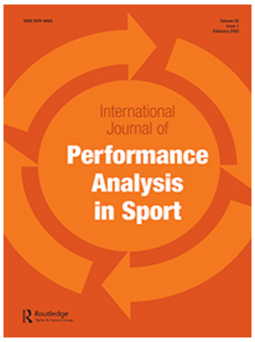

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Key technical factors and steadiness in Olympic and regional sailors in ILCA class: insights from a sailing simulator study

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ABSTRACT
Little attention has been given to the study of sport sailing. A new trend in performance analysis of cyclic sports involves examining steadiness between cycles. Therefore, the aims of this study were as follows: to determine which technical aspects differ between Olympic and regional-level sailors to maximise performance in the ILCA class, and to analyse whether steadiness in these technical variables is enhanced in athletes at a higher competitive level. A total of 36 ILCA sailors participated in the study—8 from Olympic teams and 28 from regional competitions – performing a sailing test on a simulator. Performance and technical variables, such as speed, heading angle, boom angle, heel angle, rudder angle, and hiking effort were assessed. Additionally, short-term and long-term steadiness of these variables were analysed. Olympic sailors demonstrated superior performance by higher speed, greater hiking effort, and lower heading, boom, heel, and rudder angles ($p < 0.05$). Furthermore, Olympic sailors exhibited greater steadiness in some technical variables ($p < 0.05$). In conclusion, Olympic sailors outperform regional sailors in specific linear tests due to higher speed influenced by technical aspects related to the mechanical behaviour of the boat and the ability to maintain more consistent force values and steadier technical aspects.

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Movement variability; sport sailing; Olympic athletes; performance; cyclic sports

1. Introduction

Currently, limited attention has been directed towards the study of sport sailing, particularly regarding the performance of elite athletes in this discipline. This gap in research is largely attributable to the inherent challenges in designing scientific studies within an environment influenced by numerous meteorological and environmental variables, such as wind, sea conditions, and the presence of competitors. The replication of identical conditions across these factors is highly improbable. As a result, the uncertainty surrounding sailors necessitates a high level of adaptability. According to under the framework of complex dynamical systems theory applied to sport sailing, the sailor who best

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adapts to continuous changes and maintains optimal control of the boat in response to both external factors (e.g. weather, competitors) and internal factors (e.g. fatigue, stress) is more likely to succeed.

Due to the difficulty of consistently replicating real-world conditions, much of the existing research has shifted towards controlled laboratory and simulation environments (Manzanares et al., 2017; Pluijms et al., 2013). Sailing simulators offer the ability to recreate conditions closely resembling real-world conditions while enabling the analysis of specific variables across sailors under uniform external conditions. However, environmental factors are not the sole determinants of sailing performance. Other factors, such as boat design, sail configurations, tactical decisions, technique, physical and mental fitness, decision-making processes, information acquisition, and injury risk, also play critical roles (Brandt et al., 2012; Manzanares et al., 2016; Pluijms et al., 2013). Given the multitude of variables influencing sailors' performance, it is essential to control external conditions in order to gain insight into internal dynamics. Thus, simulators serve as an invaluable tool for regulating sailing variables within a controlled laboratory context.

Research on sailing performance has traditionally emphasised variables related to physical conditioning, physical capabilities, and technical proficiency (Cunningham & Hale, 2007; Vangelakoudi et al., 2007). Noteworthy studies have examined the impact of competition on biochemical markers, such as cortisol, as well as factors like fatigue (Philippe et al., 2022). Other researchers have sought to compare performance across different groups based on psychological variables (Brandt et al., 2016), fatigue resistance, or neuromuscular performance (Philippe et al., 2022; Vangelakoudi et al., 2007) given the strong correlation between physical fitness and overall sports performance. In any discipline involving technical movements, superior physical fitness can often be a decisive factor. However, in sailing, performance may also be influenced by a combination of technical and physical factors. Moreover, the technical manoeuvres executed during competition can lead to variations in specific performance aspects. For example, changes in rudder angle may alter the boat's heading, while increased hiking efforts can help maintain optimal heel angle values (Lovas et al., 2022).

