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A novel measure to quantify technical ability in on-water rowing

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ABSTRACT

This study developed a new measure that quantifies technical ability in on-water rowing by accounting for the effects of an athlete's physiological capabilities and the given environmental conditions. Maximal 2000 m efforts for both ergometer and on-water ($n = 340$ of each) were collected from 162 national and international athletes (78 women, 84 men) over 16 years. A linear mixed model predicted on-water performance from static ergometer performance (physiological capability), accounting for day of on-water testing (environmental condition effects). *On-water delta* was the difference between predicted and actual on-water performance. The model revealed significant fixed effects (intercept = 17.70 s, 95% CI = [8.43, 26.97], $p < 0.001$; ergometer coefficient = 0.87, 95% CI = [0.81, 0.93], $p < 0.001$), and random effects for year ranged from −15.43 s to 47.98 s (median = −6.29 s). *On-water delta* ranged from −32.8 s (faster than predicted) to 51.1 s (slower). *On-water delta* provides a new dependent variable that can be used to quantify technical ability in future investigations. The current data provide contextual *on-water delta* values from a large sample of high-level athletes, and the outlined modelling approach can be applied to new datasets to provide population-specific quantifications of technical ability.

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KEYWORDS
Athletes; ergometry; linear mixed model; statistics; technique; water sports

Introduction

Performance outcome in rowing is determined by the ability to cover a set distance (typically 2000 m) on water in the fastest time possible. As in all sports, performance is influenced by numerous factors. On-water technical ability is clearly one important factor that contributes towards on-water performance, as illustrated by the relationships between on-water performance and technique parameters such as mean-to-peak oar force ratio (R. Smith & Draper, 2006), timing of peak oar force (Warmenhoven et al., 2017), and oar force asymmetries (Warmenhoven et al., 2018), for example. The underlying physiological capabilities of the athletes will also influence on-water performance, as illustrated by the significant correlations between 2000 m on-water time and factors such as strength (peak handle force) and $\dot{V}O_{2max}$, both measured using a rowing ergometer (Barrett & Manning, 2004; Jürimäe et al., 2000). If biomechanics researchers and practitioners wish to investigate how specific features of technique relate to performance outcome, it is important that an appropriate performance measure, with minimal bias from other factors, is used as the dependent variable (Bezodis et al., 2010). Investigations focusing on on-water technique in rowing must therefore consider this because outcomes may be biased by other factors such as the athletes' physiological capabilities when using absolute on-water performance as the dependent variable (e.g., R. Smith & Draper, 2006; Warmenhoven et al., 2017, 2018).

The physiological capabilities of an athlete can be quantified in a rowing specific manner using static ergometers. Concept2 ergometer performance, measured by a 2000 m time trial, has very large correlations with lean body mass and $\dot{V}O_{2max}$, for example (both $r = 0.85$, $p < 0.001$; Cosgrove et al., 1999). Static ergometer performance thus provides a valuable rowing-specific measure of an athlete's physiological capability in a task that is broadly similar to on-water rowing in terms of key features such as drive and recovery phase durations and average muscle activations (Fleming et al., 2014). Importantly, it also possesses considerably fewer technical demands than on-water rowing where additional degrees of freedom, such as rotations of the boat and oars, are involved (Loschner et al., 2000; R. Smith & Draper, 2006; Warmenhoven et al., 2018). Therefore, correlating on-water performance against ergometer performance would theoretically yield residuals that provide information about athletes' on-water technical ability given their physiological capabilities. Relatively large positive correlations, ranging from $r = 0.68$ to 0.92, between ergometer times and single scull on-water rankings or times have been observed in several studies on participant groups ranging in size from $n = 10$ to 24 (Barrett & Manning, 2004; Jürimäe et al., 2000; Mikulić, et al., 2009a, 2009b). A weaker correlation ($r = 0.12$) has also been reported for 19 men's athletes during a national team training camp (McNeely, 2011). These typically large, but not perfect, correlations indicate that some athletes perform better or worse on water than might be expected based solely on their respective static ergometer performance. Some of this variation will therefore be due to their on-water

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technical ability because of the aforementioned increased technical demands on water (Loschner et al., 2000; R. Smith & Draper, 2006; Warmenhoven et al., 2018).

