DEVELOPING A NEW PERFORMANCE MEASURE TO QUANTIFY THE DIFFERENCE BETWEEN ACTUAL AND PREDICTED ON-WATER ROWING PERFORMANCE

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This study developed a measure of on-water rowing performance (*on-water delta*) that quantifies the difference between actual on-water performance and on-water performance as predicted from ergometer performance. Maximal effort 2000 m ergometer and on-water times ($n = 340$) were collected from 162 athletes over a 16-year period. A linear mixed model was fitted to the dataset to enable predictions of on-water performance from ergometer performance whilst accounting for repeated measures and other factors such as potential environmental effects. *On-water delta* was defined as a model residual and ranged from -32.8 s (overperformed) to 51.1 s (underperformed). On-water under or overperformance compared to that predicted from ergometer performance could provide valuable context for future biomechanical investigations of on-water rowing technique.

KEYWORDS: linear mixed model, rowing ergometer, single scull, technique

INTRODUCTION: Rowing performance is measured by the ability to cover a set distance (typically 2000 m) in the fastest time possible. Elite racing occurs on water, and consequently so does most of the training. However, ergometers are also used for many purposes. Despite the use of both on-water and ergometer rowing in practice, the relationship in performance between the two has not been extensively researched. It is also likely that some athletes perform better or worse when rowing on water than might be expected from their respective ergometer performance because of the extra technical ability required during on-water rowing. Ergometer and on-water performance is positively correlated. Strong positive correlations have been observed for 15 male single scullers at a national team selection camp ($r = 0.90$, $p < 0.001$; Barrett & Manning, 2004) and for 10 experienced male single scullers ($r = 0.72$, $p < 0.05$; Jürimäe et al., 2000). However, a weaker non-significant correlation ($r = 0.12$) was also reported for 19 male athletes during a national team training camp (McNeely, 2011). Despite methodological differences in all three studies, these results confirm that some athletes perform better or worse when rowing on water than might be expected based solely on their ergometer performance. Any apparent on-water under or overperformance may be influenced by several factors. These may include uncontrollable factors such as environmental conditions, but it is also likely that on-water rowing technique plays an important role.

In many sports biomechanics investigations, it is important that the chosen performance measure, which is often used as a dependent variable, appropriately represents the desired focus (Bezodis et al., 2010). On-water rowing technique has been analysed in the context of absolute on-water performance, for example, the time taken to cover 2000 m, mean boat velocity (Holt et al., 2022), or competition level (Warmenhoven et al., 2017). Investigating rowing technique in the context of on-water under or overperformance may provide novel insights into the features of technique that may relate to disparities between on-water and ergometer performance. However, there is no current performance measure in rowing that quantifies the difference between actual on-water performance and on-water performance as predicted from ergometer performance. Any such performance measure in rowing should consider potential environmental effects since on-water times from any given performance are affected by water and air conditions (Holt et al., 2022). It is therefore important to consider the potential effects of the environment when attempting to determine relative on-water performance measures and make comparisons across a range of environmental conditions. Linear mixed models (LMMs) appear to offer a suitable approach for achieving this as they have previously been used with the inclusion of race ID as a random factor to estimate between-race variation due to potential environmental conditions when predicting on-water boat velocity (e.g., Holt et al., 2022). The aim of the current study was to develop an appropriate measure of on-water rowing performance that quantifies the difference between actual on-water performance and on-water performance as predicted from ergometer performance, whilst accounting for the potential environmental effects on any given performance day. Such a measure of performance would provide valuable context for subsequent biomechanical investigations of on-water rowing technique.

METHODS: Maximal effort ergometer (time taken to cover 2000 m) and on-water (time taken to cover 2000 m in a single scull) performance data from 2006-2022 (excluding 2021 due to COVID-19) were provided with the national governing body's permission. The database comprised male and female open weight sculling athletes who were senior or U23 and competed at national or international level. The athletes had either trained and competed in single sculling or were trained in single sculling but usually competed in a sculling crew boat. The ergometer data were collected routinely as part of their regular training programme, and the on-water data were collected on a single day each year as part of national squad selection trials. The final dataset consisted of 340 entries, each with one 2000 m ergometer time, one on-water 2000 m single sculling time, the year they were performed, and the anonymous ID of the corresponding athlete. Every on-water 2000 m single sculling trial was carried out within 29 ± 13 days (mean ± SD; range = 2 to 54 days) following an ergometer test. Athletes could appear multiple times in the dataset if they completed both rows in multiple years, but due to on-water trials occurring on a single competition day each year they could only have one set of ergometer and on-water performance data within each year. The performances in the final dataset were from 162 different athletes (84 male, 78 female) over 16 years. The minimum number of performances in a single year was eight (2008) and the maximum was 37 (2013). Meanwhile, the minimum number of performances by a single athlete was one and the maximum was 10. At the request of the data provider and for athlete anonymity purposes, the fastest ergometer time and on-water time in the whole dataset were subtracted from all ergometer and on-water times, respectively.

