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Physical and technical attributes associated with on-water rowing performance in junior and elite rowers

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ABSTRACT

On-water rowing performance consists of the integration of physical and technical attributes. This exploratory study aimed to describe key physical and technical variables for elite and junior rowers and examine the associations and predictive capacity of these variables with on-water rowing performance outcomes. Twenty-eight junior (16 females, 16 ± 0.8 years and 12 males, 17 ± 0.7 years) and 24 elite rowers (12 females, 24 ± 2.7 years and 12 males, 27 ± 2.6 years) completed an on-water, single sculling biomechanics assessment combined with a series of physical, strength and power tests. Elite men and women were superior in mean gate force, distance per stroke and recovery distance compared to junior groups as determined by independent t-tests and effect size appraisal ($p < 0.017$, d > 1.2). Large associations ($p < 0.01$) were evident between anthropometry, strength and power assessments with the on-water measures of catch angle, mean gate force, recovery distance and boat speed. Differences in ROM and flexibility attributes did not distinguish between elite and junior rowers. Linear discriminant analysis revealed that individual rowers can be appropriately categorised by sex and performance level based on their physical and technical attributes. This battery of testing with world-class athletes represents an excellent level of ecological validity for the assessment of rowers pertinent to on-water performance.

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Introduction

On-water rowing performance consists of the integration of both physiological and technical attributes. A number of researchers have established standards on physical measures for rowing performance (Akça, 2014; Lawton et al., 2012; Slater et al., 2005), however, research on specific technical attributes is limited. Guidelines are unclear on the characteristics of the technique that leads to optimal boat velocity (Holt et al., 2020; McGregor et al., 2007) and a deeper understanding of on-water rowing performance is required, specifically, understanding how the physical attributes of the rower are associated with the on-water technical performance (Legge et al., 2023). In the context of the rowing stroke, range of motion requirements are essential at the hip, knee, and ankle along with associated force producing capabilities of the hip and knee extensors that ensure critical positions can be maintained for the duration of the rowing stroke and repeated over extended periods of time (Rawlley-Singh & Wolf, 2023). It is therefore important to have a holistic view of the rower's performance through capturing the physical and technical aspects of performance. This study addresses a gap in the research through contributing knowledge to the limited on-water rowing literature. In addition, establishing performance-related attributes that are relevant to the rowing development pathway for male and female athletes. Exploring these characteristics for junior and elite rowers can provide coaches, athletes, and support staff with knowledge to inform the development pathway alongside gold standard references from current successful elite athletes (Otter-Kaufmann et al., 2020).

Maximal force and rate of force development have been closely linked to rowing performance, with rowing-specific strength and power associated with 2000 m ergometer performance (Akça, 2014; Gee et al., 2011; Thiele et al., 2020). While related to some aspects of rowing performance, ergometer rowing is significantly different to on-water rowing, particularly from a technical perspective (Fleming et al., 2014). Altered acceleration and deceleration of the body segments on the ergometer as well as shorter drive lengths and higher handle forces all contribute to a reduced representative design for ergometer rowing in comparison to on-water rowing performance (Elliott et al., 2002; Kleshnev, 2005). Therefore, results from ergometer-based biomechanical assessments likely do not directly relate or transfer to on-water rowing performance. On-water rowing reveals differences in both amplitude and temporal aspects of handle forces compared to ergometer rowing, implying distinct demands of the on-water task (Millar et al., 2017). The maximal force requirements of on-water rowing have been established through specially instrumented

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measurement devices that fit onto the oar or oarlock during on-water rowing or instrumented ergometers in the laboratory (Draper, 2005; Nolte, 2011). To further understand the physical requirements of on-water rowing and the interrelationship with technique, it is important to incorporate on-water rowing assessment as a performance outcome measure (Millar et al., 2017).

Exploring key physical and technical attributes and the differences between junior and elite rowers has the potential to provide knowledge for practitioners in how they approach training and competing at the development pathway and elite levels. Along with the physical and technical aspects of rowing assessment, the anthropometric profile of rowers at both junior (Bourgois et al., 2000) and elite levels (Barrett & Manning, 2004) is an important component of rowing performance (Bourgois et al., 2001). Further, range of motion at certain joints is an essential biomotor quality to ensure optimal execution of the rowing stroke and plays an important role in efficient force transfer across the kinetic chain (Rawlley-Singh & Wolf, 2023). Range of motion requirements for rowing have typically been reported in peer-reviewed research pertaining to rowing injuries rather than attributes being associated with performance (Thornton et al., 2017). There may be additional applications of such measurements given the importance of stroke length, body position and force producing capability throughout the stroke cycle (Rawlley-Singh & Wolf, 2023). Assessing and describing these variables for junior rowers is important to evaluate their position on the development pathway while exploring such measures in elite cohorts provides a gold standard comparison and this information may play an important role in predicting future success (Clephas & Brückner, 2020).

Descriptive performance characteristics of representative groups of junior and elite-level rowers reported by sex may highlight important differences for male and female performance measures which have the potential to inform different stages of the rowing development pathway (Olszewski-Kubilius et al., 2019). In the sporting context, exploring current performance levels in certain attributes can provide a critical gauge to predict an individual's current or future potential of success against established elite benchmarks (Lawton et al., 2012). Given the absence of information in this domain, it is clear that a greater understanding is required about the associations between certain physical attributes and technical attributes of on-water rowing to produce optimum boat velocity. This study encompassed an on-water rowing biomechanical assessment in a single scull as the primary performance outcome measure alongside a comprehensive physical assessment to address this existing knowledge gap. Demographic characteristics, anthropometry, range of motion, strength and power assessments in combination with an on-water sculling assessment were explored with the intention of providing coaches and support staff interested in improving rowing performance with insightful outcomes applicable to their daily training environment and their approach to training prescription and planning.

The aim of this exploratory study was to describe key physical and technical variables for elite and junior rowers. Additionally, to bridge the research gap, the study examined the associations and predictive capacity of these variables to explore the interaction of physical and technical attributes with on-water rowing performance outcomes. The results of this study will contribute knowledge to the limited on-water rowing research, including the relationship between a rower's physical attributes with their on-water technical output. This information may provide valuable knowledge for coaches, athletes and support staff in how they approach physical and technical aspects of training and competing at the development pathway and elite levels.

Method

Participants

Fifty-two rowers volunteered to participate in the study and provided written informed consent prior to any testing. The participants comprised 28 junior (16 females, 16 ± 0.8 years and 12 males, 17 ± 0.7 years) and 24 elite heavyweight rowers (12 females, 24 ± 2.7 years and 12 males, 27 ± 2.6 years). The sample size was calculated to be a minimum of 10 participants for each category group. This was calculated using an a-priori power analysis for independent t-tests with an expected effect size of 0.95, alpha error of 0.05 and power 0.65 (G*Power 3.1 version 3.1.9.6). Furthermore, the elite male and female rowers from the National training program represent the entire population of elite-level athletes in this sport in Australia. This depicts a high level of ecological validity in the results, and it was not possible to recruit more rowers of this calibre in Australia, regardless of the sample size calculation. The elite >male and female rowers reported 11.7 ± 3.0 years and 8.0 ± 2.3 years of rowing experience, respectively. Elite participants were classified as world-class (McKay et al., 2022), recruited through the national rowing network and were all competitors at recent world championships. The male and female junior rowers had 3.8 ± 1.0 and 3.9 ± 1.1 years, respectively, and were a combination of trained developmental pathway and highly trained national level participants. All junior participants were recruited through promotional information sheets that were sent to rowing clubs and school rowing programs (McKay et al., 2022) in NSW, Australia. Junior rowers were competent and competitive scullers with at least 2 years of rowing experience, under 19 years of age, and currently training a minimum of 6 h per week. Ten of the 28 junior participants were current junior national representatives. The study protocol was approved by the Human Research Ethics Committee of the local institution.

Overview

Participants completed two separate testing sessions in the early stages of a rowing season. The first was an on-water rowing assessment in a single scull conducted on an enclosed waterway with no tidal flow and a buoyed racecourse. The second was a series of physical, anthropometrical, strength and power tests conducted in a high-performance training facility. Both testing sessions were scheduled within a two-week period for each participant to minimise training effects between testing sessions. Descriptive statistics and correlation analysis were reported for on-water technical attributes and physical assessments. Furthermore, a linear discriminant analysis (LDA) was applied to identify whether a combination of physical and technical variables selected from the dataset could accurately distinguish individuals to their correct rower category.

