Cochrane's Q, and publication bias was assessed by estimating funnel plot asymmetry via the ranked regression test (rank test function)[37,39].

Results

The bibliographic search through the electronic databases identified 1,117 articles, of which 631 were duplicates. The remaining 486 articles were filtered by title and abstract, leaving 124 studies to read and analyze. After a full review of the 124 studies, 45 were eliminated for not meeting the inclusion criteria. In the search for articles oriented by bibliographic references, 24 studies were added. As a result, 103 articles were included for the systematic review and meta-analysis (Figure 1).

The bias analysis showed that 34.0% of the included studies did not show random sequence generation. At the same time, 63.9% of the studies did not show allocation concealment. Likewise, 31.9% of the included studies did not show the blinding of participants and personnel. In the remaining criteria, there was no risk of bias[36] (Figure 2).

To view the risk of bias for each article included in the systematic review and meta-analysis, please refer to Supplementary Figure S1.

Of the 103 studies selected, 57 correspond to the "adult" category[4,6,15,19,20,28,29,34,40-88], three to the "amateur" category[23,24,69,], 25 to the "elite" category[5,14,33,42,45,66,89-107], eight to the "junior" category[25,26,34,45,68,108-110], 10 to the "juvenile" category[18,22,32,68,69,110-114], three to the "novice" category[21,22,115], one to the "master" category[77]. In parallel, a weight category analysis was carried out, categorizing nine to the "lightweight" category[14,15,28,54,56,67,73,85,104] and six to the "heavyweight" category"[28,45,54,56,62,65]. The normalized values by category and, in addition, by sex are reported in Table 1.

Aerobic tests

The analysis showed that the internal load most evaluated in the rowers is the VO_{2max}[5,44]. This same analysis showed that weighted mean values are disparate among the different categories[5,96]. Thus, the highest weighted mean value was in the "elite" men's category with 5.46 ($LO_2 \cdot min^{-1}$)[5,33,45,90,96,99-105,107], while the lowest value for the same variable was in the "novice" women's category with 2.88 ($LO_2 \cdot min^{-1}$)[22]. Likewise, the HR max, associated with the evaluation of VO_{2max}, also showed disparate mean values between the different categories. The highest value for this variable was in the "amateurs" men's category with 203 bpm[24], while the lowest was in the "master" men's category with 167 bpm[77]. The normalized values by category and, in addition, by sex for the internal loads of VO_{2max} and HR max are reported in Table 2 and Table 3, respectively.

Within the external loads, the MAP also showed disparate weighted mean values among the different categories. In this sense, the "heavyweight" male category showed the highest weighted MAP with 405.2 ± 27.5 W, followed by the "lightweight" male category with 362.9 ± 23.9 W[54]. In parallel, the "heavyweight" female category showed a MAP equivalent to 266.0 ± 26.0 W, while the "lightweight" female category showed a MAP equivalent to 248.0 ± 15.0 W[28].

The stratification of the performance in aerobic tests, specifically maximum distance tests and time trials in rowing ergometers, showed disparate weighted mean values among the different categories. Thus, the "elite" men category had the highest performance in the 2,000 m