A linear mixed model was fitted to the final dataset with on-water time as the dependent variable and ergometer time as a fixed factor. Year and athlete ID were defined as random intercept factors to capture year-specific variation (likely primarily due to environmental effects) and to account for repeated measures. Prior investigations of separate male and female LMMs revealed that the intercepts (male model = 18.80, female model = 24.17) and ergometer fixed effects (male model = 0.80, female model = 0.78) were similar between the two models. This provided justification for a single combined model. Main effect and interaction terms for sex were not included in the final combined model because they were not significant predictors of on-water time and there was not a significant improvement in the Akaike or Bayesian information criterions when these were included. An equation for the final LMM is represented in Equation 1.

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

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 performance measure reflecting the difference between actual on-water performance and on-water performance as predicted from ergometer performance, termed *on-water delta* (*δ*), was defined as the model residual without incorporation of the athlete-specific random intercepts. A negative time indicates that the actual on-water performance was faster than the predicted on-water performance, and vice versa. The predicted on-water performance for a given athlete was obtained from Equation 2. All data analysis was completed using Python 3.8.17 (Python Software Foundation, python.org).

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

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

RESULTS: The model intercept (β_0) and fixed effect for ergometer time (β_1) was 17.70 (t = 3.74, p < 0.01) and 0.87 (t = 27.99, p < 0.01), respectively. The *on-water delta* times for every set of ergometer and on-water performance times for each athlete are shown in Figure 1. The most extreme positive and negative *on-water delta* times were 51.1 s and -32.8 s. Figure 2 shows the fit of the linear mixed model by year. The dashed regression lines represent the mean effect of ergometer time on on-water time across all athletes within a given year when adjusted using the year-specific random effect coefficients. These regression lines provided the predicted on-water times used to quantify *on-water delta*.

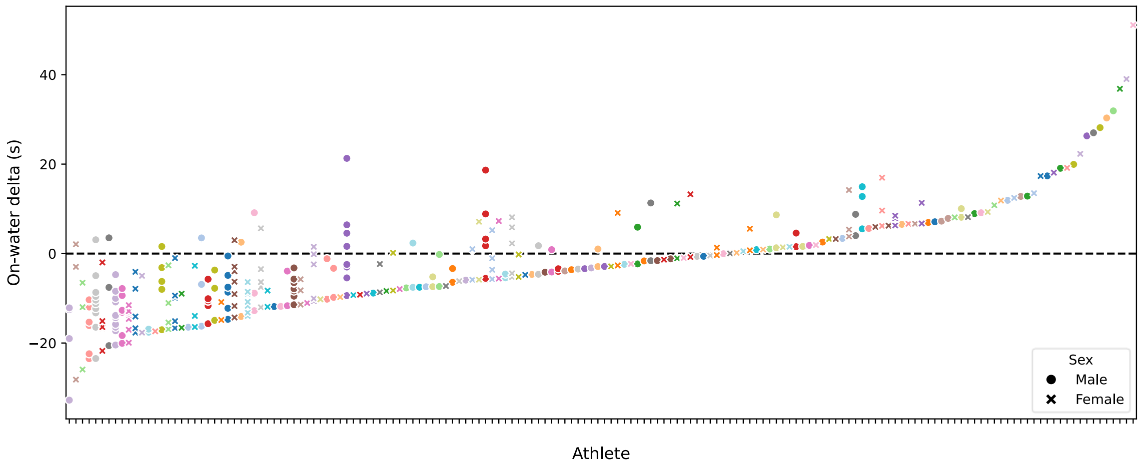

Figure 1: *On-water delta* time for every set of ergometer and on-water performance times for each athlete. Every increment on the x axis represents a different athlete. Multiple performances from the same athlete are plotted vertically.

