BMC Sports Science, Medicine and Rehabilitation

RESEARCH

Open Access

Investigation of physical, physiological and neuromuscular performance parameters of elite sailing athletes

Aksoy Ömer[1*], Soyal Mehmet[1†], Gökmen Ünal Can[1†], Caba Ugur[1†] and Yildirim Onur[1†]

Abstract

Background Elite sailing performance depends on the interaction of anthropometric features, strength–power capacities, postural control, and physiological fitness. However, sex-specific neuromuscular and physiological profiles in competitive sailing remain insufficiently characterized. Therefore, this study aimed to examine sex-related differences in the physical, physiological, and neuromuscular attributes of elite sailors using an integrated laboratory-based test battery.

Methods This cross-sectional study included 26 national- and international-level sailing athletes (14 men, 12 women). Participants completed standardized assessments of anthropometry and body composition, isometric strength, static and dynamic balance, bimanual visual reaction time, anaerobic power (30-s upper- and lower-limb Wingate tests), and maximal aerobic capacity (treadmill VO_{2max}, Bruce protocol). Sex differences were analyzed using multivariate general linear models (MANOVA/MANCOVA), with fat-free mass (FFM) included as a covariate. Pearson correlations were calculated separately for men and women.

Results A significant multivariate effect of sex was observed. Male athletes demonstrated higher VO_2max, greater lower-limb peak power, stronger handgrip and trunk extension strength, and greater sitting height and arm length ($p < 0.05$, partial $\eta^2 = 0.18$–0.81). No significant sex differences were found for Wingate fatigue indices, upper-limb peak power, reaction time, or static/dynamic balance measures. After adjustment for FFM, sex differences in handgrip and trunk strength remained significant, whereas the difference in lower-limb peak power became borderline, indicating that muscle mass partly, but not fully, explained the performance gap. Correlation analyses further suggested sex-specific relationships between body composition and performance variables.

Conclusions Elite sailing performance appears to reflect the combined contribution of anthropometric characteristics, body composition, strength–power output, and postural control rather than a single dominant factor. These findings support the importance of sex-specific profiling and may help inform individualized, role- and class-specific training strategies in competitive sailing.

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Keywords Elite sailing, Physiological performance, Neuromuscular function, Balance performance, Female Sailor, Male Sailor

Introduction

Performance in sailing depends not only on technical and tactical skills but also on the simultaneous interaction of physical, physiological, and neuromuscular systems. Elite athletes must be able to withstand prolonged submaximal loads in variable wind, wave, and current conditions both in competition and during training, while maintaining high power generation and rapid sensory-motor response during maneuvers [1]. It has also been reported that branch-specific movements create high cardiorespiratory stress in athletes, resulting in a heart rate of 165–172 beats min-1 and oxygen consumption of 40–48 mL/kg-1/min-1 during "sail pumping" in windsurfing [2]. It has been reported that while mid-altitude applications improve VO_2 thresholds and economy, especially in endurance training, the effect on VO_{2max} may be limited [3]. However, the performance of athletes is not only limited to intrinsic characteristics but also influenced by the environment.

When environmental factors are evaluated, heat and fluid balance contribute positively to the performance of athletes, and constant fluid intake in hot conditions maintains hydration [4]. At the same time, it is stated that a ~ 1 °C increase in core temperature in a hot-humid environment over a long period of time is associated with approximately a 6% performance decrease [5]. Therefore, physiological strain in the organism is not only limited to metabolic outputs but can also shape the control of neuromuscular performance. Parameters such as neuromuscular properties, upper/lower isometric explosive power, postural balance, and reaction are stated to be determinants of rapid adaptation to boat control, boom-sail interaction, and course changes that occur under competition conditions [6]. Acute psychological stress has been reported to decrease neuromuscular performance and increase lactate response [7]. Although determinants of balance and strength factors in young and elite sailors have been presented, the heterogeneity of methods and research groups limits the comparability of the findings. This situation reveals the need for new studies in which physiological, neuromuscular, and anthropometric measures are examined simultaneously in the same research group [8].

Anthropometry and body composition have been shown to be tightly linked to performance, with body mass and characteristics such as sitting height and arm length being directly related to power output [9]. Separating the confounding effect of body mass in gender comparisons makes an important contribution to a clearer assessment of performance differences [1]. On the other hand, it has been reported that COP-based balance measurements can be used reliably with appropriate sampling methods and filtering processes, as well as being a valid indicator of static and dynamic balance in practice [10, 11]. Despite the growing body of research on sailing performance, studies that simultaneously examine anthropometric, physiological, and neuromuscular characteristics within the same elite sample remain limited [1, 8]. In addition, sex-specific performance profiles in elite sailors have not yet been sufficiently characterized through an integrated multidimensional approach. This gap limits the development of evidence-based strategies for training design, talent identification, and performance optimization in competitive sailing [8]. Therefore, the present study aimed to (i) analyze physical, physiological, and neuromuscular parameters, (ii) evaluate sex-related differences, and (iii) examine the relationships among selected variables in elite sailing athletes. Based on the existing literature, the study was guided by the following hypotheses: (i) male and female elite sailors would differ significantly in selected anthropometric, physiological, and neuromuscular performance parameters; (ii) some of these sex-related differences would remain significant after controlling for fat-free mass (FFM); and (iii) anthropometric and body composition variables would show significant associations with performance outcomes within each sex group.