In addition to the interaction between various sailing variables, performance can also be defined by the ability to maintain stable angles that optimise boat speed. Thus, analysing the stability of technical factors influencing performance becomes crucial. Previous studies have successfully investigated the steadiness of technical movements in other water sports, such as canoeing (Abellán-Aynés et al., 2022), where consistent or prolonged variations during trials were found to reduce speed. This suggests that a more consistent movement cycle is associated with better performance. In human-powered water sports like swimming (Fernandes et al., 2022; López-Plaza et al., 2024), the relationship between the variability of speed, stroke rate, and performance has also been examined. This trend appears to be a defining characteristic of cyclic sports, where steadiness can significantly affect the speed of an athlete or a boat in competition or specific trials.

In sailing, performance may be compromised by a lack of consistency in technical aspects. Instantaneous deviations in fixed angles, whether in the transverse plane or along the waterline, can result in reduced boat speed due to increased hydrodynamic friction (Li et al., 2022). Therefore, there is a pressing need to examine how these stability factors impact performance in order to optimise outcomes in Olympic sailing competitions.

The aims of this study were: first, to identify the technical differences between Olympic and regional-level sailors in the Ilca class that impact performance; and second, to investigate whether athletes at higher competitive levels exhibit better steadiness in these technical aspects during tests and to estimate performance based on both technical and steadiness variables through regression analysis. It was hypothesised that a greater steadiness in technical aspects would lead to further speed, being Olympic sailors those who show the greatest stability.

2. Material and method

2.1. Participants

A total of 36 sailors from the ILCA sailing class participated in the study. Among them, 8 were members of Olympic teams from Norway, Canada, Mexico, and Spain, with a mean body mass of 75.21 ± 10.36 kg and a mean height of 177.67 ± 8.32 cm. This group included 6 men (mean age: 31.67 ± 6.86 years) and 2 women (mean age: 27.5 ± 2.12 years). The remaining 28 sailors, with a mean body mass of 60.2 ± 8.2 kg and a mean height of 171 ± 7.3 cm, competed in the Regional Championship of the Murcian Sailing Federation. This group comprised 23 men (mean age: 16.5 ± 1.7 years) and 5 women (mean age: 16.3 ± 1.4 years). All participants, as well as their parents or legal guardians, provided consent to participate in the research.

The study was approved by the Ethics Committee of the Catholic University of Murcia (registry no. 6776). Additionally, the research adhered to the ethical standards for human studies outlined in the Declaration of Helsinki. All participants signed an informed consent form after receiving a detailed explanation of the study.

2.2. Measurements and procedures

To measure the determinants of performance, a sailing simulator (vSail-Trainer®, Virtual Sailing Pty Ltd, Parkville Victoria, Australia) was utilised, which has been previously employed in other studies (Menayo et al., 2018). The simulator comprises two main components. The first is the hardware, which includes a boat hull and a portable computer. The computer manages the second component, the software, which controls the virtual simulation, sailing conditions, projection, and sound effects of the simulated environment. The boat hull is equipped with an electronic system and a hydraulic arm. The electronic system controls the movement of the hull and is connected to the computer, which adjusts sailing conditions such as wind direction and intensity. For this study, the simulator used a hull modelled after the Ilca boat, allowing for realistic movement reproduction. The simulator operates similarly to a real boat, with a rudder for direction control and a sheet for mainsail adjustment. Additionally, it simulates the boat's pitch angle, requiring sailors to continuously adjust their position relative to the pitch. A 2.00 m × 2.50 m screen was used to project an image that replicates the actual dimensions (Figure 1)

The measurement protocol involved a simulated sailing scenario on the simulator with a wind speed of 16 knots. Sailors navigated using sail dimensions corresponding to either the Ilca 7 or Ilca 6, depending on their actual sailing class. Data for both classes

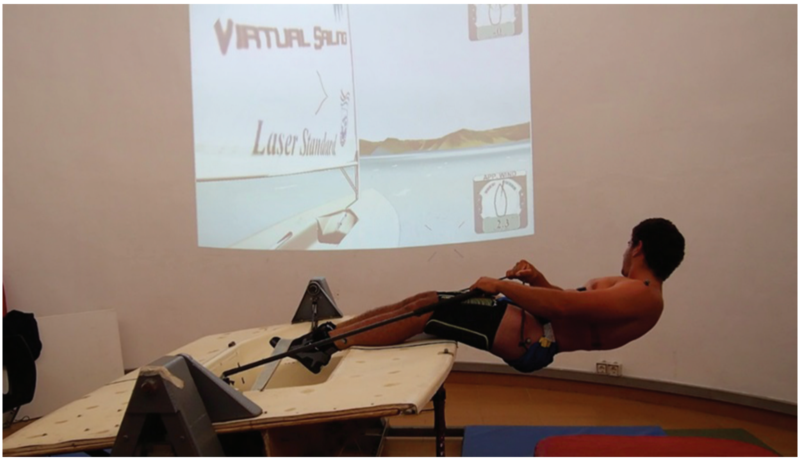

Figure 1. Sailor performing the fatigue test.

