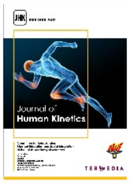

Strength and Aerobic Determinants of 2000-m Rowing Ergometer Performance: Comparative Analysis of Expert versus Novice Rowers

by

Xinyu Dai [1], Jihong Yan [2,], Xuecui Bi [3]*

This study aimed to establish a strength assessment framework for weight room training and identify key strength and aerobic determinants of rowing-specific performance, with particular focus on power, lower-body strength, upper-body pulling strength, and maximal oxygen uptake. Forty-three male open-weight rowers were stratified into expert and novice groups. Participants completed a 2000-m time trial on Concept2 rowing ergometers, VO_{2max} testing, and 1RM assessments for four compound lifts. Split power output and total completion time were recorded. The power clean and the back squat strongly correlated with average power ($r = 0.50$–0.69) and negatively with 2000-m time ($r = -0.47$ to -0.62) ($p < 0.05$). The bench pull showed moderate correlation with first 500-m power ($r = 0.43$–0.47), but not overall performance. Notably, the power clean correlated more strongly with ergometer performance in experts, whereas the back squat showed higher associations in novices. For aerobic capacity, absolute VO_{2max} correlated better with performance in experts, while relative VO_{2max} had stronger associations in novices. The power clean and the back squat 1RM emerged as cornerstone metrics for rowing strength assessment, requiring experience-specific interpretation. VO_{2max} remained a critical performance predictor. We recommend integrating periodized strength testing with sport-specific training while investigating the synergistic development of power and aerobic capacity. These findings provide practical guidance for implementing free-weight training to evaluate and enhance rowing-specific strength. Given the repeated power demands of 2000-m racing, future research should incorporate multi-load strength testing or develop specialized strength assessments to improve ecological validity.

Keywords: *performance determinants; strength and conditioning; bench pull; maximal oxygen uptake; free weights*

Introduction

Rowers routinely engage in both strength and aerobic training, which are critical for enhancing racing performance (Smith and Hopkins, 2012). Given that on-water competitions are susceptible to weather and hydrological conditions, coupled with the logistical challenges and financial burdens of water-based monitoring, the 2000-m rowing ergometer test has become the standard indoor method for evaluating athletic performance (Cerasola et al., 2022). This approach provides more reliable assessment of performance changes while controlling for confounding variables. Among various determinants, race tactics, strength capacity, maximal oxygen uptake (VO_{2max}), and anthropometric characteristics (e.g., body mass and height) significantly influence test outcomes (Cerasola et al., 2016; Legge et al., 2023). Notably, strength development cannot be adequately achieved through rowing training alone but requires specialized resistance training (Lawton et al., 2013), given its substantial correlation with rowing performance. This relationship stems from the biomechanical characteristics of rowing—a highly coordinated cyclic movement comprising

[1] *Physical Education Department, Xiamen University of Technology, Xiamen, China.*
[2] *Physical Education College, Jimei University, Xiamen, China.*
[3] *College of Physical Education and Training, Capital University of Physical Education and Sports, Beijing, China.*
* Correspondence: jihongyan@jmu.edu.com

two distinct phases: the recovery phase and the drive. The drive phase in particular relies heavily on explosive lower-body, core, and upper-body strength to maximize force transfer through the oar, and movement patterns demonstrate significant biomechanical correspondence with specific strength exercises (Cataldo et al., 2014). Therefore, developing strength is essential not only for enhancing power output but also for improving movement efficiency and injury resilience throughout the rowing cycle.