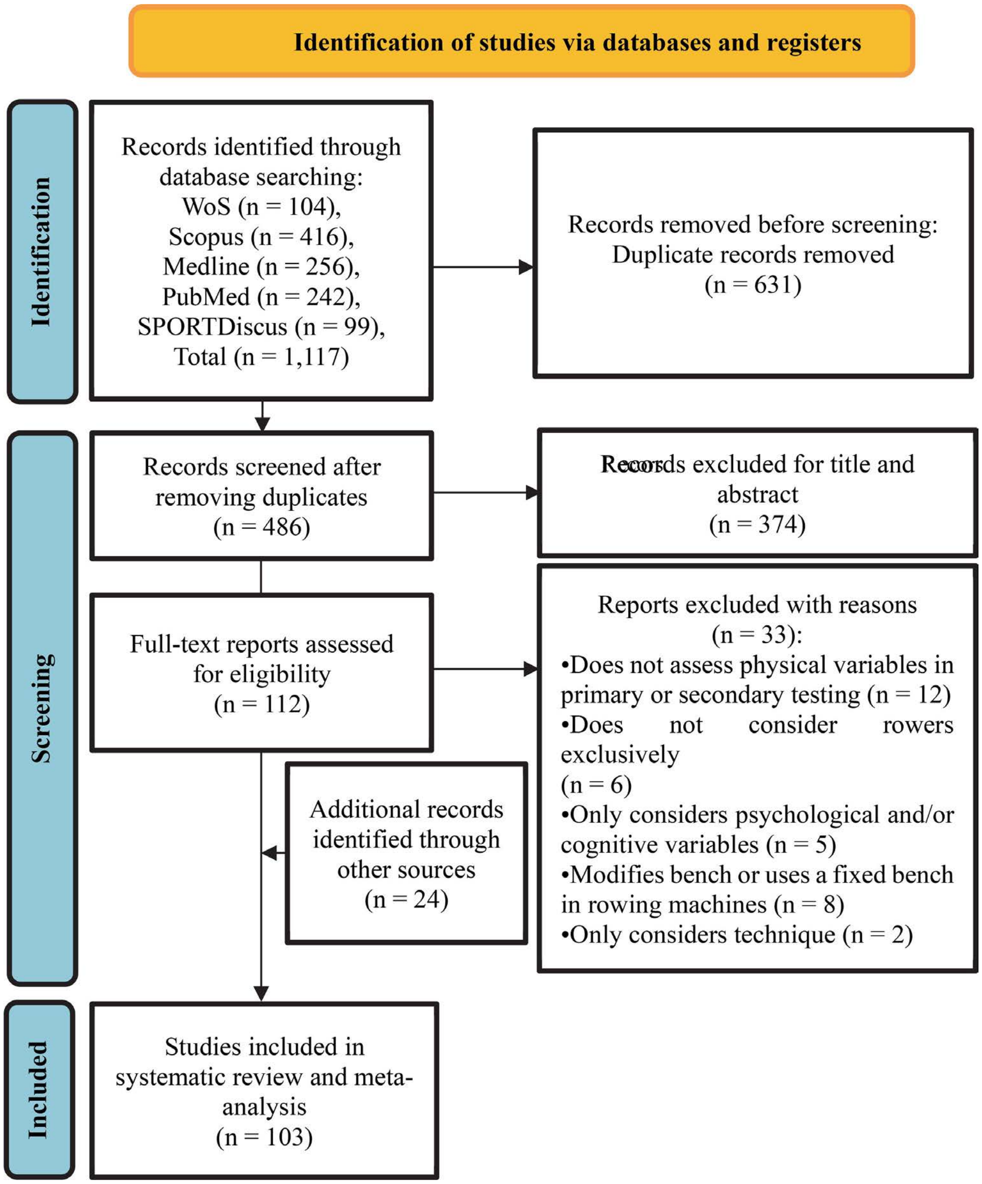

Figure 1 - PRISMA flow diagram of articles that were selected.

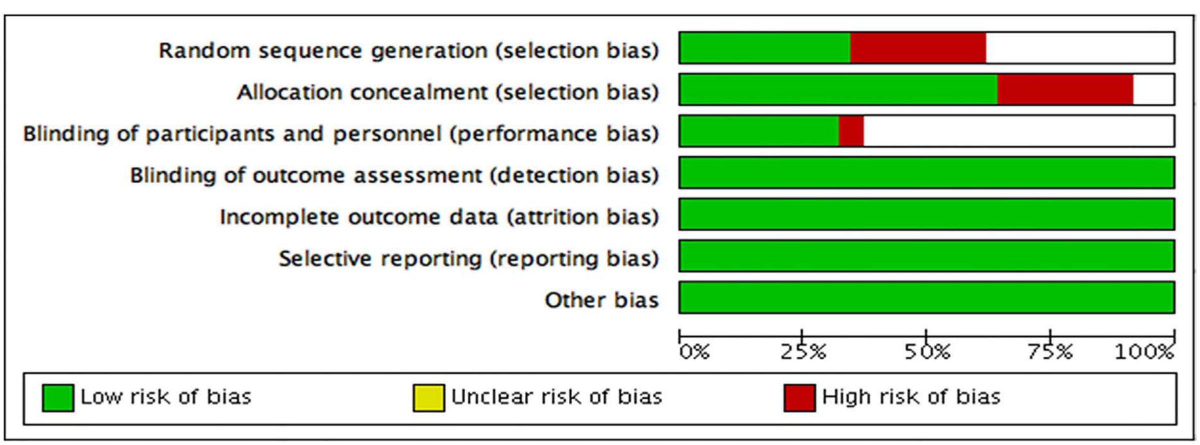

Figure 2 - Risk of bias graph: reviewers' judgments on each element of risk of bias in the included studies.