On-water testing procedures

The Peach PowerLine Instrumentation system (Peach Innovations, UK) including instrumented gates, foot stretcher, boat sensor (GPS) and accelerometer sampling at 50 hz were installed on each single scull to measure the on-water biomechanical assessment. The single sculls were set up according to each individual's standard rigging measurements and the setup was completed in consultation with their coach. The Peach PowerLine instrumentation system is used frequently within elite and school rowing environments for monitoring purposes. Established levels of validity for the system have been reported with the standard error of the estimate (SEE) ≤8.9N for gate force, ≤0.9° for gate angle and an r^2 of 1.00 for both variables (Coker et al., 2009). Additional validation was conducted on all gates and foot stretcher sensors prior to testing (see supplementary material).

Environmental conditions including wind direction and speed, water temperature and air temperature were recorded periodically during every testing session to ensure conditions were comparable across all testing days. Venue environmental conditions (measured using the Kestrel 5500 Weather Meter) were: 19.1 ± 3.4°C air temperature (mean ± SD), 20.1 ± 1.7°C water temperature and 0.8 ± 1.0 $m{\cdot}s^{-1}$ wind speed, ranging in direction from calm to a light cross-tail direction. The on-water testing included a 1000 m piece at maximal intensity with a set stroke rate of 28 strokes per minute (spm) for the first 500 m and 30spm for the 2nd 500 m. The stroke rate selected for analysis represented an intensity level that was comparable across the two groups, elite and junior. Extensive pilot testing revealed that 30 spm was the highest common stroke rate to facilitate between-group comparisons across all variables measured. For analysis purposes, a sample of 20 strokes were extracted from the data at 30spm for each participant, representing a mid-section of each testing piece at 30spm. A sample of 20 strokes from the mid-section of a rowing piece has been shown to be a representative of a rower's technical output (R. Smith & Draper, 2006; R. M. Smith & Loschner, 2002; Warmenhoven et al., 2017). Each stroke cycle was identified from catch to catch using the horizontal gate angle, where the catch was at the largest negative and the finish at the largest positive angle.

Raw data files were downloaded using the Peach Innovations software and time-series data (50 hz) was exported as csv files for processing. Discrete data was determined from time-series data using a custom script written in the R platform (http://www.r-project.org/). Gate angle time-series data was filtered with a low-pass 4th-order Butterworth filter at a cuff-off frequency of 20 hz to assist in determining catch and finish events. The peakdet R function (Eli Billauer, http://www.billauer.co.il/peakdet.html) was used to determine local minima and maxima in the horizontal gate angle time-series data which corresponded to catch and finish events, respectively. Discrete metrics were determined per stroke by calculating between catch events and total gate force was the sum of bow side (left) and stroke side (right) horizontal gate force sensors. Drive distance was determined from the distance travelled between the Catch and Finish events, while Recovery Distance was the distance travelled between the Finish to the next Catch.

Physical testing procedures

All participants undertook a standardised warm-up before the physical testing session including dynamic stretching and exercises as directed by a strength and conditioning professional. All anthropometrical measures were assessed as per the International Society for the Advancement of Kinanthropometry (ISAK) guidelines by an accredited exercise scientist (SC). Measurements included body mass (A&D FG-150KAM Platform scale, Adelaide Australia), stature (Harpenden wall-mounted stadiometer, Crosswell, UK), sitting height (Holtain Sitting Height Table, Crosswell, UK), leg length and arm span (segmometer, Crawley, Australia). Range of motion measurements were completed by a qualified allied health professional (NL) and included sit and reach (steel Baseline Sit N Reach Box, New York, USA), knee to wall dorsiflexion, passive hip flexion and active knee extension (12-inch Prestige paddle Goniometer, Dublin, Ireland).

The Isometric Mid-Thigh Pull (IMTP) and Squat Jump (SJ) were completed using the ForceDecks FDMax Dual Force Platforms (ForceDecks, London, UK) sampling at 1000 hz. The setup and positioning for the IMTP followed the description by Comfort (2019). The instructions to the participants involved a gradual ramping over a count of 2 s followed by a maximum push for 5 s. For familiarisation purposes, participants were instructed on the technique of the IMTP prior to testing and feedback was provided as required during the warm-up attempts to ensure a level of competence to complete the IMTP. The Net Peak Force was calculated by subtracting the individual's body mass from their peak force. This was to avoid any discrepancies in pre-tension applied by participants (Brady et al., 2020). The IMTP provides a reliable measure of isometric strength of the lower body (Comfort et al., 2019) while the SJ has been shown to be associated with 2000 m ergometer performance (Giroux et al., 2015). The SJ set up, positioning and instructions followed the methods as described by Sebastia-Amat et al. (2020). The specific squat jump variables reported were concentric peak power in Watts and jump height in centimetres. The relative peak power was subsequently calculated by dividing peak power by the participant's body mass in kilograms. The Biering-Sorensen test was performed as described by (Latimer et al. 1999). Participants held their body in a horizontal position for as long as possible with their head and neck in a neutral position staring at the ground and their arms crossed on their chests. Ergometer performance tests were conducted using the Concept 2 Rower Model D and included the 7-stroke maximum power test (Nugent et al., 2019) and the 500 m test for average power (H. Smith, 2000). Personal best times for the 2000 m ergometer test were reported by participants as part of a demographic questionnaire, however, they did not complete this test as part of the testing battery (Bourdin et al., 2017; Schabort et al., 1999).

Statistical analysis

Descriptive statistics were calculated for on-water technical attributes and physical assessments and the data was checked for normality using the Shapiro–Wilk test. The mean, standard deviation and 95% confidence intervals were calculated for each measured variable and presented in Tables 1 and 2. T-tests (two tailed, equal variance) were used to compare the elite and junior rowers within each sex, with the significance level determined using an alpha level of 0.0017. This value was calculated based on the standard p-value cut-off of 0.05 divided by the number of assessed variables ($n = 29$) to account for multiple comparisons. Effect Size (Cohen's d) was calculated to represent the magnitude of the difference between groups, with values represented as: Effect size values of <0.20, 0.20–0.60, 0.61–1.20, 1.21–2.00 and >2.01 represented trivial, small, moderate, large and very large differences, respectively (Hopkins et al., 2009). Pearson's correlation coefficients between the physical and on-water technical attributes were calculated to determine the strength of these relationships. Correlation magnitudes were based on the guidelines of Hopkins et al. (2009); <0.1: trivial, 0.1 ≤ small < 0.3, 0.3 ≤ moderate < 0.5, 0.5 ≤ large < 0.7, 0.7 ≤ very large < 0.9, ≥ 0.9: extremely large. All descriptive statistical analyses were conducted using SPSS v29.0 (SPSS Inc., Chicago IL, USA). Linear discriminant analysis (LDA) was applied using the R platform (http://www.r-project.org/) and utilising the MASS package (Venables & Ripley, 2002) to identify whether a combination of physical and technical variables selected from the dataset could accurately distinguish individuals to their correct rower category (Williams, 1981). Variables were first screened to ensure they met the assumptions of LDA. Histograms and QQ plots were used to determine if the data was normally distributed. Sample independence was assessed using correlation analysis. Homogeneity of covariance matrices was checked using the Box M test. Relative measures were used to ensure the data was

Table 1. On-water single sculling biomechanics metrics for male and female rowers (Mean ± SD, 95% CI).

