

Reliability of the Maximal Lactate Accumulation Rate in Rowers



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ABSTRACT

The maximal lactate accumulation rate (VLamax) has been linked to lactic anaerobic performance. Hence, accurate and reliable assessment is crucial in sport-specific performance testing. Thus, between-day reliability data of rowing-specific VLamax assessment was examined. Seventeen trained rowers (eight females and nine males; 19.5 ± 5.2 yrs; 1.76 ± 0.08 m; 70.2 ± 8.9 kg; $\dot{V}O_{2\max}$: 54 ± 13 ml/min/kg) performed 20-s sprint tests on two separate days (one week apart) on a rowing ergometer. VLamax, peak lactate concentration, time to peak lactate, and mean rowing power were measured. Good to excellent intraclass correlation coefficients (ICCs), low standard error of measurement (SEM), and acceptable levels of agreement (LoAs; 90% confidence interval) for VLamax (ICC = 0.85; SEM = 0.02 mmol/L/s; LoA ± 0.09 mmol/L/s), peak lactate (ICC = 0.88; SEM = 0.3 mmol/L; LoA ± 1.4 mmol/l), time to peak lactate (ICC = 0.92; SEM = 0.1 min; LoA ± 0.5 min), and mean rowing power (ICC = 0.98; SEM = 3 W; LoA ± 39 W) were observed. In addition, VLamax was highly correlated ($r = 0.96$; $p \leq 0.001$) to rowing power. Thus, VLamax and sprint performance parameters can be measured highly reliably using this sport-specific sprint test in rowing.

Introduction

Aerobic or oxidative capacity is considered the major contributor to rowing performance [1]. Depending on boot class, race length and discipline, the proportion of anaerobic metabolism to rowing performance is estimated to vary between 20 to 30% [1, 2]. Since

2000-m rowing has been cut to a distance of 1500 m meters in advance of the 2028 Olympic Games in Los Angeles, the relevance of anaerobic performance testing and training attracted notable attention in rowing exercise science, physiology, and coaching [3]. Consequently, it is vital for athletes and coaches to accurately and

reliably measure not only aerobic capacity but also anaerobic performance parameters [4]. Besides a variety of different approaches to assess anaerobic capacity (maximal accumulated oxygen deficit (MAOD) [5], W prime, gross efficiency, anaerobic speed/power reserve [6]) in running, swimming [7], triathlon, and cycling, the Wingate (sprint) test can still be regarded as the most frequently investigated and applied framework to determine anaerobic capacity [8]. So far, only one study on power and velocity profiling has been conducted in young rowers over a distance of 1500 m [9].

Within the last three years, the maximal lactate accumulation rate (VLamax) and its impact on anaerobic capacity has regained scientific attention within sprint testing [10, 11]. VLamax is calculated as the maximum difference in lactate levels before and after short maximal sprints, divided by the duration of the sprint [10, 11]. Importantly, a defined period of alactic energy supply, as a time constant during which lactate is not produced, is considered in this calculation to ensure an accurate representation of lactate dynamics [10, 11]. However, anaerobic performance testing conducted with short tests commonly ranging between 10 and 30 seconds is genuinely challenging from a methodological perspective. Besides motivational aspects, objective, precise, and reliable (absolute and relative) testing procedures need to be established and followed. Therefore, an appropriate estimate of absolute and relative reliability are mandatory (i. e., the quantification of baseline variability of a given variable due to system-immanent errors and/or biological variability) [12]. These methodological requirements affect study design conceptions and are of even more importance in a (sub) elite setting with only a small remaining margin of gains [13]. If a primary endpoint would not be measurable with very high reliability indices (very high intraclass correlation coefficient (ICC) and sufficient level of agreements, less variability) [4], meaningful acute or chronic performance changes cannot be detected reliably. Worthwhile changes of a given variable induced by an intervention rather than due to its variation (biologically or even by chance) can only be estimated precisely if absolute and relative reliability are high [14]. As described earlier, VLamax [10, 11] parameters might be a promising approach for assessing anaerobic parameters in rowing.