Table 1 - Age by categories and sex of participants included in the systematic review and meta-analysis.

Categories	n	weighted mean [CI] (years)	(min-max)
Adults[4,6,15,19,20,28,29,34,40-88]			
M[4,15,19,29,41,43-47,49-51,53-68,71-73,77,79,82,83,85-87]	805	21.74 [21.13-22.36]	(18.9-28.8)
W[4,6,19,28,40,42,45,47,48,50,52,53,56,60,69,81,84,88]	417	20.57 [19.60-21.53]	(17.9-25.3)
M-W[20,70,78,82]	78	22.56 [21.11-24.01]	(21.0-25.5)
Amateurs[23,24,69]			
M[23,24]	28	20.57 [19.81-21.33]	(18.0-27.0)
W[69]	7	18.00	(18.0-18.0)
Elite[5,14,33,42,45,66,89-107]			
M[5,14,42,45,66,90,91,93-96,98,99,102-105,107]	780	23.43 [21.89-24.98]	(18.0-28.5)
W[45,89,96,99,102]	76	22.60 [19.53-25.68]	(19.4-28)
M-W[92,97,100,101]	53	23.60 [19.08-28.12]	(20.0-29.9)
Junior[25,26,34,45,68,108-110]			
M[25,26,45,108110]	401	15.80 [15.01-16.59]	(14.8-17.8)
W[45,68]	201	15.91 [14.81-17.00]	(14.9-17.7)
M-W[34]	98	13.3	(13.3-13.3)
Juvenile[18,22,32,68,69,110-114]			
M[32,110-114]	123	16.70 [16.00-17.40]	(14.8-17.7)
W[18,22,68,69]	102	17.60 [15.91-19.30]	(14.9-19.3)
Novice[21,22,115]			
M[21]	12	20.33 [19.34-21.32]	(19.0-24.0)
W[22]	16	19.30	(19.3-19.3)
M-W[115]	20	19.30	(19.3-19.3)
Master[77]			
W[77]	11	58.59	(58.5-58.5)
Class by body weight	n	weighted mean [CI] (years)	(min-max)
Lightweight[14,15,28,54,56,67,73,85,104]			
M[14,15,54,56,67,73,104]	90	23.59 [22.58-24.61]	(21.77-25.30)
W[28]	27	21.90	(21.9-21.9)
M-W[85]	7	23.00	(23.0-23.0)
Heavyweight[28,45,54,56,62,65]			
M[45,54,56,62,65]	309	21.78 [19.42-24.15]	(17.2-28.8)
W[28,45]	155	19.65 [18.08-21.23]	(17.1-23.0)

CI: 95% confidence intervals; M: men; H-W: sample including men and women; max: maximum; min: minimum; n: number of subjects included in the analysis; W: women.

tests with a weighted mean time of 382.2 s[14,45,66,93-95,99,107], followed by the "adult" men category with a performance of 404.9 s[45,49,50,53,54,58,60,63,66,71,73,75,76,79]. On the other hand, the "novice" women category presented the lowest performance in the 2,000 m with 485.8 s[22]. Likewise, the "junior" men category had the highest performance in the 6-min test (maximum distance tests) with a performance of 1,812.1 m[51]. In comparison, the "adult" women category had a performance of 1,520.0 m in the 6-min test[88]. The normalized values by category and sex for maximum distance and time trials in the rowing ergometer are reported in Table 4.

Recurrent use tests

The results show that the most commonly used tests to evaluate VO_{2max} in all categories are incremental and 2,000 m, both on the rowing ergometer. Also, but less used than the previous ones, is the 6-min test on the rowing meter[5,15,23,24,88,104] (Table 5).

Discussion

At the end of the systematic review and meta-analysis, it was observed that the most used variable to determine internal loads and thus physical performance in

Table 2 - Internal loads through VO_{2max} in rowers by category and class by body weight.