The drive phase, which generates primary propulsion, initiates from the catch position where the rower's hip, knee, and ankle joints attain maximal flexion, resembling the bottom position of a squat. Subsequently, explosive lower limb extension (primarily driven by quadriceps) propels the seat backward while the trunk extends (layback position). This kinetic chain mirrors the concentric phase of squats (knee extension) and hip extension mechanics in deadlifts. Electromyographic (EMG) studies reveal that increased rowing intensity elevates activation in the rectus femoris and vastus medialis (Fleming et al., 2014), demonstrating similar muscle recruitment patterns to squat and deadlift exercises. During the late drive phase, completion of the stroke through trunk extension and arm flexion relies on coordinated contraction of the latissimus dorsi, erector spinae, and biceps brachii muscles. The bench pull exercise effectively replicates this kinetic pattern by emphasizing scapular retraction and elbow flexion, closely mimicking the "finish" portion of the rowing stroke. EMG analyses indicate that elite rowers exhibit higher integrated EMG (iEMG) values in the latissimus dorsi during bench pulls (Robbins, 2010), showing significant positive correlation with late drive phase mechanics during on-water rowing. While isometric multi-joint testing represents the most precise method for assessing maximal and rapid force development capacity (Comfort et al., 2019), the 1-repetition maximum (1RM) test remains the most practical and widely implemented measurement. It provides rowers with a valid, reproducible assessment of strength progression while enabling longitudinal comparisons. Therefore, 1RM testing for bench press, deadlift, and power clean exercises offers appropriate strength evaluation.

Previous research has established the 1RM squat (Folk et al., 2022), the 1RM bench pull (Pérez-Castilla et al., 2023), the 1RM power clean, and the bench press (Behm, 2025) as valid strength metrics for rowers. However, controversy persists regarding the relative contributions of upper- versus lower-body strength to ergometer time trial performance. Although power cleans and bench pulls activate similar muscle groups, their distinct force-velocity profiles raise questions about which better predicts ergometer performance. Furthermore, training experience significantly modulates the development of maximal strength and aerobic capacity, resulting in differential predictive value of these metrics when comparing expert versus novice rowers' ergometer performance (Kendall et al., 2011). This variability complicates the interpretation of training efficacy. Elucidating the relationships between upper- and lower-body strength measures and various ergometer performance tests will facilitate a more effective strength and conditioning program design. Notably, aerobic capacity remains a crucial determinant—potentially the single best predictor of 2000-m ergometer performance (Secher, 1983). This consideration gains particular relevance with the 2028 Los Angeles Olympics reducing race distance to 1500 m, where maximizing initial 500-m power output will become increasingly decisive. Therefore, this study aimed to investigate the relationships among maximal strength, particularly as demonstrated in bodyweight exercises such as squats, deadlifts, and bench presses, VO_{2max}, and performance in both the 2000-m ergometer test and initial 500-m average power among male rowers with diverse training backgrounds. The inclusion of these fundamental strength movements was motivated by their biomechanical correspondence to the kinetic chain and force generation pattern characteristic of the rowing drive phase.

Methods

Experimental Approach to the Problem

This study employed a cross-sectional design to examine the relationships among 2000-m rowing ergometer performance and key indicators of maximal strength, power output (as a measure of starting capability) and aerobic capacity. Data collection was conducted across three sequential sessions: during the first and second sessions maximal strength and power output were assessed, the third session involved the 2000-m rowing ergometer performance test, and during the third session, VO_{2max} on a rowing-specific ergometer was determined. A 48-h recovery period separated each testing session, during which participants abstained from supplementary strength training. Since all testing protocols were routinely incorporated into the athletes' national team preparation regimen, no additional familiarization trials were deemed necessary beyond standardized warm-up procedures.

Participants

Forty-three male competitive rowers were stratified into two cohorts: an expert group (n = 22; training experience >5 years; age 23.4 ± 1.8 years; stature 1.94 ± 0.04 m; body mass 97.48 ± 5.67 kg; body fat content 12.15 ± 3.31%) and a novice group (n = 21; 3–5 years of training experience; age 20.4 ± 1.8 years; stature 1.90 ± 0.06 m; body mass 86.27 ± 8.56 kg; body fat content 12.23 ± 3.42%).