Other factors will also contribute to performance differences between ergometer and on-water rowing. A crucial consideration is the environmental conditions during the on-water performance (Holt et al., 2022; Smith & Hopkins, 2011). This would be especially important to consider if on-water performances are carried out on different days. Whilst analysing performance data from a single location over a short duration of time (e.g., a single session) would limit these environmental effects, this would also likely restrict the volume of available data, in turn limiting the confidence in the results obtained. However, if data collected across multiple days are to be used to yield a large dataset, the effects of differing environmental conditions must be considered. Some studies have attempted to record and correct for environmental conditions (e.g., Diafas et al., 2006; Pomerantsev et al., 2022) whilst others have used relative time comparisons (e.g., Kimmins & Tsai, 2021), but there is currently no general consensus on how to best account for environmental effects in on-water rowing (Binnie et al., 2023). The use of linear mixed models could offer a valuable approach to quantify these effects if multiple groups of performances each from a given day and/or location are used, provided that data from a sufficient number of days – and from a sufficient number of performances on each given day – are available. For example, linear mixed models have previously been used with the inclusion of race identity as a random factor to estimate the between-race variation due to environmental conditions when predicting on-water boat velocity (e.g., Holt et al., 2022).

Clearly, factors such as physiological capability and the environmental conditions contribute to on-water performance outcome. However, if the effects of these can be appropriately accounted for, a performance measure that is more reflective of an athlete's on-water technical ability could be obtained. The use of a large dataset comprising competitive ergometer and on-water trials, at which athletes are aiming to be at their physiological and psychological peak, with groups of numerous on-water performances occurring on certain days, would theoretically enable this. The aim of the current study was therefore to develop a novel approach that would yield a new measure of technical ability in on-water rowing that quantifies the difference between an athlete's actual on-water performance and on-water performance as predicted from their ergometer performance. Such a measure would more appropriately reflect athletes' on-water technical ability by reducing the influence of their underlying physiological capabilities or the environmental conditions on the given day, thus providing a valuable and less-biased dependent measure for use in biomechanical investigations of on-water rowing technique. As a secondary aim to yield an initial independent evaluation, values for this newly developed technical ability measure for a sample of athletes were then compared against the expert opinion of experienced coaches.

Methods

Maximal effort ergometer (time taken to cover 2000 m) and on-water (time taken to cover 2000 m in a single scull, hand-timed with a stopwatch) performance data from 2006 – 2022 (excluding 2021 due to COVID-19) were provided, with permission, from the database of a rowing national governing body. Static Concept2 ergometer data were routinely collected as maximal performance efforts during training and were also used to inform national squad selection. The athletes frequently used these ergometers, and thus their performance times were highly reliable (Schabort et al., 1999; Smith & Hopkins, 2012; Soper & Hume, 2004). Furthermore, these static ergometers also yielded a rowing-specific measure of physiological capability that best aligned with our aim as it was less influenced by technical ability than performance times from other ergometers designed to better match the dynamics of on-water rowing. The on-water data were collected on a - single day each year as part of national squad selection trials. The database comprised women's and men's open weight sculling athletes who were senior or U23 and competed at national or international level. Data were extracted for athletes who had either trained and competed in single sculling or were trained in single sculling but usually competed in a sculling crew boat. The final dataset contained 340 rows, each of which comprised the anonymous ID of the corresponding athlete, a 2000 m ergometer time, a 2000 m on-water single sculling time, and the date on which each were performed. Every on-water 2000 m single sculling trial was carried out on the same day within each year, and the corresponding ergometer performances occurred 29 ± 13 days beforehand (mean ± SD; range = 2 to 54 days). Athletes could appear multiple times in the dataset if they completed both rowing performances in multiple years, but due to on-water trials occurring on a single competition day each year they could only have one set of paired ergometer and on-water performance data within each year. The performances in the final dataset were from 162 different athletes (78 women, 84 men) spanning 16 years. Of the 340 paired ergometer and on-water performances, 158 were by women and 182 were by men. The minimum number of performances in a single year (2008) was eight and the maximum (2013) was 37 (mean = 21.3; median = 23). The minimum number of performances by a single athlete was one and the maximum was 10 (mean = 2.1; median = 1).

The fastest ergometer time was subtracted from all ergometer times and the fastest on-water time was subtracted from all on-water times at the request of the national governing body for anonymity purposes. The fastest times may have come from different athletes. This linear transformation only affected the performance times, and therefore the subsequent overall model intercept, but not the relationship between ergometer and on-water performance. Thus, there were no effects on any outcomes relevant to our analysis. All athletes had previously been provided with an athlete privacy notice that confirmed their anonymised performance data may be used for research purposes, and ethical approval for this study was then granted by the Science and Engineering Ethics Committee at Swansea University (approval number 2 2024 9517 9164).

A linear mixed model was fitted to the data with on-water time as the dependent variable and ergometer time as a fixed factor. Athlete ID was defined as a random intercept factor to account for repeated measures by capturing athlete-specific variation. Year – representing the single day within each year on which the on-water national trials finals were performed –

was also defined as a random intercept factor to capture year-specific (i.e., day-specific given the structure of the current dataset) variation which can be assumed to primarily come from the differing environmental conditions (Holt et al., 2022; Smith & Hopkins, 2011). Confidence intervals (95%) for the standard deviations of these random factors were calculated using 100,000 bootstrap samples.