were normalised by applying a correction factor based on the Ilca 7 sail area to standardise the Ilca 6 results. The protocol required sailors to complete a navigation test to exhaustion. During the test, sailors were instructed to sail upwind for the entire duration while keeping the boat as flat as possible to maintain maximum performance. This was monitored through real-time navigation speed and angulation data provided by the simulator. To enhance engagement, the boat's speed indicator was placed within the sailor's view, and sailors were encouraged to sail as fast as possible on that course until reaching maximum fatigue. The test concluded when sailors could no longer maintain the boat's flatness without slowing down or changing course (see Figure 1).

Before the protocol, each sailor underwent a familiarisation session with the simulator to eliminate any learning effects on performance. This was followed by a warm-up consisting of joint mobility exercises and 5 minutes of free navigation to prepare the sailor for the sub-maximal effort. All sailors performed the test on the starboard side.

The variables evaluated with the simulator were as follows: (1) Speed: the speed at which the sailor navigated during the test, measured in knots; (2) Heading angle: the angle of the boat relative to the wind direction. In this upwind course test (45º), sailors should aim to maintain this angle as closely as possible; (3) Rudder angle: the degrees of rudder deflection from the position needed to keep the boat sailing straight. This angle also corresponds to the boat's cruising plane; (4) Heeling angle: the lateral angle of the boat's hull during the test, which is counteracted by the force exerted through hiking; (5) Boom angle: the degrees of separation of the boom from the boat's centerline (the line dividing the boat into port and starboard sides); (6) Hiking: the force exerted during the action of hiking, measured in newtons.

2.3. Steadiness analysis

For each of the tests, a time series of the following type was obtained $\{DP_1 \ldots, DP_i, \ldots, DP_N\}$ where DP is each data point obtained at a frequency of 6 hz. Once all the time series were processed, the long-term steadiness (LTS) was first analysed based on the standard deviation of the values of all the data points. Therefore, the equation used to obtain the LTS was:

$$LTS = \sqrt{\frac{\sum_{i}^{N} \left(DP_i - \overline{DP}\right)^2}{N-1}} \tag{1}$$

Once the LTS of each variable was obtained, the short-term steadiness (STS) was analysed based on the root mean square of successive differences between data points to establish the instantaneous variability between consecutive data points for each time series of each variable. In this way, the STS calculation was established with equation (2)

$$STS = \sqrt{\frac{\sum_{i=1}^{N-1} \left(DP_i - DP_{i+1}\right)^2}{N-1}} \tag{2}$$

2.4. Statistical analysis

Data analysis was carried out entirely in Statistical Package for the Social Sciences (SPSS) version 23 (IBM, New York, U.S.A.) for Windows. The Shapiro–Wilk test was used to check the existence of behaviour statistically different from the normality curve in each of the variables. For intergroup comparisons, a t-test for independent samples was used for those variables that did not differ significantly from the normal curve, while the Mann–Whitney U test was used for those variables that did differ statistically from normality. It was set at a significance level of $p < 0.05$. Finally, to study the predictability of boat speed based on technical variables and steadiness variables, a stepwise multiple linear regression was performed based on two different criteria. The first criterion was the use of only technical variables without taking steadiness variables into account, while the second criterion was a regression using technical variables as well as steadiness variables to predict average test speed. Those variables that did not make a significant contribution to the regression model ($p < 0.05$) were not considered. The variables included in the final model were selected automatically through a stepwise linear regression approach. This allowed to objectively determine which variables contributed most to the model, refining the analysis without introducing bias. All results are expressed as mean and standard deviation (SD).