An a priori power analysis (G*Power 3.1) indicated a minimum sample size of 21 participants per group to achieve 80% statistical power (α = 0.05, effect size = 0.5) for detecting between-group differences. Participants provided written informed consent after attending an orientation session and were instructed to: (1) maintain a 3-h fast prior to testing, (2) abstain from caffeine and alcohol for 48 h before testing, and (3) avoid strenuous exercise during the 48-h pretest period.

This study was conducted in accordance with the principles of the Declaration of Helsinki and was approved by the Ethics Committee of the Capital University of Physical Education and Sports, Beijing, China (approval code: 2025A015; approval date: 11 January 2025). Medical clearance verified all participants as medically fit for intensive training prior to testing.

Procedures

Warm-Up

All participants commenced with a standardized warm-up, which included 5 min of steady-state rowing at 50–60% of their perceived maximum effort. This was followed by a series of dynamic stretching exercises and individualized muscle activation routines. Additionally, prior to each specific test, a standardized, task-specific warm-up was conducted. This tailored warm-up was designed to meet the demands of the subsequent assessment and included progressively intense practice repetitions or intervals. The physical performance testing protocol for rowers in this study was completed over five days, with tests systematically arranged to separate strength and endurance assessments. The detailed schedule was as follows:

Day 1: Squat (1RM) and bench pull (1RM) tests.

Day 2: Bench press (1RM) and power clean (1RM) tests, with a 48-h recovery period between strength testing sessions to ensure adequate muscular recovery (consistently with prior research on strength testing intervals).

Day 3: 2,000-m rowing ergometer time trial, conducted 48 h after the final strength test.

Day 5: Maximal oxygen uptake (VO_{2max}) test, performed 48 h after the 2,000-m trial.

This testing sequence was designed in accordance with established international research protocols (Kendall et al., 2011; Ledergerber et al., 2023), ensuring sufficient recovery between assessments (48 h for strength tests, 48 h for endurance tests) while minimizing interference between different energy system evaluations. The schedule adhered to standard exercise physiological testing guidelines. All tests were conducted under consistent environmental conditions and administered by the same research team. Testing sessions were uniformly scheduled between 8:00 and 10:00 AM to control for diurnal variation.

Deep Squat

Prior to the 1RM back squat assessment, athletes adjusted the squat rack hooks to clavicle level with safety bars positioned slightly below the anticipated lowest squat depth. The testing protocol required participants to stand with feet shoulder-width apart under the barbell, employing a closed grip (slightly wider than shoulder width) with the bar positioned on the upper trapezius or below the scapular spine while maintaining core engagement and spinal neutrality. The movement was initiated with controlled hip and knee flexion until the thighs reached parallel to the ground (or hip crease below knee level), followed by simultaneous hip and knee extension to full leg straightening. Warm-up phases utilized progressive loading (50%, 70%, and 90% of estimated 1RM) with 3–5 repetitions per set. During formal testing, successful attempts were followed by 5–10% load increments with 3–5-min rest intervals. Failed attempts triggered 2–5 kg load reductions for subsequent trials. Testing concluded when participants could no longer maintain proper form (e.g., knee valgus or excessive torso lean), with spotters recording the last successfully lifted load as 1RM. Through systematic load adjustments, participants typically established their 1RM within five attempts.

Bench Pull

The bench pull movement mimics the pulling phase of rowing stroke mechanics (McNeely, 2005). Participants performed this bilateral assessment on a standardized bench pull apparatus, positioned prone with arms fully extended. The barbell height was adjusted via padding according to individual arm length. Following verbal cueing, participants executed concentric arm flexion against weighted resistance from full extension to complete flexion (bench contact). The warm-up consisted of one set of 5 repetitions at 40–60% of the estimated maximum load. Subsequently, 5–6 isolated attempts were performed until failure to achieve required flexion. The highest successfully maintained load was designated as 1RM, with 3-min inter-trial rest periods.