	Males		Females	
Metrics	Junior	Elite	Junior	Elite
Catch Angle (°)	−62.8 ± 2.9 (−64 – −61)	−66.4 ± 3.8 (−69 – −64)	−55.2 ± 5.8 (−58 – −52)	−65.1 ± 2.6*# (−67 – −64)
Finish Angle (°)	42.9 ± 3.1 (41 – 45)	43.6 ± 2.6 (42 – 45)	42.3 ± 4.8 (40 – 45)	42.8 ± 2.5 (41 – 44)
Stroke Length (°)	105.7 ± 3.9 (104 – 108)	110.0 ± 4.3 (108 – 112)	98.5 ± 5.0 (96 – 101)	108.0 ± 2.3*# (107 – 109)
Peak Total Gate Force (N)	980 ± 74 (938 – 1022)	1144 ± 75*# (1102 – 1186)	760 ± 97 (713 – 808)	866 ± 96 (815 – 916)
Mean Total Gate Force (N)	493 ± 39.2 (470 – 515)	602 ± 40*# (579 – 624)	365 ± 41 (345 – 385)	446 ± 57*# (416 – 476)
Mean to Peak Ratio of Force (RAM)	50.4 ± 2.9 (49 – 52)	52.6 ± 2.2 (51 – 54)	48.2 ± 2.6 (47 – 50)	51.5 ± 3.9 (50 – 54)
Gate Angle at Peak Force (°)	−21.1 ± 4.5 (−24 – −19)	−18.6 ± 5.5 (−22 – −16)	−18.0 ± 6.6 (−21 – −15)	−23.6 ± 6.9 (−27 – −20)
Distance per Stroke (m)	8.32 ± 0.3 (8.2 – 8.5)	9.06 ± 0.3*# (8.9 – 9.2)	7.51 ± 0.4 (73 – 7.7)	8.41 ± 0.2*# (8.3 – 8.5)
Drive Distance (m)	3.87 ± 0.3 (3.7 – 4.0)	4.21 ± 0.2 (4.1 – 4.4)	3.59 ± 0.2 (3.5 – 3.7)	4.06 ± 0.1*# (4.0 – 4.1)
Recovery Distance (m)	4.45 ± 0.3 (4.3 – 4.6)	4.85 ± 0.2*# (4.8 – 4.9)	3.92 ± 0.3 (3.8 – 4.1)	4.35 ± 0.2*# (4.2 – 4.5)
Boat Speed ($m.s^{-1}$)	4.21 ± 0.2 (4.1 – 4.3)	4.61 ± 0.1*# (4.6 – 4.7)	3.86 ± 0.2 (3.8 – 4.0)	4.30 ± 0.1*# (4.3 – 4.4)

Key: CI = Confidence Interval; o = degrees; N = Newtons; kg = kilogram; m.s-1 = metres per second.
*Significantly different from junior cohort for same sex ($p < 0.0017$), #Large effect size compared to junior cohort for same sex (d > 1.2).

Table 2. Anthropometry, range of motion, flexibility, strength and power characteristics for male and female rowers (Mean ± SD (±95% CI)).

	Males		Females	
Metrics	Junior	Elite	Junior	Elite
Weight (kg)	82.2 ± 7.0 (78.2 – 86.1)	91.8 ± 3.1*# (90.0 – 93.6)	69.5 ± 8.8 (65.2 – 73.8)	76.6 ± 8.2 (72.3 – 80.9)
Height (cm)	184 ± 4.5 (181.0 – 186.1)	191 ± 4.5*# (188.2 – 193.3)	173 ± 5.3 (170.3 – 175.5)	179 ± 5.5 (176.0 – 181.8)
Sitting height (cm)	97.2 ± 3.1 (95.5 – 99.0)	99.3 ± 2.7 (97.8 – 100.8)	91.4 ± 3.0 (89.9 – 92.8)	93.4 ± 2.5 (92.0 – 94.7)
Arm span (cm)	187 ± 6.4 (183.6 – 190.8)	196 ± 5.9 (192.3 – 199.0)	176 ± 6.6 (172.4 – 178.9)	182 ± 8.2 (177.9 – 186.6)
Leg length (cm)	95.4 ± 2.1 (94.2 – 96.6)	100 ± 3.2*# (98.2 – 101.9)	91.2 ± 4.5 (89.0 – 93.4)	95.3 ± 4.1 (93.1 – 97.4)
Sit & reach (cm)	6.29 ± 7.8 (1.9 – 10.7)	14.1 ± 6.6 (10.3 – 17.8)	13.5 ± 8.0 (9.6 – 17.4)	19.2 ± 5.8 (16.2 – 22.2)
Passive hip flexion (°)	122 ± 5.3 (119 – 125)	130 ± 4.3*# (128 – 132)	131 ± 7.7 (128 – 135)	135 ± 7.1 (132 – 139)
Active knee extension (°)	−28.0 ± 13.0 (−35.4 – −20.7)	−16.6 ± 8.4 (−21.3 – −11.8)	−22.3 ± 10.2 (- 27 – −17)	−3.96 ± 6.9*# (−8 – 0)
Knee to wall dorsiflexion (cm)	9.89 ± 4.8 (7 – 13)	14.9 ± 4.2 (12 – 17)	13.7 ± 1.8 (13 – 15)	15.0 ± 3.4 (13 – 17)
IMTP Net Peak Force (N)	2300 ± 519 (2006 – 2593)	2926 ± 487 (2650 – 3201)	1487 ± 339 (1321 – 1653)	2184 ± 277*# (2039 – 2329)
Relative IMTP Net Peak Force ($N.kg^{-1}$)	28.1 ± 6.5 (24.4 – 31.8)	31.9 ± 5.4 (28.9 – 35.0)	21.6 ± 4.70 (19.3 – 23.9)	28.6 ± 2.93*# (27.1 – 30.2)
7 Stroke Peak (Watts)	648 ± 81 (603 – 694)	816 ± 98*# (761 – 872)	403 ± 43 (382 – 424)	525 ± 64*# (491 – 558)
Relative 7 Stroke Peak (Watts/kg)	7.89 ± 0.73 (7.5 – 8.3)	8.92 ± 0.85 (8.4 – 9.4)	5.85 ± 0.74 (5.5 – 6.2)	6.77 ± 0.39*# (6.6 – 7.0)
500 m Avg Power (Watts)	515 ± 55 (484 – 546)	624 ± 59*# (591 – 658)	312 ± 33 (296 – 329)	406 ± 45*# (382 – 429)
Relative 500 m Avg Power (Watts/kg)	6.28 ± 0.5 (6.0 – 6.6)	6.84 ± 0.7 (6.5 – 7.2)	4.52 ± 0.5 (4.3 – 4.7)	5.29 ± 0.3*# (5.1 – 5.5)
Biering Sorensen Trunk Endurance Hold (s)	122 ± 40 (99 – 145)	165 ± 30 (148 – 182)	157 ± 21 (147 – 168)	155 ± 24 (143 – 168)
SJ Peak Power (Watts)	4144 ± 543 (3837 – 4452)	4563 ± 580 (4235 – 4892)	2857 ± 459 (2632 – 3081)	3343 ± 355 (3157 – 3529)
SJ Relative Peak Power (Watts/kg)	50.5 ± 5.8 (47 – 54)	49.7 ± 6.4 (46 – 53)	41.3 ± 5.4 (39 – 44)	43.0 ± 4.6 (41 – 45)
SJ Height (cm)	34.0 ± 4.7 (31 – 37)	34.0 ± 9.4 (29 – 39)	25.3 ± 4.2 (23 – 27)	27.4 ± 3.5 (26 – 29)

Key: CI = Confidence Interval; SD = standard deviation; cm = centimetres; N = Newtons; kg = kilograms; o = degrees; s = seconds.
*Significantly different from junior cohort for same sex ($p < 0.0017$), #Large effect size compared to junior cohort for same sex (d > 1.2).

not skewed based on absolute strength and athlete weight. The selected variables, passive hip flexion, leg length, IMTP relative net peak force, relative 7 stroke peak power and on-water distance per stroke, were chosen by the authors, as variables related to performance, based on the literature (Lawton et al., 2012; Podstawski et al., 2022) and designed to represent the different attribute groups of rowing. The chosen variables represent the range of motion, anthropometry, maximal force, rate of force development and on-water rowing technique. The four categorical groups were elite men (M), elite women (W), junior men (B) and junior women (G).

Results

The descriptive analysis identified differences between junior and elite rowers separated by sex in several physical and on-water characteristics. The on-water biomechanics assessment (Table 1) identified elite female rowers to be superior in catch angle, stroke length, mean total gate force, distance per stroke, drive distance, recovery distance and boat speed when compared to the junior females. Male elite rowers demonstrated significantly greater peak total gate force, mean total gate force, distance per stroke, recovery distance and boat speed than the junior males. Significant differences between junior and elite groups were reported with $p < 0.0017$ and a large effect size of $d > 1.2$. The significant p-value was calculated by dividing the standard p-value of 0.05 by the 29 variables to account for multiple comparisons given the number of variables reported.