Against this background, the current study aimed to investigate the variability of anaerobic parameters during rowing sprint testing in trained rowers. Therefore, the between-day reliability (i. e., with a one week separation) was examined. We hypothesize that the corresponding anaerobic parameters demonstrate sufficiently robust reliability indices to be applicable in sports practice. This study delivers important information that allows the interpretation of acute or training-induced changes of anaerobic surrogate parameters in rowing.

Materials and Methods

In this controlled crossover reliability test, trained female ($n = 8$; 17.7 ± 2.2 yrs; 1.71 ± 0.04 m; 64.4 ± 6.1 kg; maximal oxygen uptake ($\dot{V}O_2\text{max}$): 46 ± 15 ml/min/kg) and male ($n = 9$ rowers; 21.3 ± 6.7 yrs; 1.82 ± 0.06 m; 76 ± 7.3 kg; $\dot{V}O_2\text{max}$: 61 ± 7 ml/min/kg) participated (total sample size: $n = 17$). Corresponding participants were categorized as lightweight ($n = 9$) and heavyweight rowers ($n = 8$). Each participant was at least 16 years old, completed at least six weekly training sessions, had competed in rowing competitions for at least four years, and had no history of skeletal or neuromuscular impair-

ments within the previous six months. The performance level of the participants ranged from the regional to national level. Based on the $\dot{V}O_2\text{max}$ data, both the female and male participants were classified as trained rowers. All participants were familiar with the necessary tools, the testing process, and the corresponding exercises prior to this study. For subjects under 18 years old, informed consent was obtained from their parents or responsible individuals. The study protocol met all international ethical standards and complied with the Declaration of Helsinki. In addition, the study received approval from the German Sport University Research Ethics Committee (No. 079/2022).

The participants performed two 20-s all-out rowing sprint tests separated by one week (T1 and T2). All measurements were made at comparable times of day for each participant in order to account for potential circadian effects on performance. In addition to the period of day, temperature and humidity in the testing environment were kept constant. Furthermore, all measurements were conducted during the pre-season. Participants completed a standardized low-intensity warm-up of 10 minutes at a low intensity/heart rate (corresponding to a blood lactate concentration of 2 mmol/L) before the 20-second all-out tests, followed by five minutes of passive rest while seated. The participants were given the directive to produce the most power possible during each measurement trial. During sprint trials, the rowing ergometer's flywheel was still when the measurements began. Participants were free to choose their preferred stroke frequency. The mean rowing power of the 20-s all-out tests was used for further analyses. On the second lab visit, $\dot{V}O_2\text{max}$ testing was performed 30 min after the 20-s sprint test. Briefly, $\dot{V}O_2\text{max}$ data were collected using a breath-by-breath spirometric system (Zan Oxi 600; Zan Messgeräte, Oberthulba, Germany) applying a ramp-like test protocol (25–40 W/min increase, depending on the performance level of participants). For this ramp-like testing, athletes manually increased their power every 30 s in accordance with their specified recommendations. The spiroergometric system was calibrated prior to each test following the manufacturer's recommendations. The highest consecutive oxygen uptake values averaged over 30 seconds were considered as $\dot{V}O_2\text{max}$. $\dot{V}O_2\text{max}$ and objective exhaustion were verified following the criteria by Midgley and colleagues [15]. All subjects fulfilled these prerequisites for objective exhaustion. Furthermore, all athletes were verbally encouraged and motivated during all testing procedures. A wind-braked rowing ergometer (Model D; Concept2, Morrisville, VT, USA) equipped with a PM5 monitor was used for all tests (Concept2). In accordance with the requirements of the national rowing federation, the rowing ergometer was calibrated with a drag factor of 145 mg/m².

Blood lactate concentration was measured via capillary blood samples from the right earlobe (Biosen C-Line; EKF Diagnostics GmbH, Barleben, Germany) before and after the all-out exercise tests as well as every minute after exercise for 15 minutes. VLamax was calculated by dividing the difference between the test time and the time at the start of exercise for which no lactate formation is assumed (alactacid duration) [10, 16, 17]. Based on a previous simulation, the alactacid duration was defined as 4 s in a 20-s test duration [16]. In addition to these calculated VLamax values, time to post-exercise lactate peak and peak lactate were included in further analyses.