Bench Press

For the 1RM bench press evaluation, the bench was leveled with rack hooks adjusted to allow safe barbell handling at full arm extension. Participants assumed a supine position with feet flat on the floor, maintaining head, shoulder, and hip contact with the bench. Using a closed grip (approximately 1.5 times shoulder width), the barbell was positioned directly above the sternum. The movement involved controlled descent to chest contact (75° elbow-to-torso angle), brief pause, and vertical press to full arm extension. Progressive warm-up loads (50%, 70%, 90% estimated 1RM) were applied in 3–5 repetition sets. Formal testing involved 2.5–5-kg increments after successful attempts (3–5-min rest intervals), with 2–5-kg reductions following failures. Termination criteria included technical breakdowns (incomplete chest contact, buttock lift, or partial extension), with the final successful load recorded as 1RM. Two spotters monitored all trials, permitting only chalk use while prohibiting supportive gear to ensure data validity.

Power Clean

The 1RM power clean assessment employed free weights with the barbell positioned 5–8 cm from the mid-tibia at the starting position. Participants adopted a hip-width stance with slight toe abduction (~15°) to optimize jumping mechanics. The movement was initiated with a hook grip (1.5 x shoulder width), maintaining spinal neutrality, thoracic extension, and scapular retraction, while hip height was individualized based on femur/torso proportions. The three-phase movement (first pull, transition, catch) was performed using a step-loading protocol. After the warm-up (3 sets at 75–90% predicted maximum), 2.5-kg increments were added with 3-min rest intervals between subsequent attempts. Testing concluded after two consecutive failures to meet technical standards (incomplete clavicle contact, insufficient catch depth, or compensatory torso lean), with the last successful lift designated as 1RM. Only chalk was permitted to enhance grip reliability, with lifting belts prohibited to eliminate intra-abdominal pressure confounding effects.

VO_{2max}

After a 48-h recovery period, participants underwent a maximal oxygen uptake test using a 7-stage incremental protocol on a Concept2 rowing ergometer. The test commenced at 150 W with 50-W increments every 3 min until volitional exhaustion. Expired gases were continuously analyzed using a portable metabolic system (COSMED K5, Italy) to measure oxygen uptake (VO_2), carbon dioxide output (VCO_2), and the respiratory exchange ratio (RER). The heart rate (HR) was monitored throughout the test. $VO_{2\max}$ was considered achieved when oxygen consumption plateaued despite the increasing workload and the RER exceeded 1.1 (Midgley and Carroll, 2009). Peak values for VCO_2, ventilation (VE), and the HR were simultaneously recorded. The raw respiratory data were exported and smoothed using a 15-s moving average. Peak values were identified as the highest 15-s averaged data obtained during the test. The attainment of $VO_{2\max}$ was further confirmed by a levelling-off of VO_2 (< 1.0 mL/kg/min change) despite the increasing workload, accompanied by an RER > 1.1.

Prior to each test, the system underwent rigorous calibration procedures: the flow sensor was calibrated using a 3-L calibration syringe, and gas analyzers were calibrated with certified reference gases (16.00% O_2 and 5.00% CO_2). All testing was conducted under standardized environmental conditions (24 ± 1°C, 46% relative humidity) to ensure measurement consistency (Shimoda et al., 2009).

2000-m Maximal Rowing Ergometer Test

The 2000-m rowing ergometer test represents the gold standard for evaluating rowing-specific endurance capacity in competitive athletes (Mikulić et al., 2009). Performance was assessed using an air-braked ergometer (Concept2 Model D, USA) with the drag factor standardized at 130 for all participants.

During the time trial, the ergometer display provided real-time feedback including remaining distance, 500-m split times, and elapsed time. Standardized verbal encouragement was provided during the final 250-m sprint phase. Key performance metrics recorded included: mean power output (W), 500-m split times (intermediate intervals), and total completion time.

The test protocol adhered to international rowing federation (FISA) recommendations for performance assessment, with particular attention to maintaining consistent pre-test hydration and nutritional status across all participants.