3. Results

Table 1 shows the comparison between the Olympic and regional sailors for the technical variables. Firstly, it can be highlighted the presence of differences between both groups in the variable speed, where Olympic sailors presented higher values. Regarding the rest of the variables, a heading value significantly closer to 45º is observed in the group of olympic sailors compared to the sailors of regional category. On the other hand, the regional sailors present values significantly closer to 0º in the rudder angle variable than the olympic sailors, while the olympic sailors show values significantly closer to 0º in the variables Heel angle and Boom angle. Finally, it should be noted the significantly higher Hiking effort exerted by the olympic sailors compared to the sailors of regional category.

Table 1. Comparison of technical variables between regional and Olympic sailors.

	Regional ($n = 28$)		Olympic ($n = 8$)		
Variable	Mean	SD	Mean	SD	p
Speed (knots)	6.17*	0.48	6.67*	0.48	0.014
Heading angle (º)	57.55*	5.37	52.4*	3.32	0.015
Rudder angle (º)	−1.45*	1.08	−2.63*	0.95	0.008
Heel angle (º)	4.6*	2.26	2.7*	1.31	0.03
Boom angle (º)	−6.71*	3.17	−3.23*	3.15	0.01
Hiking effort (N)	1018.37*	97.65	1608.17*	195.04	<0.001

SD: Standard deviation; N: Newton; *Statistically significant differences ($p < 0.05$).

Table 2. Comparison between regional and Olympic sailors in steadiness variables.

	Regional ($n = 28$)		Olympic ($n = 8$)		
Variable	Mean	SD	Mean	SD	p
$Speed_{STS}$ (knots)	0.02	0.01	0.02	0.02	0.808
$Speed_{LTS}$ (knots)	0.47	0.18	0.48	0.26	0.421
$Heading_{STS}$ (º)	0.8	2.17	0.39	0.2	0.867
$Heading_{LTS}$ (º)	6.63*	3.16	4.74*	1.27	0.016
$Rudder_{STS}$ (º)	1.6	0.65	1.75	0.74	0.578
$Rudder_{LTS}$ (º)	4.81	2.02	4.6	1.9	0.799
$Heel_{STS}$ (º)	0.14	0.08	0.17	0.12	0.34
$Heel_{LTS}$ (º)	0.88	0.61	1.25	0.70	0.168
$Boom_{STS}$ (º)	0.48*	0.65	0.08*	0.05	<0.001
$Boom_{LTS}$ (º)	3.25*	1.65	1.47*	1.12	0.007
$Hiking_{STS}$ (N)	18.71	7.97	21.81	10.8	0.375
$Hiking_{LTS}$ (N)	119.83*	51.66	74.88*	14.54	<0.001

SD: Standard deviation; STS: Short-term steadiness; LTS: Long-term steadiness; Heading: Heading angle; Rudder: Rudder angle; Heel: Heel angle; Boom: Boom angle; Hiking: Hiking effort; N: Newton; * Statistically significant differences ($p < 0.05$).

Regarding the steadiness of the technical variables mentioned, Table 2 shows that concerning the LTS variables, regional level sailors present significantly higher values of Boom angle, Heading angle and Hiking effort compared to Olympic sailors ($p < 0.05$). Regarding STS variables, regional sailors show significantly higher values ($p < 0.05$) than Olympic-level sailors only in the Boom angle while the rest of variables do not show differences between groups.

Finally, Table 3 shows the results of the multiple regression with mean speed as the dependent variable. We observed that Heel and Heading angle as well as Hiking effort present an $r = 0.919$ as predictors of speed taking into account only the technical variables. On the other hand, when introducing steadiness variables in the model, we obtain an $r = 0.964$ when considering Heel, Heading and Rudder angle along Hiking effort and $Heel_{LTS}$ in the model.

Table 3. Regression equations for the whole group of sailors ($n = 36$) to predict mean speed from steadiness variables and/or mean values.

Type-of-variable based	Equation	r	SEE
Technical variables	$-0.077 \cdot Heel + 0.061 \cdot Heading + 0.001 \cdot Hiking + 1.835^{**}$	0.919	0.213
Mean-values and steadiness-based variables	$-0.49 \cdot Heel + 0.42 \cdot Heading + 0.001 \cdot Hiking + 0.161 \cdot Rudder - 0.073 \cdot Heel_{LTS} + 2.851^{*}$	0.964	0.148

SEE: Standard error of estimate; Heel: Heel angle (º); Heading: Heading angle (º); Hiking: Hiking effort (N); Rudder: Rudder angle (º) LTS: Long-term steadiness. *Significant contribution ($p < 0.01$) to the predictive model. **Significant contribution ($p < 0.001$) to the predictive model.