All data are presented as the group mean \pm standard deviation. Normal distribution of VLamax, peak lactate, time to peak lactate, and mean 20-s rowing power data was verified by Shapiro–Wilk tests ($p \geq 0.10$). In addition, variance homogeneity was visually verified by plotting the residuals. Several paired t-tests (day 1 vs. day 2) were computed separately for the mean 20-s test power, VLamax, peak lactate, and time to peak lactate as primary outcome measures. Furthermore, sex differences for the mean 20-s test power, VLamax, peak lactate, and time to peak lactate data were examined via independent t-test (female vs. male). Standardized mean differences as a measure of pairwise effect size estimation were calculated (SMD; trivial: $|SMD| < 0.2$; small: $0.2 \leq |SMD| < 0.5$; moderate: $0.5 \leq |SMD| < 0.8$; large $|SMD| \geq 0.8$) [18]. The agreement of the between-day reliability was analyzed by calculating the systematic bias (mean difference between measurements) and the limits of agreement (LoA: $1.65 \times$ standard deviation of the difference between both tests), considering a 90% random error component [4] and by plotting Bland–Altman plots [19]. Standard error of measurement (SEM) and intraclass correlation coefficients (ICCs) were calculated [4]. The SEM was calculated by multiplying the standard deviation of the differences between the two sets of meas-

urements ($SD_{\text{difference}}$) with the square root of one minus the ICC [4]. ICC(2,1) were calculated as random effect variance divided by the total variance, i. e., the sum of the random effect variance and the residual variance [20]. In addition, ICCs were rated as excellent (0.9 to 1), good (0.74 to 0.9), moderate (0.4 to 0.73), and poor (0 to 0.39) [21]. The statistical analyses were conducted using R (version 4.0.5) and RStudio (version 1.4.1106) software. Statistical significance was set at $p < 0.05$.