Statistical Analysis

Descriptive statistics are presented as mean ± standard deviation (mean ± *SD*). All data and statistical results were recorded using Microsoft Excel (Microsoft Corporation, USA) or SPSS (IBM SPSS Statistics, Version 29). Normality of all complete test datasets was assessed using the Shapiro-Wilk test ($p > 0.05$). Correlation analyses were performed using the Pearson's r coefficient (for normally distributed data) or the Spearman's ϱ coefficient (when normality assumptions were violated). The strength of correlations was interpreted as follows: 0–0.09 = trivial, 0.1–0.29 = weak, 0.3–0.49 = moderate, 0.5–0.69 = strong, 0.7–0.89 = very strong, and ≥0.9 = near-perfect (Hopkins et al., 2009). To compare the differences in correlation coefficients between the expert and novice groups, the Fisher’s z-transformation was applied. The resulting *z*-statistics and corresponding *p*-values were reported to objectively evaluate the significance of between-group differences in correlation strength.

Results

The 1RM strength in the back squat, bench pull, bench press, and power clean exercises was 161.0 ± 9.2 kg, 97.6 ± 5.6 kg, 108.5 ± 10.2 kg, and 105.3 ± 6.3 kg, respectively, in expert athletes, compared to 147.89 ± 6.24 kg, 84.47 ± 5.37 kg, 82.63 ± 5.56 kg, and 87.63 ± 4.78 kg in novices. The absolute and relative VO_{2max} values were 5580.6 ± 526.3 mL/min and 58.5 ± 5.1 mL/kg/min (experts) versus 5289.47 ± 364.27 mL/min and 59.09 ± 3.07 mL/kg/min (novices). The 2000-m ergometer performance was 369.3 ± 16.8 s (experts) and 400.05 ± 10.96 s (novices) (Table 1).

Table 2 presents the correlations between rowing-specific test measures and physical fitness performance indicators. The correlation analysis revealed that in strength assessments, both power clean and back squat exercises demonstrated strong positive associations with average power (r = 0.50–0.69, $p < 0.05$), while showing significant negative correlations with 2000-m ergometer time (r = –0.47 to –0.62, $p < 0.05$). Interestingly, although the bench pull showed no significant relationship with these two ergometer variables, it exhibited moderate correlations with first 500-m average power output (r = 0.43–0.47, $p < 0.05$). Comparative analysis indicated that the power clean displayed stronger associations with ergometer performance in expert rowers compared to novices, whereas the back squat showed greater correlation with 2000-m time trial performance in novice rowers.

To statistically validate the observed differences in correlation patterns between groups, Fisher’s z transformation tests were performed. The results confirmed that the correlation between the power clean 1RM and mean power was significantly stronger in the expert compared to the novice group ($z = 2.15$, $p = 0.032$). Conversely, the difference in correlation strength for the deep squat 1RM between the two groups, while descriptively higher in novices for total time, did not reach statistical significance (for total time: $z = 0.38$, $p = 0.704$; for average power: $z = 0.24$, $p = 0.810$).

Regarding aerobic capacity measures, absolute VO_{2max} values demonstrated stronger correlations with ergometer performance in expert athletes, while relative VO_{2max} values showed weaker associations in this group compared to novice rowers. Fisher's z-test results revealed that the group difference in correlations for absolute VO_{2max} with average power was statistically significant (z = 2.42, p = 0.016). For relative VO_{2max}, the correlation with total time was significantly stronger in novices than in experts (z = 2.01, p = 0.044).

Table 1. Aerobic and strength characteristics along with 2000-m performance data of the participants (mean ± SD).

