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Performance and Tactical Indicators in Elite Olympic RS:X Sailing Across Different Wind Conditions Using GPS Data

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Abstract

The variables determining performance according to wind speed have not yet been clarified for men and women in the RS:X class. The aim of this study was to examine the variables influencing performance under different wind conditions in Olympic RS:Xclass sailors using global positioning system (GPS) devices. Fifty-four Olympic RS:Xclass sailors (26 women) who competed in a World Cup event were selected. Using GPS devices, first-leg ranking, velocity made good (VMG), number of maneuvers, and distance covered in each leg (upwind, beam reach, and downwind) of every race were evaluated under three wind conditions (medium wind: ≥8 to ≤12 knots; strong wind: >12 to ≤15 knots; very strong wind: >15 knots). A total of nine races were analyzed for both the men's and women's groups. For both groups and under all wind conditions, first-leg ranking was the main determinant of overall performance. VMG in upwind and downwind legs was among the most decisive variables in medium wind conditions for both men and women. In very strong wind, VMG during the beam reach was a key variable influencing performance in both groups. In the women's group, regardless of wind speed, VMG during the first upwind leg was the determining factor for achieving a better first-leg position. In the men's group, particularly in medium wind conditions, a favorable first-leg position was mainly determined by VMG during the first upwind leg.

Keywords: performance; sailing; windsurfing; Olympic; GPS

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1. Introduction

Windsurfing is a highly demanding discipline that merges the technical principles of sailing with the dynamic balance requirements of board sports. Performance depends on the athlete's ability to efficiently harness wind energy through a specialized board–rig system, while simultaneously managing substantial physiological and mechanical loads [1]. Within Olympic competition, the RS:X class follows a standardized race format designed to evaluate upwind efficiency, downwind control, and tactical decision-making under variable environmental conditions [2]. Although minor adjustments may occur depending on venue and wind characteristics, RS:X events typically employ a trapezoid course, a configuration widely adopted in Olympic sailing to ensure consistency and fairness across races [3].

The trapezoid layout consists of four primary marks that structure a sequence of upwind, reaching, and downwind legs. The internal angle is commonly set at 70°, and the reach between Mark 1 and Mark 2 is standardized at 0.5 nautical miles, providing uniform tactical demands across events. Mark 3 is positioned slightly to windward of the start line—approximately 0.05 nm—to prevent athletes from cutting the line while planing at high speeds, a modification specific to RS:X due to the board's hydrodynamic behavior. Race duration typically ranges from 20 to 25 minutes, with total distance varying between 6 and 9 km depending on wind intensity. Most Olympic RS:X races include two full laps followed by a short final leg to the finish [2,3].

The physical and technical requirements of RS:X windsurfing are considerable. Athletes must combine aerobic and anaerobic capacity, isometric strength, and dynamic postural control to maintain optimal board speed and stability across rapidly changing conditions [1]. Physiological studies indicate that elite competitors frequently sustain intensities exceeding 75% of VO_2max and 85% of maximal heart rate during racing [1]. These demands are largely attributable to the sail-pumping technique, a repetitive, high-frequency action that generates significant mechanical stress on the upper limbs, trunk, and lower extremities, increasing the risk of overuse injuries, particularly in the lumbar region [4]. As a result, high-performance training programs emphasize unilateral coordination, muscular endurance, and the management of concentric loading patterns [5].

In competitive contexts, particularly within the Olympic RS:X class, success depends on a precise understanding of the variables that determine velocity under different wind conditions [6]. The incorporation of Global Positioning Systems (GPS) and Global Navigation Satellite Systems (GNSS) has transformed performance analysis in sailing by enabling accurate quantification of external load, kinematic patterns, and tactical behavior [7,8]. High-frequency GPS devices (e.g., 5 Hz) allow detailed assessment of mean velocity, distance covered, and temporal efficiency across race segments. Among these metrics, Velocity Made Good (VMG)—the effective speed toward the windward or leeward mark—has emerged as one of the most relevant performance indicators, consistently distinguishing elite from sub-elite competitors [9].