Methods

Research model

The study was designed with a cross-sectional and comparative correlational survey model. Relational survey models are research models that aim to determine the existence and degree of change between two or more variables. Although the correlational survey model does not give a real cause-effect relationship, it is known that if the situation in the variable is known, it allows the other variable to be predicted [12]. Accordingly, in this study, both statistical comparison of differences between groups and correlations between variables were aimed to be revealed.

Research group

A total of 26 athletes (12 females and 14 males) participated. Participation in the study was voluntary, and all athletes were asked to complete an informed consent form. All athletes participating in the study regularly participate in national and international competitions and were asked to verbally declare whether they had any history of injury or chronic disease during the research

period. Ethical approval was obtained for this study from the Istanbul Gelişim University Rectorate Ethics Committee, dated October 3, 2025, and numbered 2025-18-09.

Study design

The study was conducted over a three-week application schedule. Athletes were divided into two groups: female ($n = 12$) and male ($n = 14$), and measurements were taken on separate weeks based on gender. All tests were conducted in the same laboratory environment, with temperatures between 20 and 22 °C and relative humidity between 40 and 60%. Athletes also underwent a 10–15-minute warm-up program prior to the tests. The testing sequence was designed to reduce potential carry-over fatigue between assessments and to standardize recovery opportunities across participants. Familiarization procedures, fixed test order, and recovery intervals between strength, balance, anaerobic, and aerobic assessments were implemented to improve measurement consistency and internal comparability. The sequential structure of the study protocol, encompassing familiarization and all subsequent assessment sessions, is illustrated in the flowchart provided in Fig. 1.

Week 1 familiarization period

All athletes were briefed on the devices and testing procedures. Athletes practiced the measurement protocols to familiarize themselves with the tests. Data obtained during this period were not included in the analysis and were used solely for practice purposes.

Measurement weeks

Week 2 (Female Athletes): All measurements were performed by female athletes.

Week 3 (Male Athletes): Male athletes performed all measurements.

The separation of testing weeks between female and male athletes was primarily due to logistical and scheduling constraints, allowing all participants to be tested under standardized and controlled conditions within each group. All measurements were conducted in the same laboratory environment, using identical protocols,