Categories	**n**	**VO_{2max} [CI] $LO_2.min^{-1}$**	**(min-max)**
Adults[15,20,28,29,40,42-47,50,52,54,60,63,64,67-69,74-76,83-88]			
M[15,29,42-47,50,54,60,63,64,67,68,74-76,83,86]	702	4.85 [4.61-5.08]	(3.70-5.68)
W[28,40,42,45,47,50,52,60,69,84,88]	303	3.50 [3.23-3.78]	(2.30-3.88)
M-H[20,85,87]	82	4.38 [3.64-5.12]	(3.19-4.70)
Amateurs[23,24,69]			
M[23,24]	28	3.95 [3.78-4.25]	(3.32-4.66)
W[69]	14	2.99 [2.13-3.85]	(2.98-3.00)
Elite[5,33,45,90,96,99-105,107]			
M[5,33,45,90,96,99,102-105,107]	513	5.46 [5.18-5.75]	(4.30-6.08)
W[45,96,99,102]	67	4.24 [3.79-4.69]	(3.68-4.45)
M-W[100,101]	22	4.65 [3.67-5.63]	(4.60-4.70)
Junior[26]			
M[26]	15	4.60	(4.60-4.60)
Juvenile[18,22,32,69,114]			
M[32,114]	38	5.06 [3.36-6.75]	(4.17-5.90)
W[18,22,69]	76	3.14 [2.55-3.72]	(3.10-3.18)
Novice[21,22]			
M[21]	12	4.32 [4.20-4.39]	(3.93-4.66)
W[22]	16	2.88 ± 0.20	-
Class by body weight	n	weighted mean [CI] (years)	(min-max)
Lightweight[15,28,54,67,85,96,104]	114	4.57 [4.06-5.07]	(3.50-5.31)
M[15,54,67,96,104]	80	4.77 [4.36-5.19]	(4.30-5.31)
W[28]	27	3.50	(3.50-3.50)
M-W[85]	7	4.70	(4.70-4.70)
Heavyweight[28,45,54]	297	4.70 [3.77-5.62]	(3.60-5.92)
M[45,54]	187	5.57 [5.03-6.11]	(5.15-5.92)
W[28,45]	110	3.87 [3.36-4.38]	(3.60-4.27)

CI: 95% confidence intervals; $LO_2 \cdot min^{-1}$: liters of oxygen per minute; max: maximum; M: men; M-W: sample including men and women; min: minimum; n: number of subjects included in the analysis; VO_{2max}: maximum oxygen consumption; W: women.

Table 3 - Internal loads through HR max in rowers by category and class by body weight.

Categories	**n**	**HR max ± [CI] bpm**	**(min-max)**
Adults[4,18,20,40,45,50,51,64,67-69,72,75,77,80,82,84]			
M[4,18,45,50,51,64,67,68,72,75,77,80]	360	191.1 [188.2-194.0]	(180.0-197.0)
W[4,40,45,50,69,84]	122	192.3 [190.1-194.5]	(186.4-197.0)
M-W[20,82]	74	189.2 [182.5 -195.9]	(186.0-193.0)
Amateurs[23,24,69]			
M[23,24]	28	190.6 [188.4-193.7]	(171.1-203.0)
W[69]	14	189.7 [185.7-193.6]	(189.4-190.0)
Elite[5,45,97,98,101,103,105]			
M[5,45,98,103,105]	412	185.0 [182.2-187.8]	(179.0-190.2)
W[45]	30	190.0 [186.5 -193.6]	(189.0-191.0)
M-W[97,101]	111	185.8 [169.7-202.0]	(177.5-195.0)

(*continued*)

Table 3 - continued

Categories	n	HR max ± [CI] bpm	(min-max)
Junior[45,108]			
M[45,108]	115	196.7 [191.5-201.9]	(192.0-201.0)
W[45]	45	198.0 [194.4-201.5]	(198.0-198.0)
Juvenile[32,112,114]			
M[32,112,114]	66	189.2 [180.2-198.2]	(181.0-198.0)
Novice[21,22]			
M[21]	12	189.8 [188.0-194.3]	(171.1-198.9)
Master[77]	11	167.0	(167.0-167.0)
M[77]	11	167.0	(167.0-167.0)
Class by body weight	n	weighted mean [CI] (years)	(min-max)
Lightweight[18,67]			
M[18,67]	40	184.2 [180.8-187.4]	(183.0-186.6)
Heavyweight[45]			
M[45]	263	190.5 [188.4-192.5]	(183.0-198.0)
W[45]	112	194.3 [192.3-196.3]	(189.0-198.0)

bpm: beats per minute; CI: 95% confidence intervals; HR max: maximum heart rate; max: maximum; M: men; M-W: sample including men and women; min: minimum; n: number of subjects included in the analysis; W: women.

Table 4 - Maximum distance tests (m) and time trials (s) in rowing ergometer.