RS:X performance results from the interaction of technical, tactical, and physiological factors, with GPS-derived variables such as VMG, mean velocity, and distance covered serving as key performance indicators (KPIs) [2]. In light-wind conditions, success is strongly associated with the metabolic efficiency of sail pumping to maximize board speed. In contrast, moderate-to-strong winds shift the performance determinants toward maintaining planing conditions, optimizing hydrodynamic efficiency, and executing superior tactical decisions during upwind legs [9]. Previous research highlights that, across wind ranges, the first upwind leg is often the strongest predictor of final race outcome [2,9,10].

The relevance of early-race positioning is not unique to sailing. In middle-distance running, for example, the first 200 meters of an 800-m race are a critical determinant of final classification, with athletes in the leading positions at the break line showing a significantly higher probability of achieving top finishes [11–15]. Early positioning reduces tactical constraints, minimizes unnecessary accelerations, and preserves anaerobic reserves for the final sprint. Conversely, athletes starting from the rear are forced to cover additional distance and expend greater metabolic energy to regain competitive positions. This analogy underscores the strategic importance of early-race dynamics in sports where pacing, positioning, and tactical decision-making interact to shape performance outcomes.

Given these considerations, the present study aimed to identify the key variables influencing performance across different wind conditions in Olympic RS:X sailors using

GPS-derived metrics. Based on previous evidence, it was hypothesized that both VMG and early-race positioning would be strongly associated with overall race performance.

2. Materials and Methods

2.1. Participants

The study sample consisted of 54 Olympic (38 females) for the RS:X class (age range 19-36 years and 19-38, man and women, respectively. The data were collected from World-Sailing [16].

2.2. Regatta

The analyzed event was the 2019 Hempel World Cup Series Final, held in Marseille, France, from June 3 to 9, 2019. The variables first-leg ranking, velocity made good (VMG, knots), distance covered (m) and number of maneuvers were recorded using the SAP-Sailing® application [17]. This system operates with a TracTrac® GPS device positioned on the sailor, with a sampling frequency of 5 Hz. The collected data were transmitted via the mobile network and subsequently processed by the application.

The average values of first-leg ranking, VMG, distance and maneuvers were obtained from the total number of races performed in the regatta. A total of 18 races were analysed: 9 in the man group and 9 in the women group. The wind speed ranges in the races were 8.4-20.7 knots and 8.1-21.1 in the man and women groups, respectively. Furthermore, wind speed was analysed in all races of the regatta. Wind speed was classified for each race according to the categories established by the Royal Yachting Association [18]: >8 to ≤12 knots (light wind), >12 to ≤15 knots (moderate wind), and >15 knots (strong wind). The racecourse comprised six legs: 2 upwind, 2 beam reach, and 2 downwind.

2.3. Statistical Analyses

The data are presented as the mean (M) ± the standard deviation (SD). All statistical tests were performed using IBM SPSS Statistics (version 20.0 for Mac, IBM Corp., Chicago, IL, USA). The values obtained for the variables were recorded for each of the 6 legs conducted in every race. The results obtained from the variables in the 18 races analyzed (9 in the women's group) were grouped according to the average value obtained between the maximum and minimum wind speed recorded in each race (light wind, moderate wind and strong wind). A Pearson correlation coefficient was carried out with the aim of examining the association between predictive variables and performance, considering the following as predictive variable: first-leg ranking, VMG, distance and maneuvers in upwind, beam reach and downwind courses [19]. Subsequently, a multiple linear regression analysis was carried out including the variables in which a correlation value greater than 0.3 was obtained [20]. The performance as dependent variable means ranking in the race. The forward stepwise regression method was used to perform the multiple linear regression analysis. The same analyses were conducted to investigate the association between the predictor variables and first-leg ranking. VMG, distance covered, and the number of maneuvers across the upwind, beam reach, and downwind legs were included as predictor variables.

3. Results

A total of 54 Olympic class sailors were studied. All GPS data were publicly accessible. Finally, GPS data from 18 races (9 for girls) of RS:X class sailors were analysed.