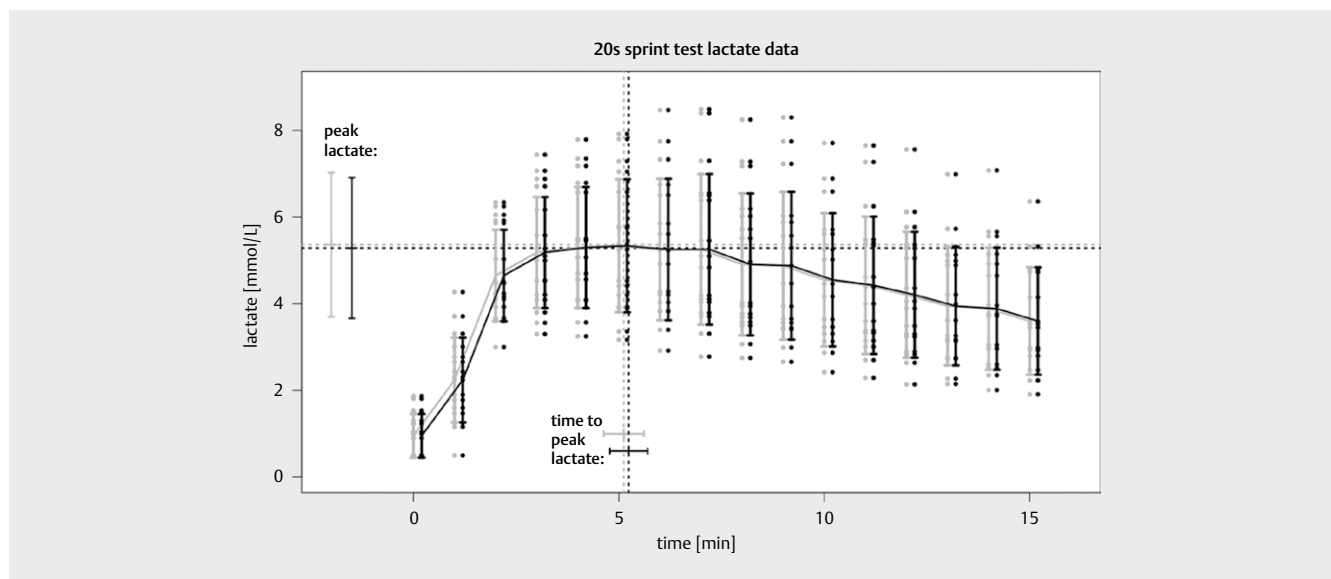
Results

The paired t-test revealed no significant difference ($p \geq 0.11$; $SMD \leq 0.25$) between both testing days for VLamax, peak lactate, time to peak lactate, and mean 20-s rowing power data. In addition, SEM and LoA were low for VLamax, peak lactate, time to peak lactate and mean 20-s rowing power data (see ► **Table 1**). Furthermore, ICCs can be classified as good to excellent for all output parameters. VLamax and lactate-time relation are described in ► **Fig. 1**. Bland–Altman plots are displayed in ► **Fig. 2** (A–D). Corresponding correlations between VLamax, peak lactate, time to peak lactate and mean 20-s rowing power data are displayed in ► **Fig. 3**.

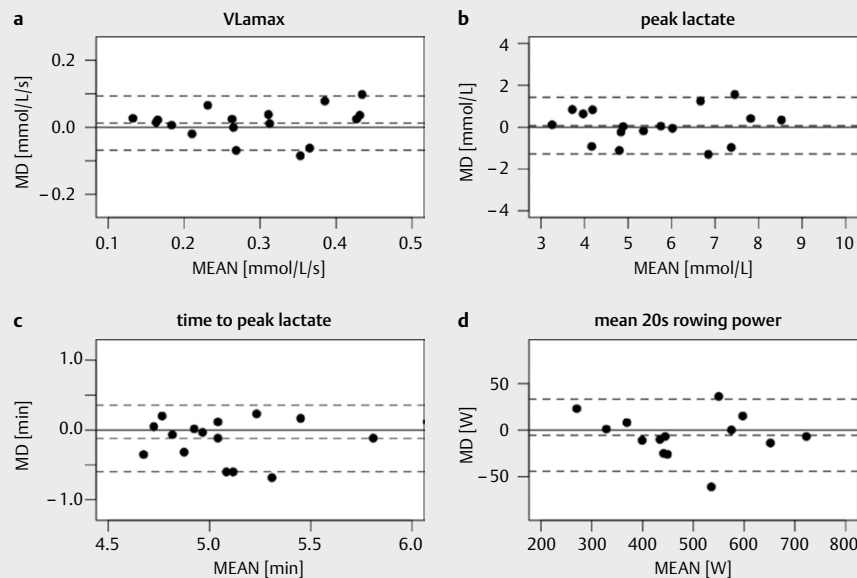
► **Table 1** Between-day reliability indicators for VLamax, peak lactate, time to lactate peak, and mean 20-s rowing power data.

Parameter	Mean \pm SD	MD \pm SD	SEM [95%CI]	ICC [95%CI]	LoA
VLamax	Day 1: 0.29 ± 0.11 mmol/L/s; Day 2: 0.28 ± 0.10 mmol/L/s	0.02 ± 0.05 mmol/L/s	0.02 [0.01 to 0.02] mmol/L/s	0.85 [0.65 to 0.94]	0.09 mmol/L/s
Peak lactate	Day 1: 5.7 ± 1.7 mmol/L; Day 2: 5.6 ± 1.6 mmol/L	0.1 ± 0.8 mmol/L	0.3 [0.2 to 0.4] mmol/L	0.88 [0.7 to 0.95]	1.4 mmol/L
Time to peak lactate	Day 1: 5.1 ± 0.5 min; Day 2: 5.2 ± 0.5 min	-0.1 ± 0.3 min	0.1 [0.1 to 0.2] min	0.80 [0.53 to 0.92]	0.5 min
Mean 20-s rowing power	Day 1: 481 ± 126 W; Day 2: 486 ± 129 W	-6 ± 24 W	3 [2 to 5] W	0.98 [0.95 to 0.99]	39 W

MD, mean difference; SD, standard derivation; SEM, standard error of measurement; ICC, intraclass correlation coefficient; 95%CI, 95% confidence interval; LoA, limits of agreement as 90% confidence interval.



► **Fig. 1** Lactate data of first (black) and second (grey) lab visit. In addition, peak lactate and time to peak lactate values were given. Overall, mean \pm standard deviation are given for each value. In addition, individual values are given as points.