Categories	n	weighted mean [CI]	(min-max)
Adults[28,40,45,48-54,58,60,63,66,71-73,75,76,78,79,81,82,86-88]			
M[45,49-51,53,54,58,60,63,66,71-73,75,76,79,86]			
2,000 m (s)[45,49,50,53,54,58,60,63,66,71,73,75,76,79]	471	404.9 [392.1-417.8]	(361.4-463.3)
2,000 m in water (s)[72]	8	515.0 ± 11.0	(506.0-524.0)
6,000 m (s)[86]	25	1,195.4 ± 36.1	-
W[28,40,45,48,50,52,53,60,81,88]			
2,000 m (s)[28,45,48,50,52,53,60]	232	483.5 [453.7 - 513.3]	(430.0-561.1)
3-min test (m)[81]	37	800.1	(800.2-800.2)
6-min test (m)[88]	22	1,520.0 ± 57.0	(1,418.0-1,639.0)
2,500 (s)[40]	20	591.0 ± 41	-
M-W[78,82,87]			
2,000 m (s)[78,82,87]	51	457.7 [431.0 - 484.4]	(431.8-476.7)
Elite[14,45,66,92-95,99,107]			
M[14,45,66,93-95,99,107]			
2,000 m (s)[14,45,66,93-95,99,107]	187	382.2 [367.3 - 397.1]	(357.7-423.8)
W[45,99]			
2,000 m (s)[45,99]	36	422.3 [401.6 - 443.0]	(411.5-436.0)
M-W[92]			
2,000 m (s)[92]	10	428.5	(428.5-428.5)
Junior[25,26,28,40,45,48-54,58,60,63,66,71-73,75,76,78,79,81,82,86-88]			
M[25,26,45,49-51,53,54,58,60,63,66,71-73,75,76,79,86]			
2,000 m (s)[45,49,50,53,54,58,60,63,66,71,73,75,76,79]	141	411.1 [402.6 - 419.7]	(394.0-417.1)
6,000 m (s)[86]	45	473.0 [466.6 - 479.3]	(462.0-484)

(*continued*)

Table 4 - continued

Categories	n	weighted mean [CI]	(min-max)
6-min test (m)[51]	8	1,812.3 ± 45.6	(1742.0-1888.0)
W[28,40,45,48,50,52,53,60,81,88]			
2,000 m (s)[28,45,48,50,52,53,60]	19	476.6	(476.6-476.6)
3-min test (m)[81]	37	800.2 ± 44.1	-
6-min test (m)[88]	22	1,520.0 ± 55.0	(1418-1639)
2,500 (s)[40]	20	591 ± 41	-

CI: 95% confidence intervals; m: meters; M: men; M-W: sample including men and women; max: maximum; min: minimum; n: number of subjects included in the analysis; s: seconds; W: women.

Table 5 - Tests used to evaluate VO_{2max} in the rowing ergometer.

Categories	n	weighted mean [CI] $LO_2 \cdot min^{-1}$	(min-max)
Adults[15,20,28,29,40,42-47,50,52,54,60,63,64,67,68,74-76,83-88]			
M[15,28,42-47,50,54,60,63,64,67,68,74-76,83,86]			
2,000 m test[45,50]	101	4.93 [4.10-5.76]	(4.38-5.38)
Incremental test in water ($mLO_2 \cdot kg^{-1} \cdot min^{-1}$)[67]	16	57.2 ± 10.4	-
Incremental test[15,28,42-47,50,54,60,63,64,67,68,74-76,83,86]	573	4.85 [4.60-5.11]	(3.70-5.68)
Maximum 6-min test[15]	12	4.6 ± 0.15	-
W[28,40,42,45,47,50,52,60,69,84,88]			
2,000 m test[45,50]	59	3.59 [2.90-4.28]	(3.19-3.88)
6:30-min test[84]	6	3.85 ± 0.24	(3.48-4.30)
Incremental test[28,40,42,45,47,50,52,60,69,84,88]	216	3.48 [3.16-3.81]	(2.30-3.80)
6-min test[88]	22	2.94 ± 0.34	(2.47-3.91)
M-W[20,85,87]			
2,000 m test[87]	22	3.19 ± 0.77	
Incremental test[20,85,87]	60	4.65 [3.83-5.46]	(4.60-4.70)
Amateurs[23,24,69]			
M[23,24]			
6-min test[23,24]	28	3.95 [3.78-4.25]	(3.32-4.66)
W[69]			
Incremental test[69]	14	2.99 [2.13-3.85]	(2.98-3.00)
Elite[5,33,45,90,96,100-105,107]			
M[5,33,45,90,96,100-105,107]			
2,000 m test[45,102,107]	128	5.61 [4.91-6.31]	(4.60-5.92)
Incremental test[33,90,96,99,103,105]	66	5.51 [5.18-5.85]	(5.12-6.08)
6-min test[5,104]	319	5.03 [3.47-6.60]	(4.30-5.90)
W[45,96,99,102]			
2,000 m test[45,102]	57	3.96 [3.28-4.65]	(3.68-4.27)
Incremental test[96,99]	10	4.44 [3.84-5.04]	(4.40-4.45)
M-W [100,101]			
Incremental test[100,101]	22	4.65 [3.67-5.63]	(4.60-4.70)
Junior[26]			
M[26]			
Incremental test ($mLO_2 \cdot kg^{-1} \cdot min^{-1}$)[26]	15	65.8 ± 8.7	-