	Measure	Expert	Novice
Physical fitness performance	Deep squat (kg)	161.0 ± 9.2	147.89 ± 6.2
	Bench pull (kg)	97.6 ± 5.6	84.47 ± 5.3
	Bench press (kg)	108.5 ± 10.2	82.63 ± 5.5
	Power clean (kg)	105.3 ± 6.3	87.63 ± 4.7
Aerobic capacity	Absolute VO_{2max} (mL/min)	5580.6 ± 526.3	5289.47 ± 364.27
	RelativeVO_{2max} (mL/min/kg)	58.5 ± 5.1	59.09 ± 3.07
2000-m ergometer performance	Total time (s)	369.3 ± 19.8	400.05 ± 10.9
	Average power (W)	410.6 ± 31.1	371.6 ± 28.3
	1st 500-m average power (W)	435.7 ± 28.4	402.5 ± 25.9

Table 2. Associations of aerobic capacity and strength with 2000-m ergometer performance.

Test	Participants	Total time	Average power	1st 500-m average power
Bench press	Expert	−0.23	0.25	0.21
	Novice	−0.25	0.22	0.18
Bench pull	Expert	−0.28	0.24	0.43
	Novice	−0.35	0.33	0.47†
Power clean	Expert	−0.62†	0.69†	0.45†
	Novice	−0.52	0.59	0.42
Deep squat	Expert	−0.47	0.53†	0.38
	Novice	−0.51†	0.50	0.40†
Absolute VO_{2max}	Expert	−0.76‡	0.82‡	0.22
	Novice	−0.61	0.66	0.19
Relative VO_{2max}	Expert	−0.68	0.74	0.21
	Novice	−0.72‡	0.78‡	0.24

† significant for $p < 0.05$; ‡ significant for $p < 0.01$

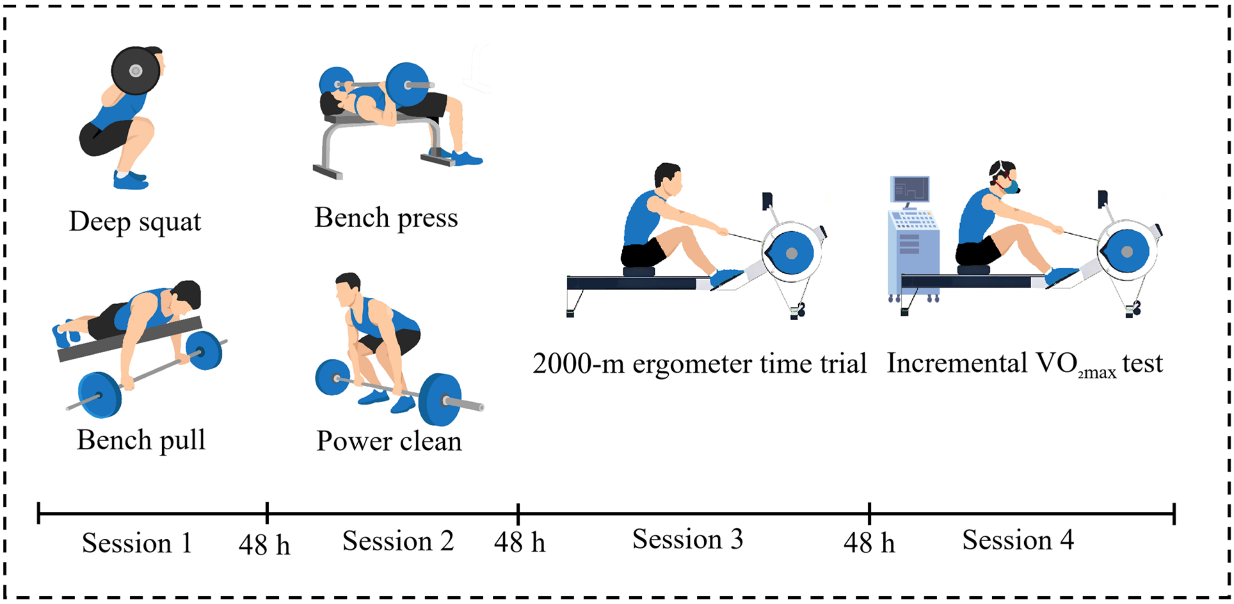

Figure 1. Schematic timeline of physical performance testing sessions.