► **Fig. 2** Bland–Altman plots with levels of agreement as 90% confidence intervals (MD: mean difference between both devices; MEAN: average of both days) for VLamax (a), peak lactate (b), time to peak lactate (c), and mean 20-s rowing power (d) data.

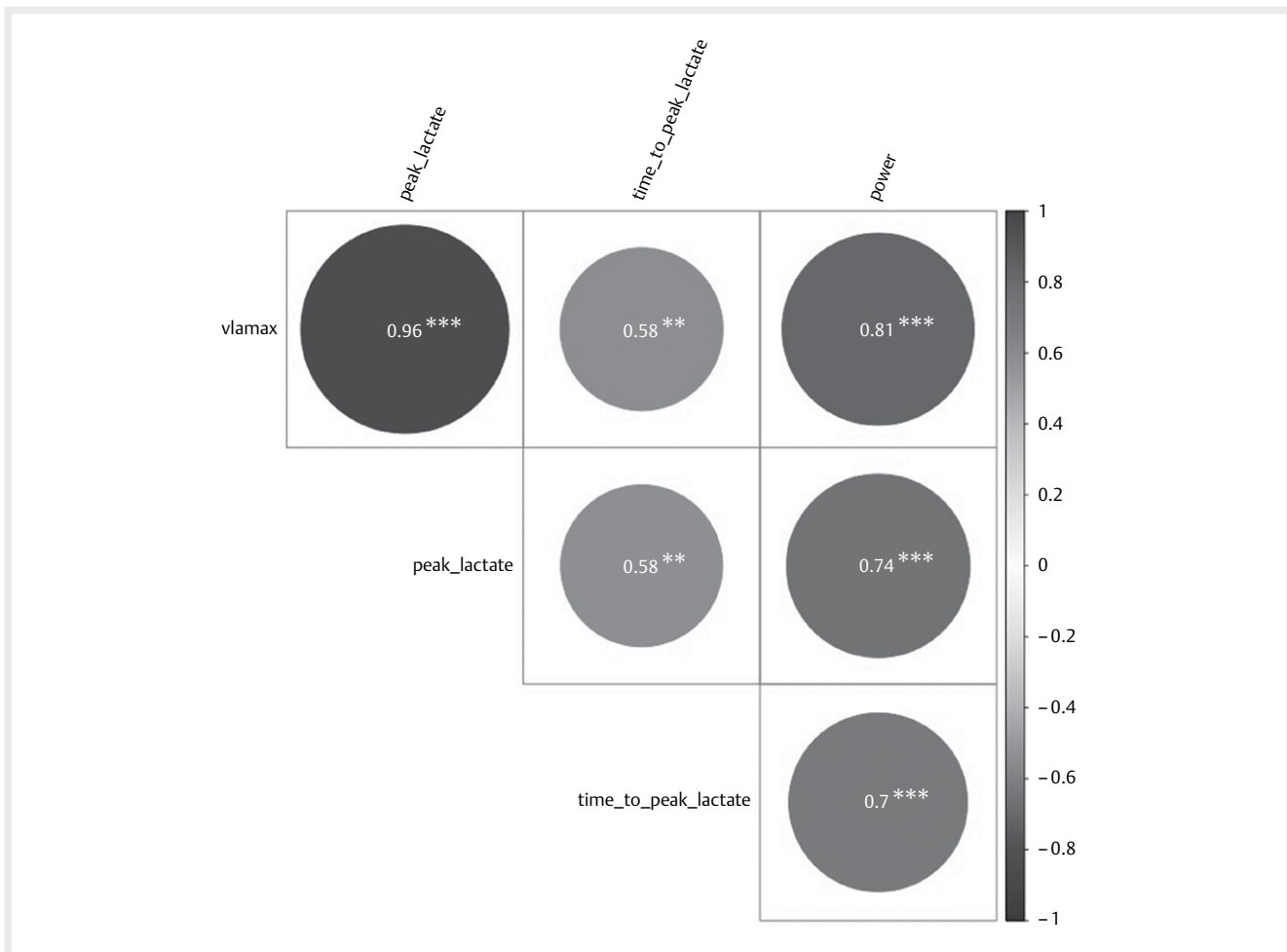
Regarding sex differences, female rowers revealed significant lower VLamax ($p=0.011$; $SMD=1.42$; female: 0.23 ± 0.06 mmol/L/s vs. male: 0.35 ± 0.1 mmol/L/s), peak lactate ($p=0.013$; $SMD=1.40$; female: 4.5 ± 0.9 mmol/L vs. male: 6.5 ± 1.8 mmol/L), and mean 20-s rowing power ($p=0.001$; $SMD=1.27$; female: 387 ± 74 W vs. male: 578 ± 94 W) data compared to male rowers. Time to peak lactate revealed non-significant ($p=0.058$; $SMD=0.99$) differences between female (5.0 ± 0.3 min) and male (5.4 ± 0.5 min) rowers.