(continued)

Table 5 - continued

Categories	n	weighted mean [CI] $LO_2 \cdot min^{-1}$	(min-max)
Juvenile[18,22,32,69,114]			
M[32,114]			
Incremental test[32,114]	38	5.06 [3.36-6.75]	(4.17-5.90)
W[18,22,69]			
Incremental test[18,22,69]	76	3.14 [2.55-3.72]	(3.10-3.18)
Novice[21,22]			
M[21]			
6-min test[21]	12	4.32 [4.20-4.39]	(3.93-4.66)
W[22]			
Incremental test[22]	16	2.88 ± 0.20	-

CI: 95% confidence intervals; max: maximum; m: meters; M: men; M-W: sample including men and women; min: minimum; n: number of subjects included in the analysis; VO_{2max}: maximum oxygen consumption; W: women.

rowers is VO_{2max}[18,26,96,116]. The highest VO_{2max} values were observed in the "elite" men's category, with weighted average oxygen consumptions of 5.46 $LO_2 \cdot min^{-1}$, reaching in some cases - world championships and Olympic competitions - values between 6.0-6.6 ($LO_2 \cdot min^{-1}$)[7]. When analyzing VO_{2max} by bodyweight class, it was found that the weighted average for "lightweight" male rowers was 4.77 ($LO_2 \cdot min^{-1}$)[28], while in the men's "heavyweight" rowers, it was 5.57 ($LO_2 \cdot min^{-1}$)[28,45]. Despite the difference between the two categories (0.80 $LO_2 \cdot min^{-1}$), it is essential to consider that the absolute VO_{2max} is evaluated in most cases in this sport[7,53]. Therefore, it is expected that those rowers with higher body mass will reach higher absolute values[7].

Maximal oxygen consumption in rowers

When analyzing and comparing this variable by sex, men presented higher VO_{2max} than women[99,102]. An example of this is the "elite" category, in which men showed a weighted average of 5.46 ($LO_2 \cdot min^{-1}$)[5,14,42,45,66,90,91,93-96,98,99,102-105,107], while women reached 4.24 ($LO_2 \cdot min^{-1}$)[45,89,96,99,102]. These differences between men and women (1.22 $LO_2 \cdot min^{-1}$) can be attributed to the different anthropometric, osteomuscular, cardiovascular, and physiological parameters[44]. In this regard, the most influential factor on VO_{2max} is the lean mass of the rower[44]. This factor generates marked differences in performance between the sexes, including the "elite" category[32,44,46]. Despite this difference between men and women, it is crucial to analyze VO_{2max} in "elite" women[84]. This group of athletes showed a weighted mean of 3.7-4.5 $LO_2 \cdot min^{-1}$, showing a high physical and sporting level[5,84], surpassing the VO_{2max} of men in other categories on several occasions[15,20].

Maximum heart rate in rowers

During the development of this systematic review and meta-analysis, it became evident that men in the "elite" category presented a maximum heart rate of 185 bpm at the end of the tests performed[5,45,97,98,101,103,105], while in the "adult" men's category, the weighted mean was 191.1 bpm[4,18,45,50,51,64,67,68,72,75,77,80]. At the same time, women in the "elite" category had a maximum HR of 190.0 bpm[45], while in the "adult" women's category, the weighted mean was 192.3 bpm[4,40,45,50,69,84]. In this sense, the differences found between the "elite" and "adult" categories, both in men and women, are attributable to a better venous return generated by a better position and execution of the rower's technique in the "elite" category[41]. In relation to this, the literature reports a strong correlation between HR and VO_2 (men: $r = 0.73$; women: $r = 0.57$)[4]. This proportional increase in HR during exercise is due to a compensatory mechanism to increase oxygen supply to the tissues[4]. Indeed, during exercise, there is a close relationship between the ventilatory and circulatory systems[4,27]. Consequently, HR is a good internal loading parameter for training control since different HR values can be associated with different zones of pulmonary ventilation[27].