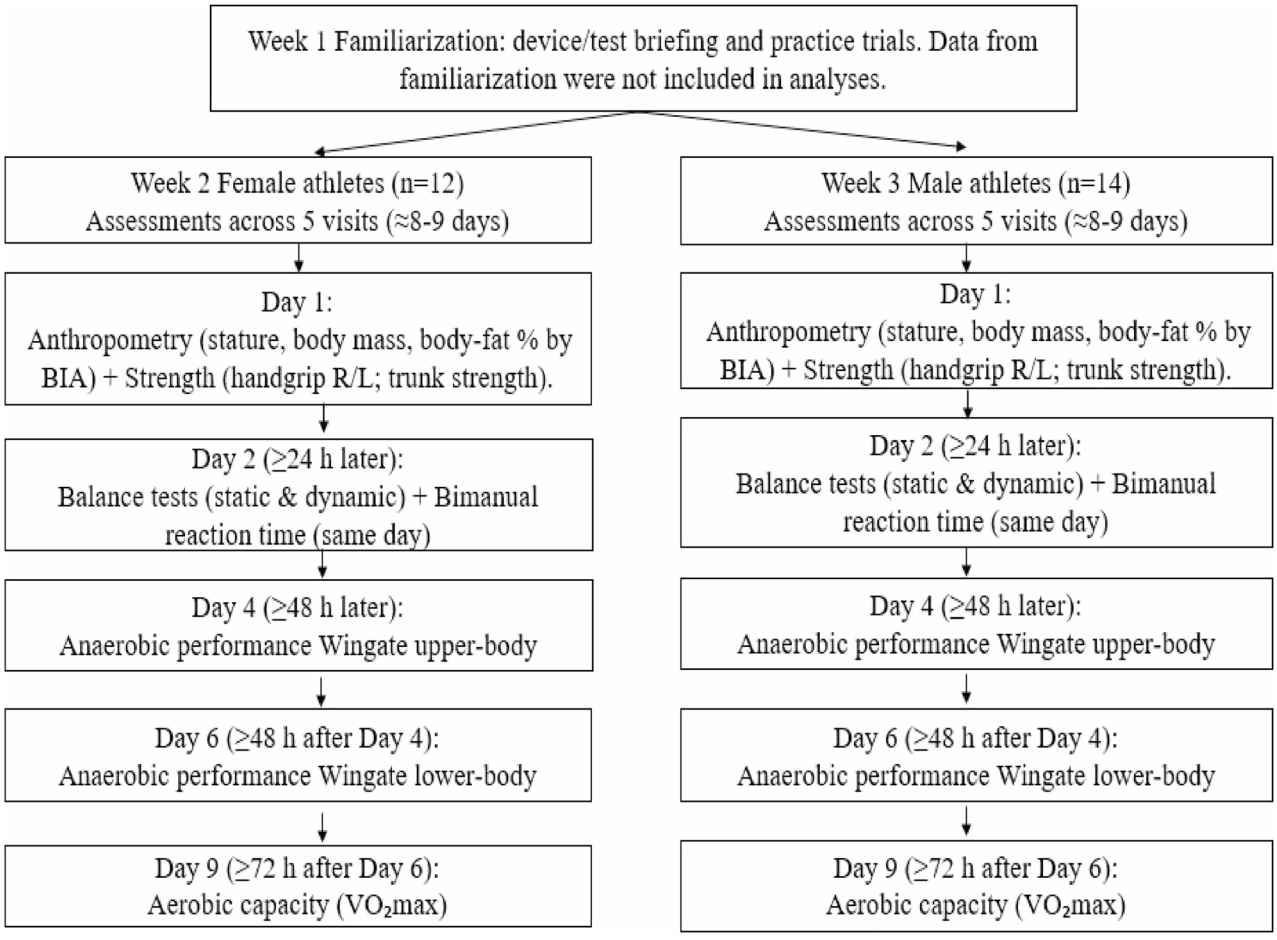


Fig. 1 Flowchart of the Study Design

equipment, and environmental conditions (temperature and humidity), in order to minimize potential variability.

Order of application of measurements

Anthropometric measurements

Body weight, height, and BIA (body fat percentage) were taken.

Strength measurements

Handgrip strength (right/left) and trunk strength were taken on the same day.

Balance tests

Static and dynamic balance measurements were taken and administered at least 24 h after the strength tests.

Hand reaction test

Bimanual reaction time measurements were taken and administered on the same day as the balance test.

Anaerobic performance tests

Wingate upper extremity and lower extremity tests were performed. These tests were performed on separate days with a minimum of 48 h of recovery time between each test.

Aerobic capacity test

The VO2max test was performed 72 h after the Wingate tests.

Data collection

The athletes' body weight (kg) and height (cm) were measured using standardized methods. Body weight was measured with a digital scale (e.g., Tanita, Japan) with a precision of ± 0.1 kg, with the athletes wearing only shorts and a T-shirt, without shoes. Height was measured with a stadiometer (e.g., Seca, Germany) with a precision of ± 0.1 cm, with the athletes in an upright position, heels together, and heads in Frankfurt am Main. Measurements were taken in the morning, on an empty stomach, and under similar environmental conditions.

Body composition measurement

Athletes' body fat percentage (BFT), lean body mass, and total body weight were determined using Bioelectrical Impedance Analysis (BIA). Athletes were asked to avoid strenuous exercise for at least 12 h before the measurement, to be fasting on the morning of the measurement, and to refrain from caffeine/alcohol consumption. During the measurement, athletes stood barefoot on the device, removed all metal accessories, and maintained a standardized, protocol-compliant position.

Hand grip strength

Athletes' right and left hands were measured separately using a hydraulic hand dynamometer (Jamar Hydraulic Hand Dynamometer, Lafayette Instrument, USA). During the measurement, athletes were standardized to be in an upright sitting position, with the shoulder in a neutral position, the elbow in 90° flexion, and the forearm in a neutral position. Three repeat measurements were taken for each hand, and the highest value was recorded for analysis [13, 14].

Body strength measurement

Trunk strength was measured using a digital back-leg dynamometer (Takei Back-Dynamometer TKK-5002, Japan). Athletes were asked to pull up on the dynamometer bar with their hands as much as possible, with their feet shoulder-width apart, knees slightly bent, and backs straight. The measurement was repeated three times, and the highest value was included in the analysis [15].

Sigma balance platform

Static and dynamic balance measurements were performed using the Sigma Balance Platform. All tests were performed on a flat, non-slip surface in a quiet, well-lit laboratory environment. Athletes were instructed to avoid intense exercise, caffeine, and alcohol consumption 24 h before the tests. Measurements were performed barefoot, with arms at the sides of the body, and gaze fixation focused on a target at eye level 2 m away. This protocol conforms to standard posture and visual fixation conditions commonly used in posturography [16]. COP data were sampled at at least 100 Hz, and a 10 Hz Butterworth low-pass filter was applied before processing. These settings are frequently used in COP-based stabilometry research and are recommended for reliability (30–60 s trials, 100 Hz sampling, 10 Hz filter) [10, 11].