Discussion

The primary objective of the present study was to analyze the variability of anaerobic parameters during rowing sprint testing in trained rowers. This is the first study that assessed between-day reliability data of VLamax testing in trained rowers. The findings highlighted an excellent intraclass correlation and a low standard error of measurement, revealing good to excellent between-day reliability for VLamax, peak lactate concentration, time to peak lactate concentration, and mean rowing power over 20-s sprint testing. Further, our results demonstrated sufficient levels of agreement for detecting chronic performance developments and high correlations between VLamax and rowing power. This suggests that VLamax could be a promising parameter for anaerobic lactic power testing. In conclusion, the sport-specific sprint test employed in this study allows for highly reliable and sensitive measurement of VLamax and sprint performance parameters in rowing, thus providing a robust tool for diagnosing adaptations in glycolytic anaerobic performance.

High reliability indices of VLamax testing in rowing are in line with previous research in cycling [22, 23], hand cycling [23], and running [10, 11]. Thereby, running ($ICC > .9$) [10], cycling ($ICC > .87$) [22, 23] and hand cycling ($ICC > .83$) [23] revealed similarly high ICC data as this rowing-related finding. In addition,

the level of agreements of VLamax testing in running (0.144 mmol/L/s) [10], cycling (0.11 mmol/L/s) [22], and hand cycling (0.15 mmol/L/s) [23] are slightly higher compared to rowing. Based on these findings, the between-day reliability of VLamax testing in rowing can be classified as comparatively high. In addition, our findings revealed high reliability indices for peak lactate, time to peak, and mean rowing power over the 20-s sprint. These findings are in line with a high ICC (> 0.9) for peak lactate during running VLamax testing [10] and ($ICC > 0.9$) mean power output during cycling VLamax testing [11]. Furthermore, our data revealed lower VLamax values (0.3 ± 0.1 mmol/L/s) compared to running (0.8 ± 0.2 mmol/L/s) [10] and cycling (0.7 ± 0.1 mmol/L/s) [22]. In addition, peak lactate concentration post-VLamax testing during running (9.3 ± 1.6 mmol/l) [10] and cycling (7.2 ± 0.6 mmol/l) [11] were noticeably higher compared to observed rowing related peak lactate values in our data (5.7 ± 1.7 mmol/l). Overall, these findings suggest that the VLamax is discipline-specific and that there are corresponding differences between rowing, cycling, running, and hand cycling. Via repeated crossover testing, previous research revealed higher VLamax values in cycling compared to hand cycling [23] and running compared to cycling [11]. The researchers [11, 23] speculated that these increased VLamax values are probably related to increased activated muscle mass during cycling and running (compared to hand cycling and cycling, respectively) [24, 25]. Based on increased activated muscle mass during rowing compared to running, cycling, and hand cycling [26], lower VLamax values in rowing cannot be explained by this assumption. Furthermore, a direct comparison between rowing and cycling provided evidence that the maximal lactate steady state decreases with increasing muscle mass engaged [27, 28]. Corresponding lower VLamax values in rowing compared to running, cycling, and hand cycling might be linked to different movement frequencies. While rowing can achieve up to 50 strokes per minute, running, cycling, and hand cy-