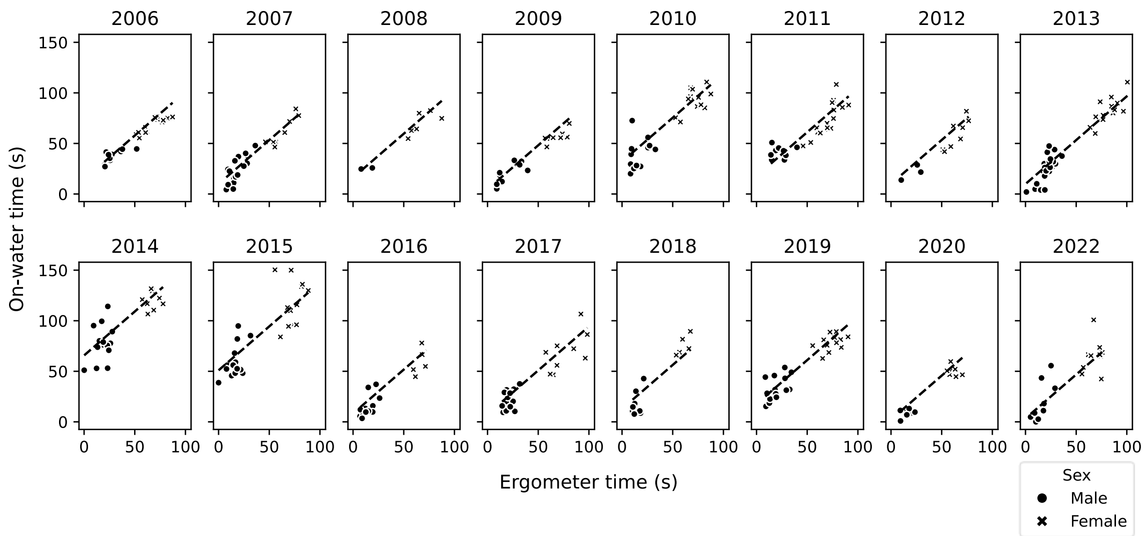

Figure 2: The linear mixed model fitted to the analysed dataset separated by year. The dashed regression lines represent the mean effect of ergometer time on on-water time across all athletes within a given year. Ergometer and on-water times are expressed relative to the fastest respective time - see methods for details.

DISCUSSION: This study developed a measure of on-water rowing performance that quantified the difference between actual on-water performance and on-water performance as predicted from ergometer performance, whilst accounting for potential environmental effects when performing on water, for example, those due to weather conditions on any given performance day. The LMM residuals calculated without athlete ID random effects quantify how much better or worse an athlete performs when rowing on water compared to how the average athlete in the dataset would be predicted to perform based on their respective ergometer performance. This LMM residual is proposed as a new performance measure, termed *on-water delta*. Excluding athlete ID from the residual calculation ensured there was not a specific adjustment for a given athlete's typical levels of under or overperformance, better enabling between-athlete comparisons.

The *on-water delta* times, which clearly differed between athletes and ranged from -32.8 s to 51.1 s (Figure 1), can be used as the dependent variable in biomechanical investigations of on-water rowing technique to yield insights regarding the technical features that lead to some athletes performing better or worse on water than expected from their ergometer performance. Defining *on-water delta* as the previously described LMM residual means that *on-water delta* captures aspects of an athlete's performance that are not accounted for by the relationship between ergometer performance and on-water performance. Given that biases due to the underlying physiological ability of an athlete are limited by the inclusion of ergometer performance as a fixed factor, and that potential environmental effects are accounted for by the inclusion of year as a random factor, an approach utilised similarly by Holt et al. (2022), this means that on-water rowing technique likely explains most of the unaccounted-for variance in the predicted on-water times (i.e., *on-water delta*). Previous investigations of on-water rowing technique have been undertaken in the context of absolute on-water performance (e.g., Holt et al., 2022), yet this means that any findings can only be interpreted in the context of on-water performance, and these may be biased by athletes' underlying physiological ability (as primarily assessed by an ergometer), and the on-water environmental conditions on a given day. *On-water delta* overcomes these potential limitations and can offer suitable context for investigating the disparities in performance between ergometer and on-water rowing, especially given the common use of both modes for athlete testing and monitoring.

CONCLUSION: A new on-water rowing performance measure was developed that quantified how much better or worse an athlete performed on water compared to how they were predicted to perform based on their ergometer performance. The use of an LMM enabled the analysis of longitudinal data spanning 16 years from national and international level athletes and predictions of on-water performance from ergometer performance whilst accounting for the potential effects of environmental conditions. *On-water delta* was defined as an LMM residual and can be used as a performance measure in biomechanical investigations of on-water rowing technique to enable coaches to better understand features of technique that may relate to an athlete performing better or worse on water than expected.

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