Initial separate models for women and men had overlapping 95% confidence intervals for the intercepts (women's model = [6.17, 42.18], men's model = [9.01, 28.59]) and ergometer fixed effects (women's model = [0.57, 1.00], men's model = [0.59, 1.02]). They were therefore deemed sufficiently similar and a single combined model comprising both women's and men's data was developed. In this combined model, main effect and interaction terms for gender were not significant predictors of on-water time and were thus not included in the final model (Equation 1), and there was not a meaningful ($\Delta > 10$; Burnham & Anderson, 2004) improvement in the Akaike (AIC; without gender = 2584.8, with gender main effect = 2581.9, with gender main effect and interaction = 2585.9) or Bayesian (BIC; without gender = 2604.0, with gender main effect = 2604.9, with gender main effect and interaction = 2612.7) information criteria when these were included. Similar checks were carried out using the number of days between the ergometer and on-water performances as a fixed factor in the model. The overall model fit was better without this factor based on the AIC (without days between = 2584.8, with days between = 2586.1) and BIC (without days between = 2604.0, with days between = 2609.1). Consequently, the number of days between the ergometer and on-water performances was also not included in the final model. The assumptions of normality of residuals and homoscedasticity of variance associated with linear mixed models were assessed (Gelman & Hill, 2007; Zuur et al., 2009). Normality was checked using visual inspections of the Q-Q plot and a kernel density estimate plot, which indicated that the residuals were sufficiently normally distributed. Homoscedasticity was confirmed through inspection of residuals versus fitted values plots. Overall, these checks confirmed that the assumptions were sufficiently satisfied, supporting the validity of the model results.

$$\text{On} - \text{water time}_i = \beta_0 + (\beta_1 \times \text{Ergometer time}_i) + \mu_{\text{Year}} + \mu_{\text{Athlete}} + \varepsilon$$

Equation 1: β_0 = overall model intercept; β_1 = fixed effect for ergometer time; μ_{Year} = random effect (intercept) for a - given year; $\mu_{Athlete}$ = random effect (intercept) for a given athlete; ε = residual term.

The new measure to quantify on-water technical ability – termed *on-water delta* – was then determined as follows. Firstly, each predicted on-water time was calculated using the model coefficients without incorporation of the athlete-specific random intercepts ($\mu_{Athlete}$; Equation 2). This predicted the on-water time from the corresponding measured ergometer time (thus accounting for the athlete's physiological capabilities) based on an average athlete in that year (thus considering the effects of the environment on the given on-water race day). *On-water delta* was then calculated as the difference between the actual on-water time and the predicted on-water time, with a negative *on-water delta* indicating that the actual was faster than the predicted, and vice versa. All data analysis was completed using Python 3.12.4 (Python Software Foundation, python.org), and statistical significance was accepted at $p < 0.05$.

$$\text{Predicted on} - \text{water time}_i = \beta_0 + (\beta_1 \times \text{Ergometer time}_i) + \mu_{\text{Year}}$$

Equation 2: β_0 = overall model intercept; β_1 = fixed effect for ergometer time; μ_{Year} = random effect (intercept) for a - given year.

Given our aim, and that there exists no gold standard measure for under or overperformance on water, we performed an independent evaluation of *on-water delta* values against the expert opinion of three national team coaches as an informal validation and to provide valuable context. Two women's coaches and one men's coach were asked to independently rank a sample of 18 women's athletes, and 14 men's athletes, respectively. These samples comprised athletes with whom the coaches were familiar as they were selected by a practitioner working with the national team. The coaches were asked to rank the athletes from best (rank 1) to worst based on how much better they perceived the athletes to row on water versus on an ergometer across their time on the national team programme. To achieve a single set of coach rankings for the women, the mean was calculated across the two coaches' rankings and these mean values were then assigned a new set of ranks. Every athlete's mean *on-water delta* was then calculated from the model across every year they had performed under the respective coach(es), and these *on-water delta* times were ranked separately for both the women and men with a rank of 1 assigned to the athletes with the most negative *on-water delta* (i.e., faster on water than expected from their ergometer performance). As the men's coach had been working with the national team since 2017, only *on-water delta* values from 2017 onwards were considered for the men. Finally, the Spearman rank correlation coefficient (ρ) was then calculated between the coaches' rankings and the *on-water delta* rankings separately for the women and the men, with values interpreted as follows: $|\rho| \le 0.10$, trivial; $0.10 < |\rho| \le 0.30$, small; $0.30 < |\rho| \le 0.50$, moderate; $0.50 < |\rho| \le 0.70$, large; $0.70 < |\rho| \le 0.90$, very large; and $0.90 < |\rho| \le 1.00$, nearly perfect (Hopkins, 2000).