Aerobic power in rowers

Within the external loads, the rowing ergometer's power is considered a predictor parameter of performance in rowers[74]. In this sense, Bourdin et al.[29] state that the power peak (Ppeak) is a variable that integrates VO_{2max}, rowing efficiency, and the capacity to sustain a power higher than the power corresponding to VO_{2max}. Consequently, the evaluation on the rowing ergometer, when training working power (Ppeak, mean power [Pmean] and MAP) has advantages over other ventilatory tests performed on rowers[28]. Despite the previously stated advantages of the Ppeak, at the end of the search, the number of studies was low compared with studies that used VO_{2max} as the primary outcome[6,77,81]. Likewise, MAP is another external load easy to measure on the rowing ergometer[28,54]. On the one hand, this parameter corresponds to the power obtained at an intensity equivalent to VO_{2max}, while on the other hand, it allows predicting performance in rowers[28]. In both the Ppeak and the MAP, it is essential to consider the weight of the categories and genders since rowers with greater muscle mass generally generate higher power levels[28,81]. In this sense, Bourdin et al.[54] and Bourdin et al.[28] showed that rowers of the "heavyweight" category have higher power levels than the "lightweight" category. This same pattern is shown in men and women (men: 405.2 ± 27.5 vs. 362.9 ± 23.9 W; women: 266.0 ± 26.0 vs. 248.0 ± 15.0 W[28]). Finally, and in the same way as VO_{2max}, all the articles included in this systematic review presented the power in absolute values. For this reason, it is difficult to compare performances in the different categories with this variable.

Tests to assess maximum aerobic capacity in rowers

The most commonly used test to estimate rowing performance in all categories, age groups, and gender is the 2,000-meter rowing test in rowing ergometer[45,50] and, less frequently, the 6-min rowing test in rowing ergometer[5,15,23,24,88,104]. Likewise, incremental tests are the most commonly used to determine VO_{2max} and other associated variables such as HR max, [La] max, and VO_2 peak[30,32,33,40]. The latter protocol shows physiological responses at progressive speeds until exhaustion[19] and, therefore, is helpful as a predictor of performance in the rower of any category[44].

When analyzing by category, it was observed that the most commonly used test in "adults" and "elites" to evaluate VO_{2max} is the 2,000 m rowing test in rowing ergometers[19,25]. This test has its genesis from the first investigations that reported ventilatory parameters in rowers[5]. However, the first ventilatory antecedents reported by Hagerman et al.[5] and Mahler et al.[15] were in a 6-min test. In this sense, we believe that these investigators used the 6-min rowing test for two reasons: first, "elite" rowers can cover 2,000 m (race distance) in less than 6-min, and second, athletes at this level reach VO_{2max} levels in the same period[5,15]. After the studies by Hagerman et al.[5] and Mahler et al.[15], all rowers began to use the 2,000-m test to assess physical performance[19]. In this context, current devices such as Concept2® allow the estimation of VO_{2max} in the 2,000 m test on the rowing ergometer without gas analysis (indirect predictor)[102]. Thus, this standardized test has reported inaccuracies in rowers with lower physical capacity[19]. Therefore, evidence shows that to increase the reliability of the test, the performers should go below 7-min in 2,000 m on the rowing ergometer[20]. However, it is essential to consider that only "elite" rowers, who go under 6-min in the test mentioned above, can reach VO_{2max} before the end of the test[5,15]. Currently, there are some investigations that have proposed the 6-min test as a valid and reliable alternative to estimate MAP and ventilatory thresholds in amateur rowers[23,24]. In fact, Huerta Ojeda et al.[21] suggest that, if rowers are not able to go below 7 min in the 2,000 m test, a test that is a direct function of the rowers' abilities should be performed. Specifically, to determine MAP in beginner and amateur rowers, Huerta Ojeda et al.[21,23,24] suggest the 6-min test.