The anthropometric, range of motion and flexibility characteristics are presented in Table 2, along with the maximal force and rate of force development characteristics. Differences were identified in elite rowers compared to their junior counterparts in peak power measured during the seven-stroke ergometer maximal power test and the average power for the 500 m ergometer test. In addition, the elite female rowers revealed higher maximal strength in IMTP net peak force, IMTP relative net peak force and the relative average power for the 500 m ergometer test compared to the juniors. No differences were evident between junior and elite groups for both sexes for Biering Sorensen trunk assessment or the SJ metrics. Pearson's correlation coefficients revealed some *large* relationships between height, weight and ergometer power tests with the on-water metrics of mean and peak force for both men and women (Tables 3 and 4).

Linear discriminant analysis (LDA) revealed that individual rowers can be appropriately categorised by sex and performance level based on their physical and technical attributes. The predictive statistical modelling of multiple variables to distinguish between all four groups was assessed using LDA with the category of rower as the dependant variable and leg length, passive hip flexion, IMTP relative net peak force, 7 stroke max power and distance per stroke as the independent variables (Figure 1). The Box's M-test resulted in a chi-square of 36.126 and a p-value of 0.204, demonstrating the co-variance was not significant, justifying these variables for the LDA. Using the five variables, 100% of the participants were correctly classified into their categorical group.

Discussion

This exploratory study provides a comprehensive descriptive dataset of the associations between physical attributes and on-water rowing biomechanical performance characteristics in junior and elite rowers, of both sexes. The findings of this study provide coaches with implications for individualised training prescription and planning. When comparing elite to junior athletes, the findings revealed differences in physical attributes for male and female cohorts with implications for development pathways to gauge progress and compare

Table 3. Pearson's correlation between anthropometric and range of motion characteristics and on-water biomechanical variables for male and female rowers.

	Sex	Weight	Height	Sitting height	Arm span	Leg length	Sit & reach	Knee to wall dorsiflexion	Passive hip flexion	Active knee extension
Catch Angle	Male	−0.47*	−0.64**	−0.40	−0.59**	−0.58**	−0.27	−0.28	−0.56**	−0.16
	Female	−0.45*	−0.54**	−0.28	−0.56**	−0.59**	−0.17	−0.23	−0.05	−0.43*
Finish Angle	Male	−0.02	−0.10	−0.39	0.18	0.09	−0.27	−0.33	0.13	−0.20
	Female	−0.15	0.08	0.27	−0.07	−0.03	−0.21	−0.11	0.08	−0.03
Stroke Length	Male	0.38	0.47*	0.09	0.60**	0.53**	0.05	0.03	0.55**	0.01
	Female	0.34	0.57**	0.44*	0.51**	0.53**	0.09	0.14	0.04	0.44*
Peak Gate Force	Male	0.79**	0.70**	0.46*	0.67**	0.66**	0.37	0.36	0.49*	0.18
	Female	0.55**	0.45*	0.20	0.53**	0.38*	0.24	0.21	−0.12	0.36
Mean Gate Force	Male	0.72**	0.68**	0.38	0.68**	0.68**	0.39	0.37	0.61**	0.32
	Female	0.51**	0.50**	0.18	0.51**	0.46*	0.15	0.29	−0.02	0.47*
Mean to Peak Ratio of Force	Male	0.09	0.15	−0.07	0.22	0.24	0.20	0.17	0.43*	0.41*
	Female	0.09	0.24	0.02	0.13	0.28	−0.13	0.20	0.14	0.34
Gate Angle at Peak Force	Male	0.07	0.06	0.00	−0.06	0.18	0.29	0.28	0.20	0.25
	Female	−0.15	−0.33	−0.12	−0.37	−0.38*	−0.18	−0.36	0.20	−0.16
Distance per Stroke	Male	0.74**	0.63**	0.27	0.71**	0.72**	0.46*	0.42*	0.65*	0.32
	Female	0.34	0.45*	0.32	0.40*	0.33	0.21	0.14	0.08	0.62**
Boat Speed	Male	0.72**	0.62**	0.32	0.61**	0.64**	0.40	0.42*	0.72*	0.22
	Female	0.30	0.44*	0.35	0.40*	0.34	0.26	0.16	0.09	0.62**
Drive distance	Male	0.59**	0.53**	0.25	0.59**	0.52**	0.30	0.28	0.68*	0.18
	Female	0.22	0.49**	0.45*	0.41*	0.41*	0.24	0.17	−0.10	0.56**
Recovery Distance	Male	0.56**	0.44*	0.18	0.50*	0.60**	0.41*	0.37	0.31	0.31
	Female	0.33	0.27	0.11	0.28	0.16	0.12	0.08	0.20	0.48**

**Correlation is significant at the 0.01 level (two-tailed).
*Correlation is significant at the 0.05 level (two-tailed).

Table 4. Pearson's correlation between strength and power characteristics and on-water biomechanical variables for male and female rowers.

		7 Stroke Peak Power	Relative 7 Stroke Peak Power	500 m Average Power	Relative 500 m Average Power	Prone suspension hold	IMTP Net Peak Force	Relative IMTP Net Peak Force	SJ Peak Power	SJ Relative Peak Power	SJ Jump Height
Catch Angle	Male	−0.45*	−0.32	−0.42	−0.20	−0.18	−0.02	0.14	−0.35	−0.07	0.00
	Female	−0.63**	−0.35	−0.58**	−0.34	0.11	−0.60**	−0.45*	−0.53**	−0.17	−0.26
Finish Angle	Male	−0.20	−0.23	−0.28	−0.30	0.07	−0.15	−0.18	0.04	0.05	0.27
	Female	−0.01	0.17	0.07	0.27	−0.01	−0.03	0.05	−0.28	−0.19	−0.26
Stroke Length	Male	0.24	0.12	0.17	−0.02	0.20	−0.07	−0.22	0.31	0.09	0.17
	Female	0.62**	0.45*	0.62**	0.50**	−0.14	0.59**	0.51**	0.35	0.07	0.10
Peak Gate Force	Male	0.62**	0.34	0.60**	0.20	0.28	0.33	0.03	0.25	−0.27	−0.23
	Female	0.60**	0.26	0.60**	0.32	−0.18	0.53**	0.29	0.41*	−0.03	−0.06
Mean Gate Force	Male	0.57**	0.33	0.56**	0.21	0.37	0.28	0.01	0.27	−0.20	−0.15
	Female	0.65**	0.35	0.67**	0.44**	−0.30	0.53**	0.32	0.40*	0.00	−0.02
Mean to Peak Ratio of Force	Male	0.10	0.10	0.11	0.12	0.34	0.03	0.02	0.12	0.08	0.13
	Female	0.35	0.30	0.41	0.40*	−0.30	0.17	0.15	0.10	0.05	0.05
Gate Angle at Peak Force	Male	0.17	0.32	0.05	0.12	0.23	0.46*	0.46*	0.17	0.15	0.09
	Female	−0.26	−0.17	−0.18	−0.08	−0.08	−0.26	−0.24	−0.29	−0.22	−0.28
Distance per Stroke	Male	0.55*	0.30	0.49*	0.11	0.21	0.31	0.03	0.36	−0.12	−0.09
	Female	0.72**	0.61**	0.75**	0.73**	−0.06	0.66**	0.58**	0.35	0.06	0.07
Boat Speed	Male	0.58**	0.36	0.62**	0.31	0.39	0.32	0.05	0.35	−0.11	−0.05
	Female	0.72**	0.67**	0.74**	0.76**	−0.04	0.62**	0.53**	0.36	0.12	0.12
Drive distance	Male	0.39	0.18	0.38	0.09	0.17	0.04	−0.18	0.38	0.01	0.02
	Female	0.64**	0.61**	0.59**	0.61**	−0.08	0.66**	0.66**	0.45*	0.29	0.32
Recovery Distance	Male	0.44	0.27	0.34	0.07	0.14	0.44*	0.24	0.18	−0.19	−0.16
	Female	0.57**	0.42*	0.66**	0.60**	−0.03	0.46*	0.33	0.17	−0.15	−0.15

**Correlation is significant at the 0.01 level (two-tailed).
*Correlation is significant at the 0.05 level (two-tailed).

abilities to world-class standards of elite performers. This novel study provides a set of baseline on-water biomechanical metrics alongside physical characteristics with useful insights for coaches and athletes. Strong relationships were evident for anthropometry, strength and power assessments with the on-water technical variables of catch angle, peak gate force, mean gate force, distance per stroke, boat speed and drive and recovery distance. Flexibility and range of motion measures did not reveal any associations with on-water metrics, however, predictive modelling demonstrated that several variables representing physical and technical attributes of the athletes were able to accurately identify individuals to their categorical group according to sex and performance level.