Results

The model intercept (β_0) and fixed effect for ergometer time (β_1) were 17.70 s (95% CI = [8.43, 26.97], $p < 0.001$) and 0.87 (95% CI = [0.81, 0.93], $p < 0.001$), respectively (Table 1 and Figure 1). The standard deviation attributed to the year random effects was 17.69 s (95% CI = [11.32, 24.01]), and the standard deviation attributed to the athlete random effects was 9.79 s (95% CI = [8.30, 11.21]; Table 2). The median coefficient for the year random effects (μ_{Year}) was

Table 1. Linear mixed model results for the fixed effects.

Fixed effects	Coefficient	95% CI for coefficient Lower	Upper	Standard error	*t*-Statistic	*p*
Intercept (β_0)	17.70	8.43	26.97	4.73	3.74	< 0.001
Ergometer time (β_1)	0.87	0.81	0.93	0.03	27.99	< 0.001

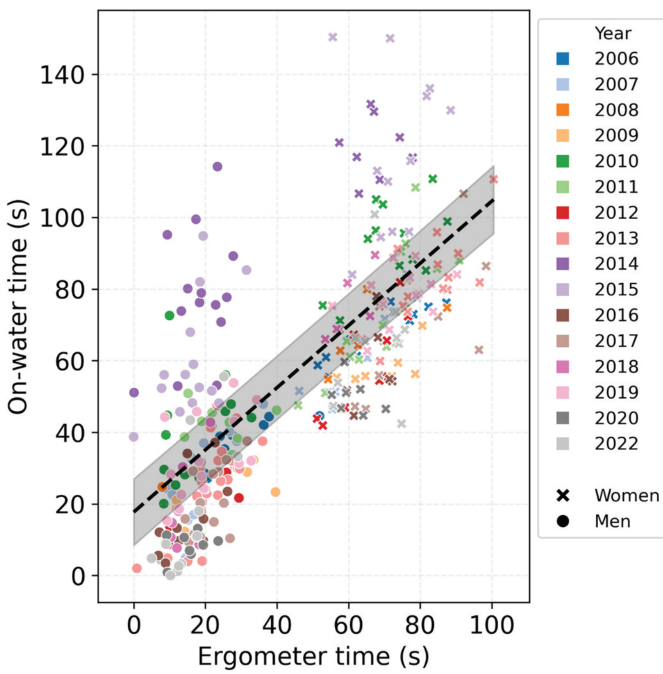

Figure 1. The linear mixed model fitted to the analysed dataset. The black dashed regression line represents the overall mean effect of ergometer time on on-water time across all years and athletes. The shaded grey area represents the 95% confidence interval for the intercept and ergometer time coefficients. Ergometer and on-water times are expressed relative to the fastest respective time – see methods for details.

−6.29 s (range = −15.43 s to 47.98 s; Figure 2). The median coefficient for the athlete random effects ($\mu_{Athlete}$) was −1.00 s (range = −17.51 s to 34.83 s). The predicted on-water times used to quantify *on-water delta* were obtained from the year-specific regression lines (Figure 2). The resulting *on-water delta* times for every pair of ergometer and on-water performance times ranged from −32.8 s (faster than expected) to 51.1 s (slower than expected; Figure 3).

The Spearman rank correlation coefficient between the *on-water delta* ranks and the mean coach ranks for the women's athletes was $\rho = 0.40$ ($p = 0.10$; Figure 4). The Spearman rank correlation coefficient between the *on-water delta* ranks and the coach's ranks for the men's athletes was $\rho = 0.59$ ($p < 0.05$; Figure 5).

Discussion

This study developed *on-water delta* as a novel measure of technical ability in on-water rowing. *On-water delta* quantifies the difference between the actual on-water performance and that predicted from a given ergometer performance, whilst accounting for the potential environmental effects on any given on-water performance day. This was achieved by developing a conceptually simple linear mixed model that accounted for ergometer time (physiological capability) as a fixed factor, and year (day-to-day environmental variation) and athlete ID (repeated measures/athlete-to-athlete variation) as random intercept factors. This model fitted a large historical dataset comprising 16 years of data from 162 national and international level rowers well, with both fixed effects (intercept and ergometer time coefficient) being significant ($p < 0.001$), and the coefficients of the random effect for year ranging by more than 60 s. This *on-water delta* measure has been developed with robust and rigorous mixed modelling methods based on a large, longitudinal dataset with high internal validity and from high-performance athletes. It quantifies the magnitude of over or underperformance when on water compared with that on an ergometer, and given that physiological capability and the variability likely explained by environmental conditions is incorporated into the model, it is thus likely a highly representative outcome of an athletes' on-water technical ability. *On-water delta* is therefore a novel dependent variable that can be used in future investigations of on-water rowing technique as it provides a more objective measure of on-water technical ability than absolute performance (e.g., 2000 m time), the latter being biased by factors such as physiological capability and environmental conditions.