In the analysis developed in this systematic review, men in the "juvenile" and "junior" categories and women in all categories reported more than 7-min in completing the 2,000 m on the rowing meter (Table 4). Likewise, Silva[117] showed the time taken in the 2,000 m test on the rowing meter by 15,420 rowers of different ages and categories. At the end of the study, the researcher evidenced that only 25% of male rowers aged between 16 and 57 years, both in the "heavyweight" (total n = 6,337) and "lightweight" (total n = 3. 218), was able to complete the test in less than 7-min; also, only 10% of females in the "heavyweight" category (total n = 4,023) and 2% in the "lightweight" category (total n = 1,842), aged 14-70 years for both categories, was able to complete the test in less than 7-min; and only 10% of females in the "heavyweight" category (total n = 4,023) and 2% in the "lightweight" category (total n = 1,842), aged 14-70 years for both categories, could complete the test in less than 7-min[117]. Consequently, the VO_{2max} obtained indirectly through the 2,000-m test on the rowing ergometer, reported in several studies, could present inaccuracies[19,20,22]. Therefore, if coaches need to assess VO_{2max} accurately in rowers with lower physical capacity, it is suggested to use incremental protocols and gas analysis on the rowing ergometer[18,22,26,69,95]. Likewise, and to increase the reliability of the evaluations in rowers with lower physical capacity, some researchers have applied tests with shorter duration[22,94]. In this sense, we believe it would contribute to scientific knowledge that the 6-min test on the rowing ergometer can be further explored in rowers with lower physical capacity[19].

Anaerobic power in rowers

Another of the variables that can condition and determine sports performance through external loads in rowers is the high AP production[33,86]. In this sense, Riechman et al.[52] predicted performance in 2,000 m indoor rowing using a 30 s sprint on the rowing ergometer. At the end of the study, the researchers found that 75.7% of the variation in time was predicted by the Pmean of the Wingate test[52]. Likewise, it has been established that muscle power production depends on both aerobic and anaerobic metabolism, balanced by the rowers' efficiency or technique[8]. Thus, and more frequently, it has been established that power at the anaerobic threshold is an important predictor of rowing test performance[8,86]. Concerning this, Mikulic[86], concluded that those rowers who completed a 6,000 m time trial in the shortest time had strong correlations ($r > 0.5$, $p < 0.05$) with power output at the ventilatory threshold (r = -0.743) and power output at VO_{2max} (r = -0.732).

Strength production in rowing athletes

On the other hand, if we consider that rowing is a sport of high-power production[66] and that power is the product of mass times acceleration[2,107], rowers also require a high capacity to generate force[107]. Consequently, rowers with greater lean mass will be able to achieve a high-power output per stroke, as well as greater fatigue tolerance[66]. In this regard, significant correlations have been found between rowing time and strength variables, both upper and lower limbs[50,60,107,116].

Limitations

A limitation of the study was the presentation of the values of VO_{2max} and MAP in the different investigations selected for the systematic review and meta-analysis. In most cases, these internal and external loads were presented in absolute rather than relative values, making comparisons complex.

Conclusions

The most crucial internal load in rowers is VO_{2max}, being a predictor of physical and sporting performance in this sport. Indeed, rowers with a higher VO_{2max} belong to the "elite" category. Likewise, within the same category, men showed a higher VO_{2max} than women.

The most used test to estimate VO_{2max} is the 2,000 m test on the rowing ergometer. This test has the same distance as the regattas (2,000 m), is easy to perform, and is reliable for rowers under 7-min (elite and adult categories). However, this test has low reliability in athletes with lower physical capacity. In the latter case, exploring tests with a shorter duration (6-min on the rowing meter) is suggested.

Practical applications

For coaches who train rowers, we recommend considering the following aspects:

- Consider the running time in the 2,000-m test on the rowing ergometer. If the rower can lower the 7-min, we suggest an evaluation of VO_{2max} through gas analysis.
- If the rower cannot lower the 7-min, the VO_{2max} estimation has low reliability. In this case, it is suggested that coaches explore tests according to the physical capabilities of the rowers (6-min on the rowing ergometer.
- Within the possibilities, it is recommended to obtain values in competitions or in open environments, mainly because the existing data, almost entirely, has been obtained in controlled laboratory environments.

Funding

This research received no external funding.

Conflicts of interest

There was no conflict of interest in conducting this study.

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Supplementary material

Figure S1 - Risk of bias summary: review authors' judgements about each risk of bias item for each included study.

Corresponding author

Álvaro Huerta Ojeda. Universidad de Las Américas, Núcleo de Investigación en Salud, Actividad Física y Deporte, Viña del Mar, Chile.
E-mail: achuertao@yahoo.es.

Manuscript received on December 5, 2023
Manuscript accepted on August 16, 2024