Research has reported on similar physical characteristics to those measured in the current study with 2000 m ergometer performance or 2000 m race time as the primary performance outcome (Akça, 2014; Lawton et al., 2012; Otter-Kaufmann et al., 2020; Slater et al., 2005). Given the disconnect between ergometer and on-water rowing technique or the use of the global measure of race time, a unique and progressive aspect of the present study was the inclusion of specific on-water rowing biomechanical variables collected on each participant during a single sculling performance. The single scull was specifically utilised so that variables measured were a direct reflection of the individual rower rather than crew skill or synchrony (T. B. Smith & Hopkins, 2012). In accordance with existing literature, the on-water rowing variable of mean gate force was significantly higher in elite men and women when compared to junior men and women, respectively (Holt et al., 2020; R. Smith & Draper, 2006). In addition, Pearson's correlation tests reinforced the relationship between power attributes and on-water performance with *large* correlations between mean gate force and 7 stroke peak power and 500 m average power for both men and women. Longer stroke lengths achieved through greater angles at the catch and finish are often desired by coaches (Holt et al., 2020). The current results demonstrated significantly longer stroke length in the elite participants which were likely related to greater catch angles, while finish angles were similar across all four category groups. This may reflect the level of difficulty and skill required to achieve an effective catch position (Legge et al., 2023). Moreover, distance per stroke is a measure that reflects performance and a strong predictor of boat speed (Gravenhorst et al., 2015). It encompasses both the drive and recovery phases of the rowing stroke and was significantly greater in the elite men and women cohorts (Holt et al., 2020). Based on these findings, the catch position appears to be a key variable related to greater stroke length, while distance per stroke may be associated with distinguishing rowers by skill level given the incorporation of both the drive phase and recovery phase.

Drive distance and recovery distance were assessed to explore differences between each of the two phases of the stroke cycle. The drive phase represents that main propulsive phase of the stroke cycle where force is generated on the feet and blade to propel the boat forward. Elite women covered significantly more drive distance then the junior women, however no difference was detected between the elite and junior men. Interestingly, the elite men and women covered significantly more distance during the recovery phase than their junior groups, respectively. This may reflect differences in skill level between elite and junior rowers and might relate to the sequencing of body movements during the recovery. The recovery phase during on-water rowing is an area of research that has largely been overlooked, with the propulsive drive phase dominating on-water rowing research (Draper & Smith, 2006; Warmenhoven et al., 2018). Elite rowing coaches perceive that the recovery phase requires a high level of skill including balance, coordination, rhythm and feel for the boat run (Legge

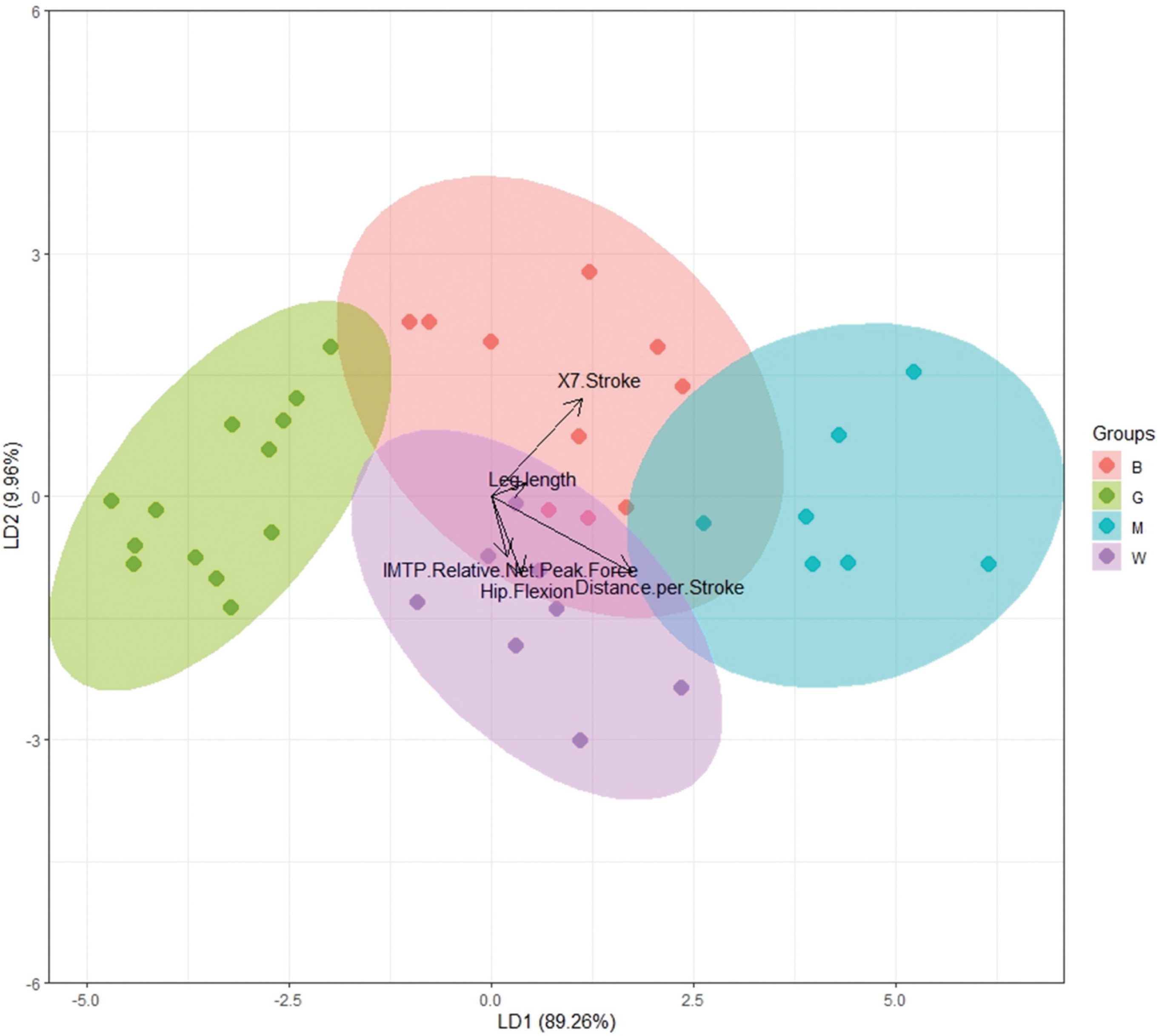

Figure 1. Scatter plot of linear discriminant analysis (LDA) model classifications. B = junior males, G = junior females, *M* = elite males, W = elite females.

et al., 2023). The recovery phase is difficult to measure given the oars are out of the water and no mechanical work is occurring during this time. However, this phase has the potential to improve boat speed without increased physiological output (Buckeridge et al., 2015). Future research should consider the recovery phase, with further development in body sequencing measures required. A better understanding of the subsequent effects on boat speed and acceleration has the potential to guide superior rowing technique in junior and elite rowers.

Elite rowers yielded superior outcomes in rowing specific measures of maximal force and rate of force development when compared to junior rowers (Lawton et al., 2012). This was evident in the ergometer power measures and the maximal force assessment of the IMTP. The elite women recorded significantly higher outputs than the junior women in power and strength assessments for both absolute and relative measures and this was reflected in the p-values ($p < 0.0001$) and effect size (d > 1.6). The elite men only revealed superior measures in absolute terms with no difference revealed for IMTP, peak power or average power relative to bodyweight. Increases in absolute strength are associated with increased muscle mass (Nuzzo, 2022) and relative strength is considered more important than absolute strength in rowing as more weight or muscle mass in the boat increases the drag forces in the water (McNeely et al., 2005). Moreover, the correlation analysis reinforced potentially strong relationships between some of the maximal force and rate of force development attributes with the on-water technical attributes. *Very large* associations were revealed between the on-water measures of peak force and mean force with 7 stroke peak power and 500 m average power ergometer tests, as well as a *large* correlation with IMTP net peak force. Boat speed, distance per stroke and recovery distance had *large* to *very large* associations with 7 stroke peak power, 500 m average power and IMTP net peak force. These physical attributes are clearly associated to the on-water rowing metrics, reinforcing their applicability to on-water rowing performance.