The values for *on-water delta* clearly differed between the athletes. The athlete with the best *on-water delta* (technical ability) was 32.8 s faster than predicted and the athlete with the worst *on-water delta* was 51.1 s slower than predicted (Figure 3). This illustrates the sensitivity and potential scope of *on-water delta* to the effects of differing technical abilities on water, even within a relatively homogeneous cohort of highly trained national and international level rowers, supporting its potential utility. Of note is that the majority of the athletes who had repeated measures in the current dataset tended to have lower *on-water delta* values, that is, they are towards the left-

Table 2. Linear mixed model results for the random effects. 95% confidence intervals (CI) were calculated using 100,000 bootstrap samples.

Random effects	Standard deviation (s)	95% CI for standard deviation (s) Lower	Upper	*p*
Year (μ_{Year})	17.69	11.32	24.01	< 0.01
Athlete ID ($\mu_{Athlete}$)	9.79	8.30	11.21	< 0.001
Residual (ε)	6.69	5.97	7.41	–

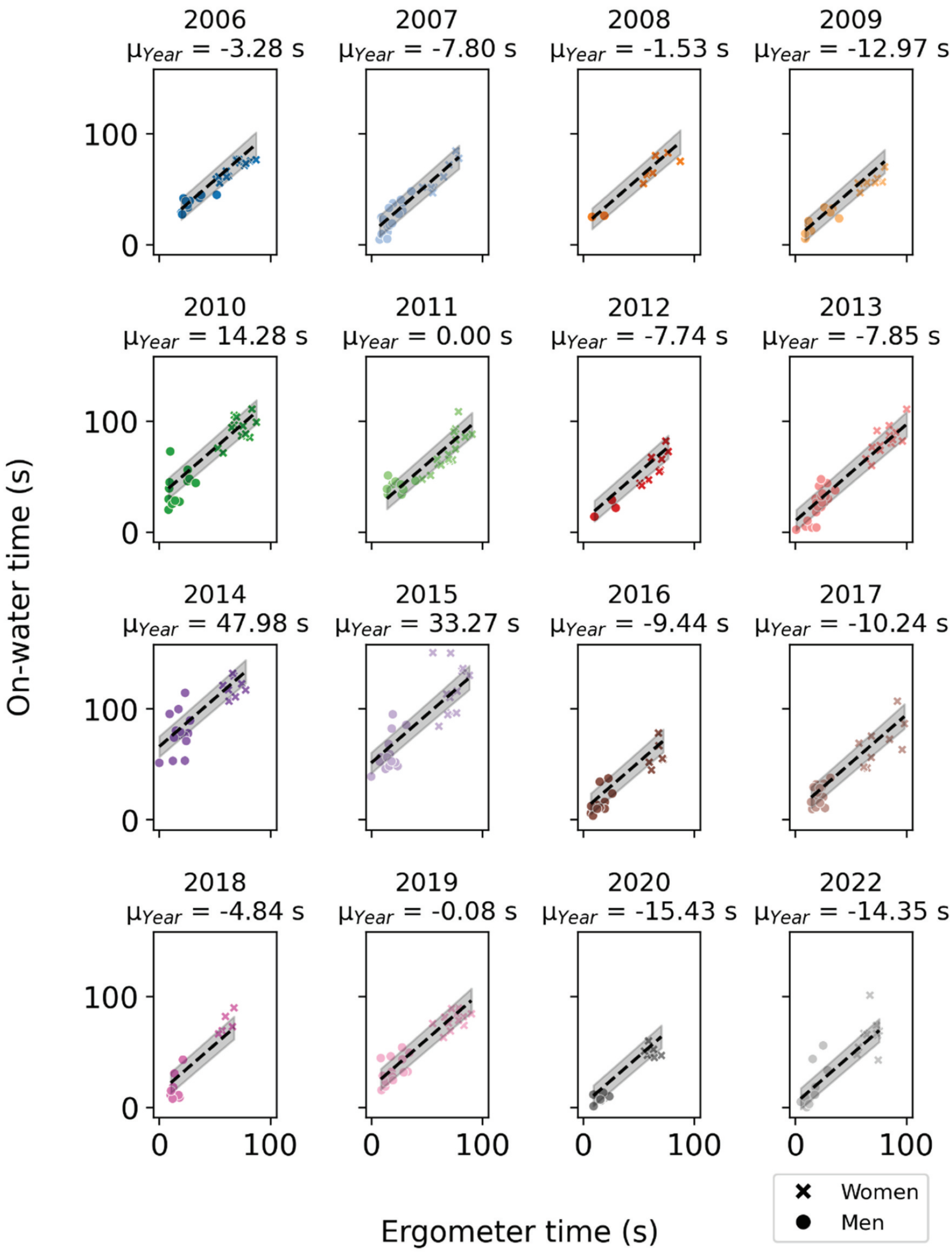

Figure 2. The linear mixed model fitted to the analysed dataset separated by year. The dashed regression lines represent the mean effect of ergometer time on on-water time within a given year across all athletes, after accounting for the random effect of year (μ_{Year}) that was due primarily to the environmental conditions on each given