Discussion

Coaches and rowers commonly emphasize the diagnostic value of strength training for performance. This study confirms the well-established importance of aerobic component (VO_{2max}) as a predictor of 2000-m performance, as shown in previous literature. However, it further highlights the critical role of specific strength exercises and their unique neuromuscular and biomechanical contributions. In line with this, our findings recommend prioritizing the power clean (1RM) alongside VO_{2max} testing as a primary standardized metric for evaluating rowing-specific performance potential across all training levels. The back squat (1RM) remains a valuable supplementary assessment. In this study, the power clean exhibited the strongest association with 2000-m ergometer performance. As a quintessential explosive movement, the power clean emphasizes hip hinge mechanics and rapid triple extension (knee, hip, ankle), which aligns kinetically with the finish phase of the rowing stroke. Although rowing primarily involves a slow stretch-shortening cycle (SSC) (Held et al., 2023), the neuromuscular adaptations from power clean training (e.g., motor unit recruitment efficiency) may enhance power output during the stroke. The deep squat, with its large-range lower-body joint motion, shares biomechanical similarities with the leg drive in rowing (Held et al., 2022). Its combination of slow eccentric control and concentric explosiveness effectively mimics the mechanical demands of the rowing's slow SSC. However, novice athlete data revealed that the power clean correlated more strongly with mean power than the back squat, underscoring its fundamental importance for power generation irrespective of the experience level. This suggests that power output in this population relies more on neuromuscular coordination efficiency than absolute strength, possibly due to their limited technical rowing proficiency. Notably, while the back squat is a valuable measure, its predictive strength for ergometer performance was generally surpassed by that of the power clean for both groups. This indicates that explosive, coordinated strength developed by the power clean is a more direct determinant of rowing performance than pure lower-body strength measured by the squat.

The bench press primarily assesses upper-body pushing musculature (pectorals/anterior deltoids/triceps), which differs mechanically from the dominant pulling kinematics of rowing (trapezius/latissimus dorsi/elbow flexors). While upper-body strength contributes to boat stability, no significant association was found between the bench press 1RM and 2000-m performance. Notably, rowers must generate exceptionally high force at the race start to accelerate the boat from rest (Nugent et al., 2020), enabling tactical and psychological advantages by leading early (Egan-Shuttler et al., 2017; Garland, 2005). Although the bench pull more closely approximates the rowing stroke (scapular retraction, elbow flexion), it is a dynamic concentric-eccentric action, whereas the rowing stroke involves sustained isometric contraction combined with the slow SSC. Nevertheless, our findings support a moderate correlation between bench pull strength and mean power during the first 500 m. These results align with Ledergerber et al. (2023) regarding the role of neuromuscular variables (maximal strength and the rate of force development), particularly the contribution of the 1RM bench pull to the initial phase of ergometer time trials. Modifying the bench pull test to emphasize slow eccentric control (mimicking stroke resistance loading) might better reflect race demands. A critical distinction lies in the slow SSC nature of rowing versus explosive strength training, where the latter enhances efficiency primarily through neuromuscular coordination. Current bench pull testing may lack translational efficacy due to insufficient emphasis on slow eccentric control (Janicijevic et al., 2025).

Training experience significantly influenced power clean performance: the 1RM power clean, reflecting whole-body explosiveness (Garhammer, 1984), directly determined ergometer leg-drive power output. While elite athletes exhibited higher absolute strength due to lean mass advantages, novices' relative strength (1RM/body weight) and movement proficiency may be more influential (McMaster et al., 2014). The contrasting results in novices might be attributed to their underdeveloped technical rowing skills, as greater emphasis is placed on neuromuscular coordination rather than pure strength (Rodiles-Guerrero et al., 2026). VO_{2max} correlated more strongly with 2000-m performance than strength metrics, as >70% of ergometer work relies on aerobic metabolism, making VO_{2max} a key limiting factor (Bermúdez Droguett et al., 2026). Strength (e.g., squat, power clean—especially the bench pull) predominantly affected the start and sprint phases but contributed less to overall performance compared to aerobic capacity. Novices depended more on relative VO_{2max}, whereas athletes with >5 years of training experience prioritized absolute VO_{2max} (Saito and Matushita, 2004) due to greater body mass and dimensions (Cerasola et al., 2020).