4. Discussion

The main finding of this study is that Olympic and regional sailors differ in technical aspects related to boat navigation. Additionally, Olympic sailors exhibit differences in steadiness variables compared to regional sailors.

While it may be expected that differences exist between Olympic and regional sailors in technical sailing variables, there are no prior studies specifically analysing these aspects. This study addresses whether specific technical aspects of sailing can influence performance in the Ilca category. The observed differences between Olympic and regional sailors indicate that technical aspects do relate to performance, as evidenced by the significantly higher speed values achieved by Olympic sailors during the test. Firstly, Olympic sailors demonstrated a higher average speed during the test, highlighting a clear performance difference compared to regional sailors. This finding underscores that Olympic-level sailors generally outperform their regional counterparts. Notably, Olympic sailors showed a heading angle significantly closer to 45º, along with higher hiking effort values. The increased hiking effort observed in Olympic sailors may be related to greater body mass and force production capacity. Thus, a higher ability to exert force on the boat appears to be associated with improved performance in this sport.

In sailing, achieving optimal boat speed involves adjusting various variables. To reach the windward mark as quickly as possible in upwind sailing, sailors must navigate the boat at an angle close to 45º, keep the sails close-hauled, and position their bodies out to maintain a horizontal alignment with the sea line. Some authors (Bojsen-Møller et al., 2007; García & Martínez, 2015; Vangelakoudi et al., 2007) have noted that high-performing sailors can maintain greater speeds while sailing upwind by generating higher hiking forces for extended periods. These findings align with the results of the present study. Additionally, Olympic sailors demonstrated a rudder angle significantly closer to zero, which suggests that a tighter rudder angle reduces speed losses due to hydrodynamic friction (Lovas et al., 2022; Pennanen et al., 2016; Roncin & Kobus, 2004). This concept is well known and practiced by sailors, and the results indicate that higher-level sailors manage this variable more effectively than their lower-level counterparts. Finally, in terms of boat movement along the waterline, a tighter boom angle results in reduced deceleration and, consequently, better performance in specific tests within the Ilca category. Sail trim, which affects both speed and heel of the boat, is better managed by Olympic sailors. Their ability to exert greater hiking force allows them to maintain a tighter boom angle and achieve higher speeds (García & Martínez, 2015).

Regarding the transverse plane of the boat during the test, Olympic sailors achieved lower heel angles. This observation suggests that a higher heel angle results in significantly reduced speed. A greater heel angle increases the surface area in contact with the water, which generates higher hydrodynamic forces in the opposite direction, potentially slowing the boat and diminishing performance during a competition (Lovas et al., 2022; Pennanen et al., 2016; Roncin & Kobus, 2004).

In the present study, we aimed not only to analyse technical variables in absolute values but also to assess whether greater instantaneous or trial-long variations in these variables could affect the mean speed and, consequently, performance. While the Olympic sailors demonstrated a significantly higher mean speed, there was no difference between the two groups in the steadiness of speed. Both groups had $Speed_{sts}$ values very close to zero, which is expected given that this was a constant course test. With no turns during the test, there were no events causing decelerations or accelerations, resulting in a constant velocity throughout.

In more technically demanding tests, such as those involving tacks or gybes, instantaneous speed variations might occur, potentially highlighting differences in performance between high-level and lower-level sailors. The $Speed_{sts}$ values were slightly higher than $Speed_{STS}$, likely because, over the long term of the test, there might be a range of speeds from standstill to maximum speed. However, there were no significant differences in $Speed_{LTS}$ between Olympic and regional sailors, possibly due to the absence of course changes in the test.