year. The shaded grey areas represent the 95% confidence interval for the intercept and ergometer time coefficients. Ergometer and on-water times are expressed relative to the fastest respective time – see methods for details.

hand side in Figure 3. This suggests that rowers who were retained on the national squad for multiple years tended to have the better on-water technical ability within the studied cohort. In contrast, those who only appeared in the dataset once and were thus either just triallists or on the squad for only one year tended to have higher *on-water delta* values that are representative of relative underperformance, and thus lesser technical ability, on water.

One crucial consideration that drove our rationale and study design as it cannot be ignored when considering on-water rowing performance is the effect of the environmental conditions (Binnie et al., 2023; Holt et al., 2022; Smith & Hopkins,

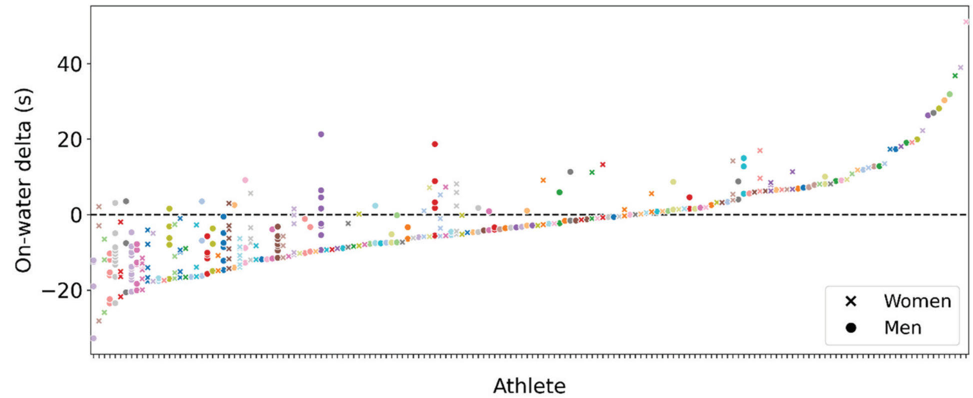

Figure 3. *On-water delta* time for every set of ergometer and on-water performance times for each athlete. Every increment on the x axis represents a different athlete. Multiple performances from the same athlete are plotted vertically.

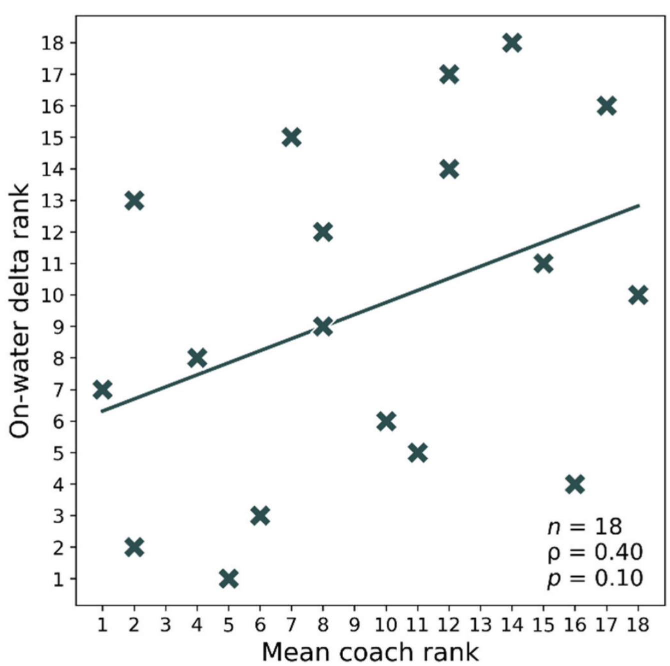

Figure 4. *On-water delta* ranks from the linear mixed model plotted against mean coach ranks from the two coaches for the women's athletes. The line represents the spearman rank correlation.