Conclusions

This study validates the power clean and the back squat 1RM as key indicators of rowing performance, with adjustments for athletes' training experience. Our findings strongly support the inclusion of the power clean as a fundamental assessment tool for rowers of all experience levels, as it emerged as a superior predictor of performance compared to the back squat, even among novices. Coaches should periodically assess these lifts while ensuring training balance for maximal strength, power, and aerobic capacity to optimize ergometer performance. Future research should refine testing protocols to better capture rowing-specific strength qualities, but these findings offer actionable insights for using free-weight training to evaluate and enhance sport-specific strength.

Limitations

1RM Testing Scope: While 1RM testing is standardized and practical, it does not assess strength endurance at submaximal loads (e.g., 5RM). Given the repeated force demands of 2000-m races, future studies should incorporate multi-load strength testing (e.g., 3–5 RM) for a comprehensive evaluation.

Velocity Metrics: Resistance training performance is governed by load-velocity relationships, yet this study recorded only 1RM weight without quantifying concentric velocity (via sensors or encoders). Adding force-velocity curve analysis (e.g., mean concentric velocity, peak power) could clarify dynamic strength-power relationships in rowing.

Ecological Validity: Current tests (e.g., power clean, squat) evaluate foundational strength but imperfectly replicate rowing kinetics. Future work should design sport-specific strength tests to improve ecological validity.

Practical Implications

For coaches and strength trainers working with competitive rowers, this study highlights key evidence-based strategies: (1) Prioritize power clean (1RM) and back squat (1RM) testing as these explosive lower-body lifts show the strongest correlations with 2000-m ergometer performance, particularly for elite rowers due to biomechanical similarities with the stroke's triple extension phase. Novice rowers should focus more on relative strength (1RM/body weight) and movement efficiency. (2) Adapt strength training to rowing's slow SSC demands by incorporating controlled eccentric phases (e.g., tempo squats) while minimizing non-transferable exercises such as the bench press. (3) Maintain aerobic capacity as the primary performance determinant—VO_{2max} (absolute for elites, relative for novices) outweighs strength metrics for overall 2000-m success. (4) Optimize testing by supplementing 1RM with velocity tracking (e.g., barbell sensors) and exploring rowing-specific strength assessments (e.g., loaded pulls with slow eccentrics). These findings advocate for an integrated approach balancing explosive power, strength endurance, and aerobic development, with testing protocols tailored to athlete experience levels.

Author Contributions: Conceptualization: X.D., J.Y. and X.B.; investigation: X.D.; formal analysis: X.D. and X.B.; writing—original draft preparation: X.D. and X.B.; writing—review & editing: J.Y. and X.B. All authors have read and agreed to the published version of the manuscript.

ORCID iD:

Xinyu Dai: https://orcid.org/0009-0008-3997-5629

Jihong Yan: https://orcid.org/0009-0005-6372-2304

Xuecui Bi: https://orcid.org/0009-0009-6797-8752

Funding Information: This research was funded by Fujian Provincial Social Sciences Association, grant number [FJ2025C132].

Institutional Review Board Statement: This study was conducted in accordance with the principles of the Declaration of Helsinki and was approved by the Ethics Committee of the Capital University of Physical Education and Sports, Beijing, China (approval code: 2025A015; approval date: 11 January 2025).

Informed Consent: Informed consent was obtained from all participants included in the study.

Conflicts of Interest: The authors declare no conflict of interest.

Received: 30 June 2025

Accepted: 25 May 2026

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