Static balance (Right/Left COP X (mm) ve COP Y (mm))

For static balance measurements on the Sigma Balance platform, the athlete was positioned in a single-leg stance. In the right single-leg condition, the right foot was placed at the center of the platform, the left leg was lifted off the floor to approximately 90° of knee flexion, and the feet were switched in the left single-leg condition. The arms were at the body's side, the head and torso were neutral, and the gaze was directed at a fixed target. Three 30-second repetitions were performed for each foot, with a 30–60-second rest period between trials. These durations and the use of multiple repetitions are standard practices that increase the reliability of COP-based balance measurements. Criteria for invalid trials were defined as the contralateral foot touching the ground, significant stepping/hopping, moving off the platform, or significant arm/head compensations. If these conditions occurred,

the trial was repeated. During recording, the software generates COP coordinates (mm) in the mediolateral (X) and anteroposterior (Y) planes specific to the single-leg condition. The use of COP-X and COP-Y signals in single-leg stance is a well-established method in the stabilometry literature, and COP-based statistical summaries (e.g., mean ± SD) are reported [11, 17].

Dynamic balance (Right/Left AFV, mm)

Measurements were obtained using a weight transfer/LOS (Limits of Stability)-like task on the Sigma Balance platform. The athlete initially stood with both feet centered, and the screen presented a sequence of near, middle, and far targets directed to the right (then left). At each target, the athlete controlledly moved their center of gravity/COP to the target, held it there for 1–2 s, and then returned to the center. For each direction, 3 levels × 3 rounds = 9 trials were performed, with 20–30 s of rest between trials and 60–90 s between rounds. In this study, AFV was defined and reported as the total path length (mm) followed by the COP during weight transfer (95% ellipse area, mm^2 if the software output is area-based). This definition is consistent with COP-derived metrics used to quantify dynamic stability (path length, maximum reach, and ellipse area). Furthermore, the validity/reliability of LOS-based goal-orientation tasks is supported by the literature, where COP path length provides complementary information to LOS measures [17–19].

Hand reaction time measurement (Bihanded)

Hand reaction time was measured using a computer-based reaction time measurement system (e.g., Lafayette Instrument Reaction Time Apparatus). Athletes sat comfortably during the test, with their forearms on a table and both hands placed on the device's buttons. Athletes were asked to respond simultaneously with both hands as quickly as possible to a visual stimulus (light signal) appearing on the screen at random intervals. Each athlete completed five trials, and the average of the best three trials was included in the analysis. A 15–20 s rest period was provided between trials. This method is widely used for reliable measurement of reaction time and allows for the assessment of bimanual motor coordination [20, 21].

Wingate upper extremity test protocol

Upper extremity anaerobic performance was assessed with a 30-second maximal effort test using an upper extremity ergometer (e.g., Monark 891E, Sweden). Before the test, athletes warmed up with 5 min of low-intensity pedaling, and device settings were adjusted according to individual measurements. Resistance load was determined as 4–5% of body weight for male athletes and 3.5–4.0% for female athletes. During the test, athletes were asked to pedal at the highest possible speed upon starting the command and to maintain maximal effort for 30 s. The tester verbally motivated the athletes throughout the test. Peak Power (W/kg), Minimum Power (W/kg), Mean Power (W/kg), and Fatigue Index (FDI, %) values were obtained from the measurements. The fatigue index was calculated using the formula [(Peak Power – Minimum Power)/Peak Power × 100]. This method was performed in accordance with Wingate anaerobic test protocols [22, 23].

Wingate lower extremity test protocol

Lower extremity anaerobic performance will be assessed with a 30-second maximal effort test on a bicycle ergometer. Before the test, athletes will warm up with 5 min of low-intensity pedaling, and the bike saddle height will be adjusted to suit each athlete.

Resistance load was determined by gender: For male athletes: 7.5% of body weight (0.075 kp/kg).

For female athletes: 6.5–7.0% of body weight (0.065–0.070 kp/kg) (Bar-Or, 1987; Inbar et al., 1996). During the test protocol, athletes were asked to pedal at the highest possible speed when the load was applied and to maintain maximal effort for 30 s. Practitioners verbally motivated the athletes throughout the test.

Peak Power (W/kg): The highest power value reached in the first 5 s.

Minimum Power (W/kg): The lowest power value reached in the last 5 s.

Average Power (W/kg): The total work produced during the 30-second test divided by the duration.