► **Fig. 3** Correlation matrix for VLamax, peak lactate concentration, time to peak lactate and mean rowing power over 20-s sprint test. Pearson correlations r and corresponding p -values (**: $p \leq 0.01$; ***: $p \leq 0.001$) are given.

cling can achieve more than 100 rotations or steps per minute [29]. These significantly lower movement frequencies in rowing might be responsible for lower VLamax values in rowing compared to running, cycling and hand cycling. Apart from this, differences between rowing, running, cycling, and hand cycling might be due to sport-specific muscle recruitment, conditions, and the participants' training background in the particular modality. Furthermore, non-significant and only moderate correlations between cycling and hand cycling ($r = 0.46$; $p = 0.06$) [23] and between running and cycling ($r = 0.42$; $p = 0.08$) [11] were observed. Since VLamax does not correlate between different sport disciplines, it should thus be determined specific to the sport [11, 23] and extremity [23]. VLamax differences between rowing, running, cycling, and hand cycling remain speculative, as these have not been directly measured and compared with each other. Corresponding crossover measurements should be examined in future research.

A significant relationship between rowing sprint power and measures of lactate response was observed in our data. The significant correlation between VLamax and mean rowing power over a 20-s sprint is in accordance with previous research in running [10, 30], cycling [11], and hand cycling [23]. Thereby, VLamax revealed a significant and high correlation to the 100-m running time

[10, 30], cycling sprint power [11], and hand cycling sprint power [23], respectively. These correlations might be linked to the turnover of adenosine triphosphate in non-oxidative glycolysis, which determines the rate of lactic metabolism [31]. Previous research concluded that this qualifies VLamax as a promising parameter of anaerobic lactic power testing in running [10, 30], cycling [11], and hand cycling [23]. Accordingly, it can be assumed that training-induced adaptations of the glycolytic anaerobic performance can be diagnosed sensitively via VLamax. These interactions should be investigated in future rowing-specific research.

A limitation of the current study is that the resulting VLamax values cannot yet be interpreted. As indicated above, rowing seems to result in reduced VLamax values compared to other sports disciplines. However, corresponding direct comparative measurements between rowing and other sports disciplines are currently still lacking. It is also not yet known how VLamax values in rowing respond to training intervention. Previous research revealed training-induced changes of VLamax in swimming [32], cycling [33], and running [17]. In detail, high intensity interval swimming [32] and cycling sprint interval training [33] induced increases in VLamax. In contrast, long low intensity running [17] and high volume swim training [32] induced a VLamax reduction. Correspond-

ing rowing-related evidence is currently not available. However, these aspects were not the focus of this current research. Before sport discipline-specific comparison or training interventions are implemented, the reliability of the testing procedure used needs to be examined [4]. Accordingly, these current results provide the foundation for further research in the field of the rowing-specific VLamax. Apart from this, future research should also target the comparison of the VLamax concept with other anaerobic performance models like the critical power [34] or anaerobic speed/power reserve [6] concept. Apart from this, participants of both sexes of different levels of performance were included (i. e., high variance between subjects), which may lead to an overestimation of the ICC values [35]. Furthermore, our data revealed lower VLamax, peak lactate and mean sprinting power values for female compared to male rowers. These differences might indicate a potential disparity in anaerobic performance or capacity. However, these observations are preliminary, and future research is necessary to fully elucidate the underlying causes and implications of these differences. Specifically, it would be valuable to investigate whether these disparities are due to inherent physiological differences between sexes or potentially modifiable factors such as training regimen, equipment use, or technique.

In summary, (i) the VLamax testing procedure in rowing revealed an excellent intraclass correlation and low standard error of measurement for between-day reliability of VLamax, peak lactate concentration, time to peak lactate concentration, and mean rowing power over 20-s sprint testing; and (ii) the levels of agreement were sufficiently low for detecting chronic performance developments. Furthermore, (iii) high correlations between VLamax and rowing power indicated that VLamax might be a promising parameter of anaerobic lactic power testing. In conclusion, VLamax and sprint performance parameters can be measured with high reliability and sensitivity using this sport-specific sprint test in rowing, which enables a highly reliable and sensitive diagnostic tool of glycolytic anaerobic performance adaptations.

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Conflict of Interest

The authors declare that they have no conflict of interest.

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