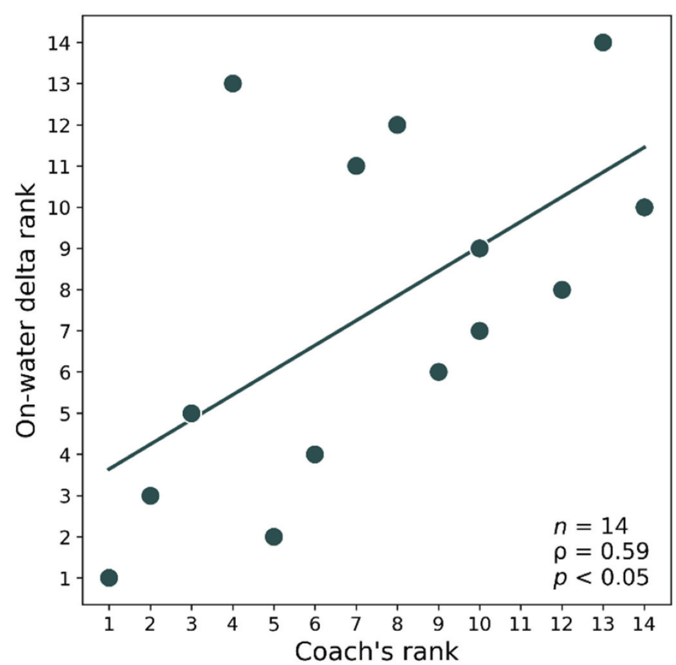

Figure 5. *On-water delta* ranks from the linear mixed model plotted against the coach's ranks for the men's athletes. The line represents the spearman rank correlation.

2011). A key advantage of our linear mixed modelling approach over more traditional methods, such as linear regression, is its ability to include random factors. The inclusion of year enabled us to quantify and account for variability that likely comprised the effects of the different environmental conditions on each given on-water performance day. A few studies have previously included race identity as a random factor, aiming to determine the between-race variation attributable to environmental conditions when predicting on-water boat velocity (Holt et al., 2020, 2021, 2022) and race time (Smith & Hopkins, 2011). The current study builds on this valuable approach by then using data from multiple groups of on-water performances that occurred on the same day and in the same location to account for the effects of the environmental conditions on any given on-water performance within the 16-year dataset. By including year – representing the single day on which the on-water trials were performed each year – as a random factor, the resulting *on-water delta* values therefore take into consideration the year-to-year (i.e., day-to-day given the structure of the current dataset) variation, which can be assumed to largely stem from differing environmental conditions (Holt et al., 2022; Smith & Hopkins, 2011). The range in μ_{Year} values (−15.43 s to 47.98 s) illustrates the varying environmental effects from one day (year) to the next, and the two years with considerably higher μ_{Year} values than any others (2014 and 2015; Figure 2) were confirmed by athletes as years in which the environmental conditions were particularly challenging. Failing to consider the environmental conditions would yield a considerable bias in on-water performance towards days when conditions were more favourable, a factor that is out of the athlete's control and must be accounted for if their technical ability is of primary interest.

The coefficient for ergometer time represented a positive gradient ($\beta_1 = 0.87$), as expected, and it was a significant predictor of on-water performance. The overall model (Figure 1) therefore supports the aforementioned positive relationship that has previously been demonstrated between ergometer performance and on-water performance (Barrett & Manning, 2004; Jürimäe et al., 2000; McNeely, 2011; Mikulić, et al., 2009a, 2009b) and that is well known by coaches and practitioners. Whilst the gradient of the relationship between 2000 m ergometer and on-water performance times has not previously been reported, significant positive relationships with strengths of $r = 0.90$ (Barrett & Manning, 2004) and $r = 0.72$ (Jürimäe et al., 2000) have been identified. These previous relationships may be biased, however, due to their small sample sizes, to the heterogeneity of the studied sample that included both lightweight and open weight athletes ($n = 15$; Barrett & Manning, 2004), or by not truly reflecting high-performance rowing due to the included athletes' relative lack of experience (Jürimäe et al., 2000). The current model uses groups of performances over a 16-year period and therefore extends this previous evidence to confirm that the known positive relationship between ergometer and on-water performance is not perfect; that is, some athletes perform better or worse than might be expected from their ergometer performance alone, even when the environmental conditions are accounted for as discussed above.