Fatigue Index (YI, %): (Peak Power–Minimum Power)/Peak Power × 100 (Peak Power–Minimum Power)/Peak Power × 100 (Peak Power–Minimum Power)/Peak Power × 100.

The test was conducted in accordance with Wingate anaerobic test protocols [22–24].

VO_{2max} measurement (Treadmill-Bruce Protocol)

VO_2max was measured on a motorized treadmill using a Bruce protocol and a metabolic system (e.g., Cosmed/Cortex) that analyzes respiratory gases breath-by-breath. Following a 3–5 min light warm-up, participants ran in 3-minute increments of increasing speed/incline until completion. 1 st increment: 1.7 mph, 10%; 2nd increment: 2.5 mph, 12%; 3rd increment: 3.4 mph, 14%; 4th increment: 4.2 mph, 16%; 5th increment: 5.0 mph, 18%; 6th increment: 5.5 mph, 20%; and, if necessary, subsequent increments were increased using the same logic. Heart rate (HR), perceived exertion (Borg 6–20), and RER (VCO_2/VO_2) were continuously monitored during the test. VO_2max was determined when the highest 30-s average achieved within the last minute was accompanied by (i) a VO_2 plateau (< 150 $ml \cdot min^{-1}$ increase), (ii) RER ≥ 1.10, and (iii) ≥ 95% of age-estimated maximal HR.

Athletes terminated the test at the onset of voluntary cessation, abnormal symptoms, or one of the ACSM termination criteria, followed by a 3–5 min active cool-down [25–27].

Statistical analysis

To clarify the analytical framework, sex (male vs. female) was defined as the primary independent variable, while anthropometric, physiological, and neuromuscular performance parameters were treated as dependent variables. Multivariate analyses (MANOVA) were used to assess overall group differences across multiple dependent variables simultaneously. To control for potential confounding effects of body composition, fat-free mass (FFM) was included as a covariate in subsequent MANCOVA/ANCOVA models. This approach allowed the evaluation of whether observed sex differences were independent of lean body mass. Additionally, separate Pearson correlation analyses were conducted within each sex group to explore sex-specific relationships between variables.

Data were analyzed using IBM SPSS Statistics 25. Descriptive statistics for all variables are reported as mean ± standard deviation and 95% confidence interval (CI). Normality was assessed using skewness/kurtosis coefficients within ± 1.5 (and visual Q–Q inspection), homogeneity of variance was assessed using Levene's test, and equality of covariance matrices was assessed using Box's M test. Differences between genders were examined using the General Linear Model–MANOVA approach; multivariate effects were reported using Pillai's Trace statistics, and univariate results were reported with F, p, and partial η^2 for each dependent variable. Estimated marginal means (EMM ± SE) are presented, and a Bonferroni correction was applied for pairwise comparisons ($\alpha = 0.05$, two-tailed). To test for the potential confounding effect of body composition, GLM–MANCOVA/ANCOVA models including lean body mass (FFM, kg) as a covariate were constructed as a pre-planned sensitivity analysis (FFM = body weight × (1 − %fat/100)). FFM-adjusted group means are reported at the FFM level at the sample mean (EMM ± SE); when necessary, homogeneity of slopes was checked with group × FFM interaction [28–30]. Relationships between variables were assessed using two-tailed Pearson correlations, separately for gender groups. Multiple testing loadings were checked using the Benjamini–Hochberg (FDR) method at q = 0.05. This analytical strategy enabled both between-group comparisons and within-group association analyses, providing a comprehensive evaluation of performance determinants in elite sailors.

Results

Table 1 presents the demographic and body composition characteristics of the male and female elite sailors.

The results of the univariate comparisons between male and female athletes are presented in Table 2.

When Table 2 is examined, a significant multivariate effect of sex was observed (Pillai's Trace = 0.947, F(19, 6) = 5.634, $p = 0.020$). Univariate analyses showed that male athletes had significantly higher VO_{2max}, lower-limb peak power, handgrip strength (right and left), trunk strength, sitting height, and arm length than female athletes ($p < 0.05$). No significant sex differences were found for lower- and upper-limb Wingate fatigue indices, upper-limb peak power, reaction time, or static and dynamic balance variables. In the FFM-adjusted analysis, the multivariate effect of sex remained significant (Pillai's Trace = 0.561, F(4,20) = 6.379, $p = 0.002$). After adjustment, males still showed significantly higher right and left handgrip strength and trunk strength, whereas the difference in lower-limb peak power became borderline ($p = 0.053$). These findings suggest that fat-free mass partly, but not fully, explains the observed sex differences. Significant correlation analyses for male athletes are presented in Table 3.

When Table 3 is examined, in male athletes, the correlation pattern indicated that lean body mass was associated with selected anthropometric and performance variables. In addition, strong bilateral associations in dynamic balance and handgrip measures suggested internally consistent within-group performance patterns.