The SJ and Biering Sorensen Trunk Endurance test revealed no differences for either sex when comparing junior to elite participants. However, there was a *large* to *very large* association between SJ peak power and the on-water metrics of boat speed, distance per stroke and recovery distance. The SJ results may be related to the training adaptations gained from the sustained practice of rowing where rowing performance and jumping performance may not be related due to the specific technical and training adaptations (Giroux et al., 2015). Given these equivocal results, further consideration is required in regard to the SJ assessment for rowing performance. Based on the trunk endurance test findings, the isometric qualities of the Biering Sorensen test may not be the most appropriate measure to relate to rowing performance and further considerations are required for future studies. Supine and lateral trunk assessments were considered but there were limitations in the number of tests that could be administered in one testing session with the participants. As the Biering Sorenson had a well-established protocol, it was the priority. The inclusion of lateral and supine tests would be an interesting addition to future studies, and we have noted this as an area for further research. Regardless, trunk strength is undoubtedly an important attribute required for successful rowing (Simon et al., 2023). Trunk extension strength has been strongly associated with rowing ergometer performance (Ledergerber et al., 2023) with the potential for the trunk to be a power producer and transmitter in the rowing stroke cycle (Simon et al., 2023).

The anthropometrical considerations of rowing are well established in the literature. Rowers tend to be taller, heavier and have longer arm span and leg length than non-rowers (Hume, 2018). However, it is not as clear when anthropometrical characteristics are compared between elite and junior rowers. Lawton et al. (2012) reported no differences between junior and elite rowers in height and arm span. The current results indicated that the elite men were taller, heavier and had longer leg lengths than the junior men, however, elite women and junior women recorded similar height, weight and limb lengths. *Large* associations were also reported between limb lengths and the on-water metrics of catch angle and stroke length. The absence of differences in female anthropometry in part may be due to the relatively small sample size of each category group. Another comparative study reported on Hungarian female rowers who demonstrated no difference in height; however, the senior rowers recorded significantly higher body weight and arm span than the junior rowers (Podstawski et al., 2022). Comparative anthropometry data on female elite and junior rowers is limited, with the literature more likely to compare within a category group of rowers and distinguish them by competitive success, 2 km ergometer score (Lawton et al., 2012; Slater et al., 2005) or to a relative group of non-rowers (Bourgois et al., 2001). In addition, maturation status should potentially be taken into account when comparing junior rowers to elite rowers, particularly considering that females mature on average 2 years earlier than males (Thompson et al., 2003). This may affect results when comparing similarly aged male and female junior athletes with their elite counterparts. Further, it has been perceived by coaches that maturation status may have implications when considering other physical attributes in junior athletes such as flexibility and range of movement (Legge et al., 2023).

Generalised range of motion (ROM) recommendations for rowing have been established in the literature mostly in regard to injury (Buckeridge et al., 2015; Soper et al., 2004), however, guidelines have not been well-established for junior or elite rowers in relation to performance, and this may be due to the subjectivity of ROM assessment (Gajdosik & Bohannon, 1987). ROM and flexibility can vary within an individual depending on the time of day and frequency of stretching (Bandy et al., 1997; Guariglia et al., 2011) and is influenced by age, sex and training (Monteiro et al., 2008). In the current study, passive hip flexion for males and active knee extension for females were greater in the elite groups compared to the juniors. *Large* associations for males between passive hip flexion and the on-water metrics catch angle, stroke length, mean gate force and drive distance further support the connection between physical attributes such as range of movement and on-water rowing performance. This may reflect training experience and also access to support services that target injury prevention strategies such as flexibility and ROM focussed around the hip and lumbar spine regions, with the lumbar spine being the most susceptible area to rowing injury (Trease et al., 2020). Flexibility and ROM in relation to rowing performance may be better assessed through longitudinal studies that monitor ROM and flexibility measures across a season alongside on-water biomechanical rowing assessment to better understand how these physical attributes affect the execution of the rowing stroke (Rawlley-Singh & Wolf, 2023). For example, anthropometric characteristics may be associated with stroke length, including height, arm span and leg length, however, stroke length may also be influenced by hip flexibility, ankle flexibility and trunk strength (Buckeridge et al., 2015). Further research is required to better understand the relationships between these attributes and the execution of the rowing stroke and the performance outcomes.

Interestingly, the LDA was able to precisely distinguish individuals to the correct categorical group with a high level of accuracy in the current participant population using a combination of the physical and technical variables independent of boat speed. This demonstrates that the selection of physical variables, including attributes of anthropometry, range of motion, rate of force development and maximal strength, can classify an individual by sex and performance level in rowing, irrespective of the main outcome measures of boat speed or race time. In addition, the elite females and junior males recorded very similar results for boat speed, a primary performance outcome measure. Similar findings have been reported when comparing heavyweight and lightweight male rowers with similar boat velocities, where the heavyweight group exhibited superior mean and peak force during on-water rowing assessment. Furthermore, differences were identified in the acceleration profiles and body segment velocities indicating different technical strategies leading to equivalent boat velocities (Doyle et al., 2007). These findings suggest that rowers can achieve a similar boat speed through the integration of different physical and technical parameters (Doyle et al., 2007; R. Smith & Draper, 2006) and the maximal strength and rate of force development attributes tested in this study are strongly related to a number of on-water rowing performance metrics. Coaches and athletes can interpret this information to better understand how the requirements of elite performance can be unique to the individual. Further, these results have implications for individualisation of training programs and planning.

Sports research concerning the physiological and technical aspects of performance are often evaluated mechanistically (Balague et al., 2013) which can lead to a simplistic and limited perspective of athletic performance. There are likely complex interactions between the variables assessed in this study that enabled the LDA to accurately discriminate between individuals by performance level and sex (Balague et al., 2013; North, 2013). This type of analysis has been used in other sports to investigate how independent variables can collectively classify athletes into groups. For example, Taekwondo athletes were correctly discriminated into groups based on kicking torques and velocities according to expertise level (Moreira et al., 2021) while a non-sport-specific testing battery of anthropometric and physical characteristics was able to identify athletes to their nine respective sports (Pion et al., 2015). Elite women and junior men in this study recorded very similar boat speeds in conjunction with differing physical and technical qualities. This highlights the complexities of performance, where the junior men and elite women had different demographics including sex, maturation status and training age alongside varied physical characteristics and attributes. The junior men revealed a higher on-water peak force, 7 stroke peak power and 500 m average power ergometer results and more favourable anthropometry, in height, weight and arm span than the elite women (Bourgois et al., 2000). In contrast, the elite women elicited slightly longer stroke length and catch angle, combined with much better flexibility and ROM compared to the junior men. Subsequently, the resultant outcome was a very similar boat speed across the two groups. Therefore, such data should be viewed by coaches in the way these physical, technical and anthropometrical variables interrelate for each rower, yielding a resultant boat speed.

The findings of this study are strengthened by the use of high-calibre athletes as participants. All elite participants were current national representatives training as part of centralised national squads and considered world-class according to the classification criteria in McKay et al. (2022). Accordingly, the elite-level data can be viewed as a descriptive appraisal of the highest performing athletes in the world. Furthermore, the junior participants were all considered members of the national talent development pathway and approximately one-third of the cohort was national junior representatives in the same season as data collection took place. Whilst being a large-scale project assessing a range of variables both on-water and on-land, the sample size was relatively small, with each of the four categories comprised 12–16 participants. While the elite cohort represents the entire population of available world-class level rowers in Australia at the time of testing, it is important to consider this limitation when interpreting the findings. Finally, there is a distinct shortage of on-water testing in peer-reviewed rowing research, particularly in combination with measured physical attributes. Accordingly, the inclusion of this battery of testing with high-level athletes represents an excellent level of ecological validity for rowing assessment.

Conclusion

This exploratory study combined a comprehensive physical assessment with an on-water single sculling biomechanical assessment to explore the interaction of physical attributes with on-water rowing technical variables. In line with the literature, strong positive relationships were apparent for anthropometry, maximal force and rate of force development attributes with on-water technical variables including the primary performance outcomes of boat speed and mean force. Differences in ROM, flexibility and trunk strength attributes were more challenging to distinguish between elite and junior rowers, with other factors potentially involved.

The combination of different categorical performance variables included in the LDA demonstrated how performance can be characterised by a wide range of attributes. This was further exemplified in the comparison of junior men and elite women, who yielded similar boat speed with the expression of distinctively different attributes. This unique comparison provided no performance context, given males and females do not compete against each other, however it affords an interesting insight into the complex and dynamic nature of performance. In addition, the results provide a descriptive dataset of physical and technical characteristics for elite and junior rowers, of both sexes, which may be useful when evaluating the status of development rowers and to gauge the possibility of achieving further success in the sport.