Whilst it is not possible to fully validate the new *on-water delta* values obtained from the model outputs, we assessed them against the opinions of expert coaches in an attempt to provide some valuable, albeit still limited, context (Figures 4 and 5). Given the independence of the data-based and the coaches' assessments, the positive and moderate-to-large nature of these relationships – which was significant for the men (Figure 5) but not for the women (Figure 4) – is encouraging as it suggests a level of general agreement between the two ranked assessments. Regardless, the fact these correlations were not perfect suggests that the model may be able to provide additional insight about the athletes' overall technical ability that was not apparent to the coaches, or that challenges their opinion. Whilst the coaches' ranks were based on their subjective expert opinions, the model provides an objective quantitative assessment that is not biased by any preconceptions. The use of *on-water delta* values in combination with coaches' experiential knowledge therefore offers a more objective data-*informed* approach to quantifying on-water performance in the context of an athlete's technical ability than using the actual on-water times as the quantitative information.

One limitation of our approach is the assumption that the environmental conditions were the primary cause of the variations in performance between the given days from each year. All performances were performed within approximately six hours on any given day and thus the conditions were likely relatively consistent across all performances within the random factor for year included in the model. Ideally, this time span would be as small as possible in future studies to limit the potential variation present in on-water performances between races within a single session due to any changes in the environmental conditions. Whilst other considerations such as the physical and psychological preparation of the athlete could affect their performance levels on any given day, we aimed to minimise the influence of these by only using competitive data that were used in squad selection. These high-performance athletes were aiming to be physically and psychologically prepared to compete at, or very near to, their peak for both on-water and ergometer performances, thus reducing the effects of these other factors that could influence the observed relationships. The use of a linear mixed modelling approach also enabled the repeat performances of certain individuals within the dataset across multiple years to be accounted for. Importantly, the coefficients for athlete ID were not incorporated into the calculation of *on-water delta*. This enabled the prediction of on-water performance whilst ensuring there was not a specific adjustment for a given athlete's typical levels of under or overperformance, enabling more appropriate comparisons between athletes. However, the inclusion of athlete ID in the overall model (Equation 1) catered for the interdependence of observations (Hopkins et al., 2009) and enabled the model to be developed using a larger dataset than if only independent observations were included. It is important to note that the current model coefficients cannot easily be applied to new datasets. Given the processing methods used to offset the times for anonymisation purposes, the overall model intercept is unique to the current dataset. Furthermore, the year random factor intercepts are specific to days on which the on-water performance trials took place; predictions of future data would require multiple performances from the same day to accurately determine a new intercept, or could only be made based on the average effect of all current years. The model should therefore be redeveloped with the addition of every new year's worth of data if the athletes have similar characteristics (e.g., performance level), and the time span from which data are included for any given day should ideally be as short as possible. Furthermore, a unique model could be developed for any other dataset of interest to provide results that are specific that dataset, and the current study has developed a novel approach to enable this.

The number of days between ergometer and on-water performances was assessed in the model, and its inclusion did not improve the model's fit. However, it is likely that there is still some variability present owing to differences in training effects over this period. We prioritised the analysis of ergometer and on-water performances from competitive trials to limit other potential effects related to acute physical and psychological preparation. Nevertheless, where possible, the number of days between ergometer and on-water performances would ideally be controlled in prospective studies, with the shortest time interval that enables full recovery between the two performances ensuring minimal changes in the athletes' physiological capabilities. Whilst body mass could also be considered because positive relationships have been identified between body mass and ergometer performance ($r = 0.68$; Nevill et al., 2010) and lean body mass and ergometer performance ($r = 0.85$; Cosgrove et al., 1999), body mass is not related to on-water performance ($r = 0.04$; Nevill et al., 2010) and it was therefore not directly accounted for in the current study since the aim was to understand on-water performance and the contribution of on-water technical ability towards this. Furthermore, the inclusion of body mass into the model would have introduced an issue of multicollinearity given the aforementioned relationships between body mass and ergometer performance (Cosgrove et al., 1999; Nevill et al., 2010).

The novel *on-water delta* measure offers a new way of quantifying the impact of an athlete's on-water technical ability on their performance. Given the modelling approach adopted, this accounts for the known effects of an athlete's physiological capability (Cosgrove et al., 1999) as determined in a rowing-specific manner by using 2000 m ergometer performance, and for the effects of varying environmental conditions (Binnie et al., 2023) by incorporating day-specific coefficients. *On-water delta* thus provides an outcome measure of on-water technical ability that is not biased by physiological capability or environmental conditions. It can therefore be used as a dependent variable in future biomechanical investigations of on-water rowing technique to improve the identification of specific features of technique that may contribute to athletes performing better or worse on water than predicted from their ergometer performance. Such information could then be the focus of future technical interventions that attempt to improve the on-water performance of an athlete with a given physiological capability.

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