Table 1 Demographic Characteristics of Athletes

Group	Variables	*N*	Min.	Max.	(Mean ± SE)	95% CI (Lower-Upper)
Male	Age (year)	14	20.00	30.00	24.07 ± 3.54	22.02–26.12
	Height (cm)	14	169.00	191.80	179.64 ± 7.35	175.39–183.89.39.89
	Body Weight (kg)	14	62.30	99.30	78.88 ± 11.97	71.97–85.80
	Body Fat Percentage (BF%)	14	7.79	21.65	13.07 ± 4.10	10.70–15.44.70.44
	Lean Body Mass (kg)	14	54.85	82.74	68.70 ± 9.21	63.38–74.02
Female	Age (year)	12	18.00	30.00	20.16 ± 1.69	19.09–21.24
	Height (cm)	12	158.20	173.80	167.16 ± 5.80	163.48–170.85.48.85
	Body Weight (kg)	12	49.40	73.60	63.40 ± 7.24	58.81–68.01
	Body Fat Percentage (BF%)	12	14.72	30.16	21.63 ± 4.86	18.54–24.73
	Lean Body Mass (kg)	12	40.86	55.46	49.34 ± 4.65	46.38–52.30

Table 2 Univariate comparisons by gender (MANOVA followed by ANOVA)

Variables	Male ($n=14$) (Mean ± SD)	Female ($n=12$) (Mean ± SD)	F	*p*	Partial η^2	Difference
VO_{2max} ml·kg^{-1}·min^{-1}	50.57 ± 3.11	46.63 ± 5.39	5.40	**0.029***	0.184	Male> Female
Wingate Peak Power– Lower Limb (W/kg)	12.57 ± 1.25	10.21±0.87	30.02	**0.001****	0.556	Male> Female
Wingate Fatigue Index – Lower Limb (%)	56.46 ± 6.38	56.26 ± 5.99	0.007	0.935	0.000	-
Wingate Peak Power – Upper Limb (W/kg)	2.56±0.43	2.72±0.38	1.08	0.309	0.043	-
Wingate Fatigue Index – Upper Limb (%)	59.25 ± 6.18	56.00 ± 7.68	1.425	0.244	0.056	-
Handgrip Strength – Right (kg)	59.52 ± 5.69	38.84 ± 4.40	104.58	**0.001****	0.813	Male> Female
Handgrip Strength – Left (kg)	56.81 ± 6.41	38.82 ± 5.26	59.78	**0.001****	0.714	Male> Female
Trunk Strength (kg)	151.03 ± 26.03	104.34 ± 13.89	30.92	**0.001****	0.563	Male> Female
Sitting Height (cm)	91.85 ± 3.40	86.42 ± 3.33	16.80	**0.001**	0.412	Male> Female
Arm Length (cm)	83.00 ± 4.65	77.49 ± 2.96	12.49	**0.002**	0.342	Male> Female
Reaction Time – Both Hands (s)	0.29 ± 0.01	0.28 ± 0.03	0.815	0.376	0.033	-
Static Balance – Right COP X (mm)	3.00 ± 2.54	3.00 ± 1.65	0.000	1.000	0.000	-
Static Balance – Right COP Y (mm)	−1.28 ± 2.58	1.41 ± 1.83	0.021	0.885	0.001	-
Static Balance – Left COP X (mm)	−1.64 ± 2.46	−1.00 ± 1.12	0.688	0.415	0.028	-
Static Balance – Left COP Y (mm)	−2.42 ± 2.59	−2.16 ± 2.48	0.069	0.796	0.003	-
Dynamic Balance – Right AFV (mm)	38.71 ± 15.91	52.08 ± 20.82	3.43	0.076	0.125	-
Dynamic Balance – Left AFV (mm)	38.28 ± 21.09	48.75 ± 18.23	1.79	0.192	0.070	-

ANOVA. Box's M could not be calculated; multivariate effect was reported using Pillai's Trace. Variables with Levene p <.05 were interpreted with caution

SD Standard deviation, *partial* η^2 partial eta-squared

* p <.05, **p <.01. p-values belong to univariate

Significant correlation analyses for female athletes are presented in Table 4.

When Table 4 is examined, in female athletes, lean body mass was positively associated with lower-limb peak power and selected anthropometric variables, while relative VO_{2max} showed an inverse association with arm length. Strong bilateral relationships were also observed for dynamic balance and handgrip measures.

Discussion

Summary of key findings

The present study examined sex-specific differences and inter-variable relationships in the physical, physiological, and neuromuscular profiles of elite sailing athletes using a multidimensional test battery.