Table 1 presents the mean values of first-leg ranking, VMG, distance, and maneuvers for the boys' and girls' groups across the three wind conditions in each of the nine races analyzed in the regatta.

Table 1. Mean ± SD of the variables analysed in girls (n = 26) and boys (n = 28) with light (>8 to ≤12 knots), moderate (>12 to ≤15 knots) and strong (>15 knots) wind.

	Light wind		Moderate wind		Strong wind	
Variable	Girls	Boys	Girls	Boys	Girls	Boys
Age (years)	25.4 ± 5.7	25.4 ± 5.1	25.4 ± 5.7	25.4 ± 5.1	25.4 ± 5.7	25.4 ± 5.1
First-leg ranking	13.5 ± 7.5	14.7 ± 8.4	13.0 ± 7.2	14.5 ± 8.1	13.0 ± 7.2	14.3 ± 8.0
1st VMG upwind (knots)	2.6 ± 0.3	2.8 ± 0.3	4.6 ± 0.9	5.7 ± 0.6	5.4 ± 0.7	6.6 ± 0.7
1st distance upwind (m)	1334.7 ± 242.2	1522.9 ± 440	2868.7 ± 502.5	2583.3 ± 260.5	3042.1 ± 445.4	2733.4 ± 153.1
1st maneuvers upwind	4.0 ± 1.6	3.7 ± 1.5	2.5 ± 0.9	1.9 ± 0.7	3.6 ± 1.3	3.0 ± 1.3
1st VMG beam reach (knots)	7.7 ± 2.3	7.2 ± 2.2	17.2 ± 2.5	18.6 ± 1.3	5.1 ± 1.0	16.5 ± 2.9
1st distance beam reach (m)	609.1 ± 14.6	641.8 ± 50.3	737.4 ± 87.1	739.7 ± 10.1	2260.4 ± 430.2	1495.2 ± 457.1
1st maneuvers beam reach	0.2 ± 0.4	0.2 ± 0.4	0.2 ± 0.4	0.2 ± 0.4	3.2 ± 2.3	1.5 ± 1.3
1st VMG broad reach (knots)	3.9 ± 0.2	5.3 ± 1.5	9.5 ± 2.1	11.1 ± 1.5	17.5 ± 4.4	7.9 ± 2.6
1st distance broad reach (m)	793.3 ± 231.2	1240.4 ± 356.4	1389.9 ± 266.2	1754.7 ± 116.2	948.4 ± 736.2	2440.6 ± 454.9
1st maneuvers broad reach	6.2 ± 3.5	3.1 ± 1.5	1.9 ± 0.5	2.0 ± 0.5	0.4 ± 1.6	2.8 ± 1.2
2nd VMG upwind (knots)	2.3 ± 0.2	2.7 ± 0.3	4.8 ± 0.8	5.1 ± 1.1	11.8 ± 2.6	17.5 ± 7.0
2nd distance upwind (m)	848.9 ± 85.9	1202.1 ± 295.1	2038.4 ± 427.2	2846.1 ± 590.0	1389.7 ± 262.6	1371.4 ± 818.6
2nd maneuvers upwind	3.7 ± 1.3	3.3 ± 1.3	1.9 ± 0.6	2.8 ± 1.8	2.7 ± 1.2	0.5 ± 0.9
2nd VMG beam reach (knots)	5.1 ± 0.7	4.4 ± 0.4	15.4 ± 2.4	10.8 ± 2.3	17.4 ± 4.0	14.4 ± 2.1
2nd distance beam reach (m)	233.6 ± 21.9	1122.4 ± 433.3	311.1 ± 37.3	1744.4 ± 291.0	262.9 ± 54.3	1443.7 ± 255.3
2nd maneuvers beam reach	0.3 ± 0.5	3.4 ± 1.9	0.4 ± 0.4	1.2 ± 0.6	0.2 ± 0.4	2.4 ± 0.8
2nd VMG broad reach (knots)	4.3 ± 0.3	6.5 ± 1.7	10.1 ± 1.6	17.2 ± 3.8	12.6 ± 2.9	18.5 ± 2.8
2nd distance broad reach (m)	876.5 ± 217.3	233.2 ± 35.6	1752.7 ± 231.0	309.5 ± 42.3	1312.8 ± 289.3	282.3 ± 32.6
2nd maneuvers broad reach	5.6 ± 3.2	0.2 ± 0.4	2.2 ± 0.7	0.0 ± 0.1	2.7 ± 0.9	0.4 ± 0.5