As for the steadiness of the technical aspects occurring on the waterline, no differences between groups are noticeable in $Heading_{STS}$. This may be due to the linear nature of the test, as no instantaneous changes in heading should occur in any of the groups due to the regularity of the test. However, the Olympic sailors show a better stability value in $Heading_{LTS}$, which indicates that part of the speed reduction in the regional group is due to a greater range of heading angles throughout the test, resulting in less efficient headings with respect to 45° to the wind and higher hydrodynamic frictions at lower speeds. Although the heading differs significantly in the long term between groups, the rudder angle does not differ between groups in both LTS and STS steadiness. This may be explained by the fact that, being a constant test without tacks or gybes, the rudder does not play a determining role in the execution of specific gestures, so hardly any variations appear in both the long and short term in any of the sailors, and no different behaviours can be observed depending on the performance levels. Finally, in the variables on the waterline, the boom angle differs between the two performance groups both in the long and short term. On the one hand, the Olympic sailors show very low and close to zero $Boom_{STS}$ values, indicating that the boom does not move instantaneously or consecutively during the test. This may be due to greater practice in this technical gesture and better course control in elite sailors. Additionally, these Olympic sailors also have significantly lower $Boom_{LTS}$ values, so a smaller range of boom movement during the test results in less aerodynamic drag, allowing for smaller reductions in speed and increased performance in competition. In contrast, the regional sailors do not show different results in the short and long-term variations in the transverse plane measured based on the heel angle, suggesting that it may be a technical aspect that is quicker to assimilate during progression in Ilca category competition.

Regarding the Hiking effort variations during the test, it is observed that the higher performance of the Olympic sailors is not due to their ability to produce forces to counteract the constant heeling instantaneously. Regional level athletes are just as capable as Olympic level athletes in maintaining constant Hiking efforts in the short term. However, in the long term, Olympic sailors are able to produce less force dispersion than regional sailors, possibly due to greater physical fitness and less fatigue during the test, translating into higher speeds and performance. Future research could focus on how fatigue may impair the steadiness of technical variables and thus reducing the speed. It can be hypothesised that muscle fatigue would reduce the capacity of maintaining efforts strong enough to avoid changes in the rudder or heading as well as heel angle and hiking effort.

Finally, our predictive model showed that Heel angle, Heading angle, and Hiking, along with rudder angle and $Heel_{LTS}$, exhibit the highest linear relationship with speed, making them the variables that best predict the boat's speed. It is interesting to note that although $Heel_{LTS}$ did not differ between performance groups, it remains a determinant variable in test performance as it is related to boat speed. Therefore, even if other variables related to steadiness did not differ between groups, they may have a direct relationship with speed that should be analysed in future studies.

This study provides novel insights into the technical and performance differences between Olympic and regional sailors in the ILCA class, shedding light on how specific technical factors and steadiness impact sailing performance. Previous research has predominantly focused on broader aspects of sailing performance or on specific types of sailing conditions (Bojsen-Møller et al., 2007; García & Martínez, 2015). Our findings contribute to a deeper understanding of the biomechanical and motor control aspects that distinguish elite sailors from their regional counterparts. The greater steadiness in technical variables observed in Olympic sailors aligns with findings from other cyclic sports where steadiness has been linked to performance (Lovas et al., 2022; Pennanen et al., 2016). This research emphasises the importance of technical precision and physical conditioning in optimising sailing performance. The results highlight the need for targeted training programs that address both technical skill and physical endurance, which could potentially enhance competitive outcomes. Future research could further explore these relationships in varied conditions and among other elite sailing classes to expand our understanding of performance determinants in sailing.

To conclude, it was observed that olympic sailors perform better than regional sailors in specific linear tests due to higher speed during the test. This speed seems to be determined, among other factors, by technical aspects related to the mechanical behaviour of the boat, which depend on the sailor's technical skill. Additionally, this technical skill allows maintaining higher boat speeds due to greater stability in keeping the boat's course and heel, as well as better physical fitness, enabling the maintenance of more constant force values throughout the test. This research highlights that both technical skill and physical fitness can be crucial determinants of performance in individual dinghy sailing categories.

These findings provide valuable insights into the factors influencing technical performance and steadiness in the ILCA class, offering a foundation for the development of targeted training programs. By identifying key variables such as the impact of fatigue on stability and technical execution, coaches and athletes can design specific interventions aimed at enhancing performance consistency under varying conditions. Simulators, as highlighted in this study, can play a pivotal role in such programs by allowing athletes to practice in controlled environments that replicate competitive scenarios. This approach can help optimise technical skills, improve decision-making processes, and ultimately enhance overall sailing performance. Further studies should focus on identifying the more specific aspects of physical fitness that contribute to performance.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Data availability statement

The data supporting the findings of this study are available from the corresponding author upon request. Due to privacy and confidentiality agreements, raw data cannot be made publicly available.

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