The main findings showed that male athletes had significantly higher VO_{2max}, strength-related parameters, and selected anthropometric measures than female athletes. These results are generally consistent with previous sailing literature reporting sex-related differences in aerobic capacity, anthropometric structure, and strength-related performance characteristics in elite sailors [31–33]. The higher VO_{2max} observed in male athletes is in line with studies showing sex-based differences in aerobic performance in Olympic-class sailing athletes [31, 32], while the present findings further support the role of aerobic capacity as an important performance component in sailing [33].

Male athletes also demonstrated significantly greater lower-limb peak power. This finding is compatible with reports indicating that lower-limb strength and power differ according to sailing role, class, and competitive demands [33, 34]. It is also consistent with broader evidence showing higher relative and absolute anaerobic power values in men during 30-s Wingate-type tests [35, 36]. Although previous studies suggest that these differences may be attenuated after controlling for lean mass or body-size normalization [37–39], the persistence of some differences in the present study suggests that lean body mass does not fully account for performance variability. Accordingly, FFM adjustment should be interpreted as a means of reducing body-composition-related confounding rather than as a complete explanation of sex-related performance differences.

Interpretation of findings

Similarly, handgrip and trunk strength were significantly higher in male athletes. These findings support previous reports emphasizing the importance of upper-extremity strength, trunk function, and hiking-related muscular demands in sailing performance [33, 40–42]. At the same time, not all previous studies have reported significant sex differences, particularly in younger sailing populations, suggesting that maturity, test type, training background, and class-specific demands may affect the magnitude of these differences [43–45]. Thus, the current results should be interpreted within the context of the adult elite sample examined here.

Anthropometric variables also differed by sex, with male athletes showing greater sitting height and arm

Table 3 Significant Pearson Correlation Analyses for Male Athletes

Variables	Associated Variable	*r*	*p*	Lower 95% CI	Upper 95%CI
Lean Body Mass (kg)	Wingate Fatigue Index – Lower Limb (%)	0.558*	0.038	0.04	0.84
	Wingate Peak Power – Upper Limb (W/kg)	−0.906**	0.001	−0.97	−0.72
	Wingate Fatigue Index – Upper Limb (%)	0.569*	0.034	0.06	0.84
	Dynamic Balance – Left AFV (mm)	−0.539*	0.046	−0.83	−0.01
	Sitting Height (cm)	0.830**	0.001	0.54	0.94
	Arm Length (cm)	0.894**	0.001	0.69	0.97
VO_{2max} ml·kg^{-1}·min^{-1}	Reaction Time – Both Hands (s)	0.622*	0.017	0.14	0.87
Wingate Peak Power – Lower Limb (W/kg)	Static Balance Right COP X (mm)	−0.643*	0.013	−0.88	−0.17
Wingate Peak Power – Upper Limb (W/kg)	Dynamic Balance – Right AFV (mm)	0.615*	0.019	0.13	0.86
	Sitting Height (cm)	−0.766**	0.001	−0.92	−0.40
	Arm Length (cm)	−0.863**	0.001	−0.96	−0.61
Static Balance – Left COP X (mm)	Reaction Time – Both Hands (s)	−0.536*	0.048	−0.83	−0.01
Dynamic Balance – Right AFV (mm)	Dynamic Balance – Left AFV (mm)	0.762**	0.002	0.39	0.92
	Handgrip Strength – Right (kg	−0.647*	0.012	−0.88	−0.18
	Handgrip Strength – Left (kg)	−0.738**	0.003	−0.91	−0.34
Handgrip Strength – Right (kg)	Handgrip Strength – Left (kg)	0.667**	0.009	0.21	0.88
Sitting Height (cm)	Arm Length (cm)	0.817**	0.001	0.51	0.94

p<0.05, *p<0.01. r = Pearson correlation coefficient (two-tailed), n = 14 (male). P-values are presented uncorrected; significance asterisks are according to the Benjamini–Hochberg FDR correction (target q = 0.05): = q <.05; * = q <.01. 95% confidence intervals were calculated with a Fisher z transformation. Only relationships that remained significant after FDR are shown in the table

length. These findings are consistent with research suggesting that anthropometric structure is linked to leverage, reach, and class-specific mechanical demands in sailing [31–34, 46–49]. Although some studies in younger or category-based samples report weaker or inconsistent sex-related differences [46], the present findings indicate