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References

Akça, F. (2014). Prediction of rowing ergometer performance from functional anaerobic power, strength and anthropometric components. *Journal of Human Kinetics*, *41*(1), 133. https://doi.org/10.2478/hukin-2014-0041

Balague, N., Torrents, C., Hristovski, R., Davids, K., & Araújo, D. (2013). Overview of complex systems in sport. *Journal of Systems Science and Complexity*, *26*(1), 4–13. https://doi.org/10.1007/s11424-013-2285-0

Bandy, W. D., Irion, J. M., & Briggler, M. (1997). The effect of time and frequency of static stretching on flexibility of the hamstring muscles. *Physical Therapy*, *77*(10), 1090–1096. https://doi.org/10.1093/ptj/77.10.1090

Barrett, R., & Manning, J. (2004). Rowing: Relationships between rigging set-up, anthropometry, physical capacity, rowing kinematics and rowing performance. *Sports Biomechanics*, *3*(2), 221–235. https://doi.org/10.1080/14763140408522842

Bourdin, M., Lacour, J.-R., Imbert, C., & Messonnier, L. A. (2017). Factors of rowing ergometer performance in high-level female rowers. *International Journal of Sports Medicine*, *38*(13), 1023–1028. https://doi.org/10.1055/s-0043-118849

Bourgois, J., Claessens, A. L., Janssens, M., Renterghem, B. V., Loos, R., Thomis, M., Philippaerts, R., Lefevre, J., & Vrijens, J. (2001). Anthropometric characteristics of elite female junior rowers. *Journal of Sports Sciences*, *19*(3), 195–202. https://doi.org/10.1080/026404101750095358

Bourgois, J., Claessens, A. L., Vrijens, J., Philippaerts, R., Van Renterghem, B., Thomis, M., Janssens, M., Loos, R., & Lefevre, J. (2000). Anthropometric characteristics of elite male junior rowers. *British Journal of Sports Medicine*, *34*(3), 213–216. https://doi.org/10.1136/bjsm.34.3.213

Brady, C. J., Harrison, A. J., & Comyns, T. M. (2020). A review of the reliability of biomechanical variables produced during the isometric mid-thigh pull and isometric squat and the reporting of normative data. *Sports Biomechanics*, *19*(1), 1–25. https://doi.org/10.1080/14763141.2018.1452968

Buckeridge, E. M., Bull, A. M., & McGregor, A. H. (2015). Biomechanical determinants of elite rowing technique and performance. *Scandinavian Journal of Medicine & Science in Sports*, *25*(2), e176–e183. https://doi.org/10.1111/sms.12264

Clephas, C., & Brückner, J. P. (2020). Variation and progression in performance of national junior athletes and their development to national athletes. *German Journal of Exercise and Sport Research*, *50*(1), 130–135. https://doi.org/10.1007/s12662-019-00602-4

Coker, J., Hume, P., & Nolte, V. (2009). Validity of the powerline boat instrumentation system. ISBS-Conference Proceedings Archive.

Comfort, P., Dos'santos, T., Beckham, G. K., Stone, M. H., Guppy, S. N., & Haff, G. G. (2019). Standardization and methodological considerations for the isometric mid thigh pull. *Strength & Conditioning Journal*, *41*(2), 57–79. https://doi.org/10.1519/SSC.0000000000000433

Doyle, M. M., Lyttle, A. D., & Elliott, B. C. (2007). The effect of rowing technique on boat velocity: a comparison of HW and LW pairs of equivalent velocity. In F. Fuss, A. Subic, & S. Ujihashi (Eds.), *Impact of Technology on Sports II* (1st ed., pp. 513–518). CRC Press.

Draper, C. (2005). Optimising rowing performance in elite women's single sculling. School of Exercise and Sport Science, Faculty of Health Sciences, University of Sydney.

Draper, C., & Smith, R. (2006). *Consistency of technical and performance based rowing variables in single sculling*. ISBS-Conference Proceedings Archive.

Elliott, B., Lyttle, A., & Birkett, O. (2002). Rowing: The Row perfect ergometer: A training aid for on-water single scull rowing. *Sports Biomechanics*, *1*(2), 123–134. https://doi.org/10.1080/14763140208522791

Fleming, N., Donne, B., & Mahony, N. (2014). A comparison of electromyography and stroke kinematics during ergometer and on-water rowing. *Journal of Sports Sciences*, *32*(12), 1127–1138. https://doi.org/10.1080/02640414.2014.886128

Gajdosik, R. L., & Bohannon, R. W. (1987). Clinical measurement of range of motion: Review of goniometry emphasizing reliability and validity. *Physical Therapy*, *67*(12), 1867–1872. https://doi.org/10.1093/ptj/67.12.1867

Gee, T. I., Olsen, P. D., Berger, N. J., Golby, J., & Thompson, K. G. (2011). Strength and conditioning practices in rowing. *The Journal of Strength & Conditioning Research*, *25*(3), 668–682. https://doi.org/10.1519/JSC.0b013e3181e2e10e

Giroux, C., Rahmani, A., Chorin, F., Lardy, J., & Maciejewski, H. (2015). Specific and non specific rowing field evaluation correlated with ergometer rowing performance. ISBS-Conference Proceedings Archive.

Gravenhorst, F., Muaremi, A., Draper, C., Galloway, M., & Tröster, G. (2015). Identifying unique biomechanical fingerprints for rowers and correlations with boat speed-A data-driven approach for rowing performance analysis. *International Journal of Computer Science in Sport*, *14*(1), 4–33.

Guariglia, D., Pereira, L., Dias, J., Pereira, H., Menacho, M., Silva, D., Cyrino, E., & Cardoso, J. (2011). Time-of-day effect on hip flexibility associated with the modified sit-and-reach test in males. *International Journal of Sports Medicine*, *32*(12), 947–952. https://doi.org/10.1055/s-0031-1283182

Holt, A. C., Aughey, R. J., Ball, K., Hopkins, W. G., & Siegel, R. (2020). Technical determinants of on-water rowing performance. *Frontiers in Sports and Active Living*, *2*, 589013. https://doi.org/10.3389/fspor.2020.589013

Hopkins, W., Marshall, S., Batterham, A., & Hanin, J. (2009). Progressive statistics for studies in sports medicine and exercise science. *Medicine & Science in Sports and Exercise*, *41*(1), 3. https://doi.org/10.1249/MSS.0b013e31818cb278

Hume, P. A. (2018). Physique Characteristics Associated with Athlete Performance. In *Best Practice Protocols for Physique Assessment in Sport* 1st ed., pp. 205–216. Springer. https://doi.org/10.1007/978-981-10-5418-1

Kleshnev, V. (2005). Comparison of on-water rowing with its simulation on Concept2 and row perfect machines. ISBS-Conference Proceedings Archive.

Latimer, J., Maher, C. G., Refshauge, K., & Colaco I. (1999). The Reliability and Validity of the Biering–Sorensen Test in Asymptomatic Subjects and Subjects Reporting Current or Previous Nonspecific Low Back Pain. *Spine*, *24*(20), 2085. https://doi.org/10.1097/00007632-199910150-00004

Lawton, T. W., Cronin, J. B., & Mcguigan, M. R. (2012). Anthropometry, strength and benchmarks for development: A basis for junior rowers' selection? *Journal of Sports Sciences*, *30*(10), 995–1001. https://doi.org/10.1080/02640414.2012.682081

Ledergerber, R., Jacobs, M. W., Roth, R., & Schumann, M. (2023). Contribution of different strength determinants on distinct phases of Olympic rowing performance in adolescent athletes. *European Journal of Sport Science*, *8*(2), 1–10. https://doi.org/10.36950/2023.2ciss022

Legge, N., Watsford, M., Sharp, P., O'Meara, D., & Slattery, K. (2023). "A feeling for run and rhythm": Coaches' perspectives of performance, talent, and progression in rowing. *Journal of Sports Sciences*, *41*(10), 927–936. https://doi.org/10.1080/02640414.2023.2249752

McGregor, A. H., Patankar, Z. S., & Bull, A. M. (2007). Longitudinal changes in the spinal kinematics of oarswomen during step testing. *Journal of Sports Science & Medicine*, *6*(1), 29.