Data presented as M ± SD. M: mean. SD: standard deviation. VMG: velocity made good.

Table 2 shows the correlation coefficients between ranking in the race and the predictor variables across light, moderate, and strong wind conditions in the boys' and girls' groups. In the boys' group, the measurement showed significant correlations with first-leg ranking and 1st VMG upwind under all wind conditions. These results were also observed in the girls' group.

Table 2. Correlation coefficients (*r*) between ranking in the race and predictive variables in girls (n = 26) and boys (n = 28) across light (>8–≤12 knots), moderate (>12–≤15 knots), and strong (>15 knots) wind conditions.

	Light wind		Moderate wind		Strong wind	
Variable	Girls	Boys	Girls	Boys	Girls	Boys
First-leg ranking	0.78**	0.75**	0.84**	0.76**	0.79**	0.78**
1st VMG upwind (knots)	-0.51**	-0.48**	-0.43**	-0.53**	-0.60**	-0.57**
1st distance upwind (m)	0.19	-0.20	-0.31	0.48**	0.22	0.51**
1st maneuvers upwind	0.25*	0.11	0.15	0.29*	0.02	0.34**

1st VMG beam reach (knots)	-0.25*	-0.24*	-0.20	-0.30*	-0.28*	-0.24**
1st distance beam reach (m)	0.00	-0.68	-0.05	-0.09	0.10	0.06
1st maneuvers beam reach	0.18	-0.19	-0.07	-0.1	0.17	-0.02
1st VMG broad reach (knots)	-0.50**	-0.32**	-0.33**	-0.24	0.51*	-0.21*
1st distance broad reach (m)	0.36**	0.12	0.02	0.15	-0.06	0.06
1st maneuvers broad reach	-0.00	-0.04	-0.06	-0.08	0.25*	0.12
2nd VMG upwind (knots)	0.07	-0.67**	-0.28*	-0.42**	-0.48**	-0.10
2nd distance upwind (m)	0.05	-0.06	-0.21	0.19	0.10	0.02
2nd maneuvers upwind	0.06	0.24*	-0.04	0.36**	0.20	-0.02
2nd VMG beam reach (knots)	-0.35**	-0.00	-0.21	0.33*	-0.39**	-0.46**
2nd distance beam reach (m)	-0.03	-0.02	-0.10	-0.10	-0.24*	0.02
2nd maneuvers beam reach	0.13	-0.29**	-0.16	-0.08	-0.18	0.17
2nd VMG broad reach (knots)	-0.36**	-0.18	-0.10	-0.30*	-0.32**	-0.38**
2nd distance broad reach (m)	0.04	-0.05	-0.21	-0.25	-0.32**	-0.12
2nd maneuvers broad reach	0.07	0.08	-0.09	0.07	0.12	-0.11

VMG: velocity made good. * $p \leq .05$. ** $p \leq .01$.

Table 3 presents the correlation coefficients between first-leg ranking and the predictive variables under light, moderate, and strong wind conditions for the boys' and girls' groups. In both the boys' and girls' groups, 1st VMG upwind showed significant correlations under all wind conditions.

Table 3. Correlation coefficients (*r*) between first-leg ranking and predictive variables in girls (n = 26) and boys (n = 28) across light (>8–≤12 knots), moderate (>12–≤15 knots), and strong (>15 knots) wind conditions.