Table 4 Significant Pearson Correlation Analyses Found for Female Athletes

Variables	Associated Variable	*r*	*p*	Lower 95% CI	Upper %95 CI
Lean Body Mass (kg)	Wingate Peak Power – Lower Limb (W/kg)	0.695*	0.012	0.20	0.91
	Wingate Peak Power – Upper Limb (W/kg)	−0.756**	0.004	−0.93	−0.32
	Sitting Height (cm)	0.778**	0.003	0.37	0.93
	Arm Length (cm)	0.663*	0.019	0.14	0.90
VO_{2max} ml·kg^{-1}·min^{-1}	Arm Length (cm)	−0.670*	0.017	−0.90	−0.16
Wingate Fatigue Index – Lower Limb (%)	Wingate Fatigue Index – Upper Limb (%)	0.629*	0.029	0.09	0.88
	Static Balance – Left COP X (mm)	0.577	0.050	0.00	0.86
Wingate Peak Power – Upper Limb (W/kg	Sitting Height (cm)	−0.632*	0.028	−0.88	−0.09
	Arm Length (cm)	−0.676*	0.016	−0.90	−0.17
Dynamic Balance – Right AFV (mm)	Dynamic Balance – Left AFV (mm)	0.824**	0.001	0.47	0.95
Handgrip Strength – Right (kg)	Handgrip Strength – Left (kg)	0.778**	0.003	0.37	0.93
Sitting Height (cm)	Arm Length (cm)	0.604*	0.037	0.05	0.87

p<0.05, *p<0.01. r = Pearson (two-tailed), n = 12 (female). P-values are raw; asterisks indicate after Benjamini–Hochberg FDR (q = 0.05) (* = q <.05; ** = q <.01). 95% CIs were calculated with the Fisher z method. Only relationships that remained significant after FDR are included in the table

that body dimensions remain an important component of performance profiling in elite sailors.

The correlation analyses provided additional insight into sex-specific performance patterns. In both sexes, lean body mass was associated with several anthropometric and performance variables, supporting its role as an important determinant of strength- and power-related outcomes [28, 29, 31, 32, 37, 38]. In men, dynamic-balance and grip-related measures showed significant bilateral associations, whereas in women, similar bilateral relationships were also observed for balance and handgrip variables [10, 11, 18, 19, 40, 42]. However, these associations should be interpreted cautiously because the present design is cross-sectional and does not permit causal inference.

Limitations

Several limitations should be acknowledged. First, the sample size was relatively small, which may restrict statistical power and the generalizability of the findings, particularly in the context of multivariate analyses. In

support of this point, a post hoc power analysis conducted in G*Power 3.1 for the VO_{2max} outcome, using the observed effect size (f = 0.475), α = 0.05, total sample size = 26, and two groups, yielded an achieved power of 0.64. Second, the cross-sectional design precludes causal interpretation. Third, laboratory-based assessments may not fully capture the environmental and tactical demands of real sailing conditions. In addition, the separation of male and female testing sessions into different weeks may have introduced temporal variability related to uncontrolled factors such as training load or recovery status. Finally, athletes were not categorized according to sailing class or role, which may influence physiological and neuromuscular characteristics.

Practical implications

Overall, the findings highlight the importance of sex-specific profiling in elite sailing. Coaches and practitioners may benefit from considering sex-related differences in aerobic capacity, strength, power, and anthropometric structure when designing training programs, monitoring athletes, and planning talent identification processes.

Conclusion

In conclusion, the present findings suggest that performance in elite sailors is associated with the combined contribution of anthropometric characteristics, body composition, strength–power output, and postural control rather than a single dominant factor. The observed sex-related differences appeared to be more pronounced in selected variables such as strength, power, and aerobic capacity. Although adjustment for fat-free mass reduced some of these differences, it did not fully account for all performance variation. Overall, these results support the value of sex-specific profiling and may help inform individualized approaches to training design, talent identification, and performance optimization in competitive sailing.

To guide future research, studies should consider class- and role-specific grouping, longitudinal or repeated-measures designs, and the integration of laboratory-based findings with onboard performance data.

Acknowledgements

No technical, financial, or intellectual support was received from any individual or institution that does not meet the authorship criteria. The research was conducted and completed solely by the authors.

Authors' contributions

Ö A and M S were responsible for supervision and investigation of the research; S M was responsible for conceptualization; ÜC G and Ö A were responsible for writing of the manuscript; Ö A were responsible for the processing of the original data; and M S, ÜC G, O Y and U C were responsible for Review and editing. All authors read and approved the final manuscript.

Funding

This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

Data availability

The data generated and analyzed in this study pertain to elite sailing athletes and are not publicly available due to confidentiality restrictions imposed by the participating club. However, with the approval of the club and the ethics committee, anonymized data can be obtained upon reasonable request from the corresponding author of the article.

Declarations

Ethics approval and consent to participate

Informed consent forms were obtained from participants for participation in the study. The study was conducted in accordance with the principles of the Declaration of Helsinki (revised in 2013) and approved by the Ethics Committee of Istanbul Gelişim University (Approval No: 2025-18-09).

Consent for publication

Not applicable.

Competing interests

The authors declare no competing interests.

Clinical trial

This study did not involve a clinical trial; therefore, a clinical trial registration number is not applicable.

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Received: 19 November 2025 / Accepted: 20 April 2026
Published online: 23 April 2026

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