McKay, A. K., Stellingwerff, T., Smith, E. S., Martin, D. T., Mujika, I., Goosey-Tolfrey, V. L., Sheppard, J., & Burke, L. M. (2022). Defining training and performance caliber: A participant classification framework. *International Journal of Sports Physiology & Performance*, *17*(2), 317–331. https://doi.org/10.1123/ijspp.2021-0451

McNeely, E., Sandler, D., & Bamel, S. (2005). Strength and power goals for competitive rowers. *Strength & Conditioning Journal*, *27*(3), 10–15. https://doi.org/10.1519/00126548-200506000-00001

Millar, S.-K., Reid, D., McDonnell, L., Lee, J., & Kim, S. (2017). Elite rowers apply different forces between stationary and sliding ergometers, & on-water rowing. *ISBS Proceedings Archive*, *35*(1), 4.

Monteiro, W. D., Simão, R., Polito, M. D., Santana, C. A., Chaves, R. B., Bezerra, E., & Fleck, S. J. (2008). Influence of strength training on adult women's flexibility. *The Journal of Strength & Conditioning Research*, *22*(3), 672–677. https://doi.org/10.1519/JSC.0b013e31816a5d45

Moreira, P. V. S., Falco, C., Menegaldo, L. L., Goethel, M. F., De Paula, L. V., Gonçalves, M., & Peyré-Tartaruga, L. A. (2021). Are isokinetic leg torques and kick velocity reliable predictors of competitive level in taekwondo athletes? *PLOS ONE*, *16*(6), e0235582. https://doi.org/10.1371/journal.pone.0235582

Nolte, V. (2011). *Rowing faster*. Human Kinetics.

North, Julian (2013). A critical realist approach to theorising coaching practice. In P. Potrac, W. Gilbert, & J. Denison (Eds.), *The Routledge handbook of sports coaching* (pp. 133–144). Routledge.

Nugent, F. J., Comyns, T. M., Ní Chéilleachair, N. J., & Warrington, G. D. (2019). Within-session and between-session reliability of the seven-stroke maximal effort test in national level senior rowers. *Journal of Australian Strength and Conditioning*, *27*(4), 22–28.

Nuzzo, J. L. (2022). Narrative review of sex differences in muscle strength, endurance, activation, size, fiber type, and strength training participation rates, preferences, motivations, injuries, and neuromuscular adaptations. *The Journal of Strength & Conditioning Research*, *37*(2), 494–536. https://doi.org/10.1519/JSC.0000000000004329

Olszewski-Kubilius, P., Subotnik, R. F., Davis, L. C., & Worrell, F. C. (2019). Benchmarking psychosocial skills important for talent development.

New Directions for Child and Adolescent Development, *2019*(168), 161–176. https://doi.org/10.1002/cad.20318

Otter-Kaufmann, L., Hilfiker, R., Ziltener, J., & Allet, L. (2020). Which physiological parameters are associated with rowing performance. *Swiss Sports & Exercise Medicine*, *68*(1), 41–48.

Pion, J., Segers, V., Fransen, J., Debuyck, G., Deprez, D., Haerens, L., Vaeyens, R., Philippaerts, R., & Lenoir, M. (2015). Generic anthropometric and performance characteristics among elite adolescent boys in nine different sports. *European Journal of Sport Science*, *15*(5), 357–366. https://doi.org/10.1080/17461391.2014.944875

Podstawski, R., Borysławski, K., Ihasz, F., Pomianowski, A., Wąsik, J., & Gronek, P. (2022). Comparison of anthropometric and physiological profiles of Hungarian female rowers across age categories, rankings, and stages of sports career. *Applied Sciences*, *12*(5), 2649. https://doi.org/10.3390/app12052649

Rawlley-Singh, I., & Wolf, A. (2023). A philosophical approach to aligning strength and conditioning support to a coaches' performance model: A case study from a national rowing performance programme. *International Journal of Sports Science & Coaching*, *18*(1), 278–291. https://doi.org/10.1177/17479541221105454

Schabort, E., Hawley, J., Hopkins, W., & Blum, H. (1999). High reliability of performance of well-trained rowers on a rowing ergometer. *Journal of Sports Sciences*, *17*(8), 627–632. https://doi.org/10.1080/026404199365650

Sebastia-Amat, S., Penichet-Tomas, A., Jimenez-Olmedo, J. M., & Pueo, B. (2020). Contributions of anthropometric and strength determinants to estimate 2000 m ergometer performance in traditional rowing. *Applied Sciences*, *10*(18), 6562. https://doi.org/10.3390/app10186562

Simon, F. R., Ertel, G. N., Duchene, Y., Maciejewski, H., Gauchard, G. C., & Mornieux, G. (2023). Prediction of rowing ergometer performance by technical and core stability parameters. *Journal of Sports Sciences*, *41*(5), 399–407. https://doi.org/10.1080/02640414.2023.2219076

Slater, G. J., Rice, A. J., Mujika, I., Hahn, A. G., Sharpe, K., & Jenkins, D. G. (2005). Physique traits of lightweight rowers and their relationship to competitive success. *British Journal of Sports Medicine*, *39*(10), 736–741. https://doi.org/10.1136/bjsm.2004.015990

Smith, H. (2000). Ergometer sprint performance and recovery with variations in training load in elite rowers. *International Journal of Sports Medicine*, *21*(8), 573–578. https://doi.org/10.1055/s-2000-8476

Smith, R., & Draper, C. (2006). Skill variables discriminate between the elite and sub-elite in coxless pair-oared rowing. ISBS-Conference Proceedings Archive.

Smith, R. M., & Loschner, C. (2002, October). Biomechanics feedback for rowing. *Journal of Sports Sciences*, *20*(10), 783–791. https://doi.org/10.1080/026404102320675639

Smith, T. B., & Hopkins, W. G. (2012). Measures of rowing performance. *Sports Medicine*, *42*(4), 343–358. https://doi.org/10.2165/11597230-000000000-00000

Soper, C., Reid, D., & Hume, P. A. (2004). Reliable passive ankle range of motion measures correlate to ankle motion achieved during ergometer rowing. *Physical Therapy in Sport*, *5*(2), 75–83. https://doi.org/10.1016/S1466-853X(03)00144-5

Thiele, D., Prieske, O., Chaabene, H., & Granacher, U. (2020). Effects of strength training on physical fitness and sport-specific performance in recreational, sub-elite, and elite rowers: A systematic review with meta-analysis. *Journal of Sports Sciences*, *38*(10), 1186–1195. https://doi.org/10.1080/02640414.2020.1745502

Thompson, A. M., Baxter-Jones, A. D., Mirwald, R. L., & Bailey, D. A. (2003). Comparison of physical activity in male and female children: Does maturation matter? *Medicine & Science in Sports and Exercise*, *35*(10), 1684–1690. https://doi.org/10.1249/01.MSS.0000089244.44914.1F

Thornton, J. S., Vinther, A., Wilson, F., Lebrun, C. M., Wilkinson, M., DiCiacca, S. R., Orlando, K., & Smoljanovic, T. (2017). Rowing injuries: An updated review. *Sports Medicine*, *47*(4), 641–661. https://doi.org/10.1007/s40279-016-0613-y

Trease, L., Wilkie, K., Lovell, G., Drew, M., & Hooper, I. (2020). Epidemiology of injury and illness in 153 Australian international-level rowers over eight international seasons. *British Journal of Sports Medicine*, *54*(21), 1288–1293. https://doi.org/10.1136/bjsports-2019-101402

Venables, W., & Ripley, B. (2002). *Modern applied statistics with S*. Springer.

Warmenhoven, J., Cobley, S., Draper, C., Harrison, A., Bargary, N., & Smith, R. (2017). Assessment of propulsive pin force and oar angle time-series using functional data analysis in on-water rowing. *Scandinavian Journal of Medicine & Science in Sports*, *27*(12), 1688–1696. https://doi.org/10.1111/sms.12871

Warmenhoven, J., Cobley, S., Draper, C., & Smith, R. (2018). Over 50 years of researching force profiles in rowing: What do we know? *Sports Medicine*, *48*(12), 2703–2714. https://doi.org/10.1007/s40279-018-0992-3

Williams, B. K. (1981). Discriminant Analysis in Wildlife Research: Theory and Applications. In D. Capen (Ed.), *The Use of Multivariate Statistics in Studies of Wildlife Habitat* (1st ed., vol. *87*, p. 59).