	Light wind		Moderate wind		Strong wind	
Variable	Girls	Boys	Girls	Boys	Girls	Boys
1st VMG upwind (knots)	-0.63**	-0.64**	-0.49**	-0.65**	-0.71**	-0.68**
1st distance upwind (m)	0.10	-0.04	0.10	0.62**	0.30**	0.62**
1st maneuvers upwind	0.18	-0.02	0.10	0.39**	0.07	0.50**
1st VMG beam reach (knots)	-0.06	-0.17	-0.18	-0.24	-0.23*	-0.18
1st distance beam reach (m)	0.01	-0.00	-0.07	-0.20	0.13	-0.08
1st maneuvers beam reach	0.14	0.05	-0.17	-0.03	0.19	-0.09
1st VMG broad reach (knots)	-0.28*	-0.18	-0.33**	-0.16	-0.41**	-0.13
1st distance broad reach (m)	0.21	0.11	0.05	0.12	-0.19	-0.03
1st maneuvers broad reach	-0.15	-0.12	-0.03	-0.25	0.22	-0.00
2nd VMG upwind (knots)	0.11	-0.44**	-0.26*	-0.25	-0.35**	-0.10
2nd distance upwind (m)	0.18	-0.04	-0.21	0.06	-0.03	0.01
2nd maneuvers upwind	0.10	0.20	-0.06	0.21	-0.05	-0.01
2nd VMG beam reach (knots)	-0.07	0.14	-0.23*	-0.25	-0.29**	-0.38**
2nd distance beam reach (m)	-0.07	-0.00	-0.11	-0.09	-0.30**	-0.05
2nd maneuvers beam reach	0.02	-0.29**	-0.12	-0.14	-0.15	0.07
2nd VMG broad reach (knots)	-0.20	0.14	-0.09	-0.26*	-0.25*	-0.31**
2nd distance broad reach (m)	0.02	-0.06	-0.23*	-0.19	-0.30**	-0.12
2nd maneuvers broad reach	0.04	0.07	-0.09	-0.02	-0.24*	-0.07

VMG: velocity made good. * $p \leq .05$. ** $p \leq .01$.

Table 4 shows the results of the multiple linear regression analysis using the forward stepwise method for boys' group across light, moderate, and strong wind conditions with ranking in the race as the dependent variable. The model obtained in light wind conditions showed a linear relationship of 87% and goodness-of-fit or R2 = 0.76. The value of Durbin-Watson (1.62) indicates that our error variance is independent; therefore, it would be appropriate to use a linear model. This model includes constant, firs-leg ranking, 1st VMG upwind, 2nd VMG upwind and 1st VMG broad reach. For moderate wind conditions, the model obtained showed a linear relationship of 85% and goodness-of-fit or R2 = 0.73 (Durbin-Watson = 1.60). The model obtained include the following variables: constant, firs-leg ranking, 1st VMG upwind, 2nd VMG upwind and 2nd VMG beam reach. In strong wind conditions, the result showed a linear relationship of 80% and goodness-of-fit or R2 = 0.64. The value of Durbin-Watson (1.53) indicates that our error variance is independent. This model includes constant, firs-leg ranking and 2nd VMG beam reach.

Table 4. Linear regression coefficients for the boy´s group with ranking in the race as the dependent variable

		Non-standardized coefficients		Typified coefficients			Confidence interval 95% for *B*	
	Model	*B*	Std. Error	*β*	t	Sig.	Lower Bound	Upper Bound
Light wind	Constant	-1.13	9.92		-0.11	0.09	-20.88	18.60
	First-leg ranking	0.85	0.09	0.86	8.55	<0.001	0.65	1.04
	1st VMG upwind	13.23	3.35	0.54	3.95	<0.001	6.56	19.90
	2nd VMG upwind	-9.73	1.88	-0.44	-5.17	<0.001	-13.48	-5.99
	1st VMG broad reach	-1.42	0.67	-0.27	-2.12	0.037	-2.76	-0.08
Moderate wind	Constant	-22.78	9.78		-2.32	0.02	-42.43	-3.13
	First-leg ranking	1.00	0.11	1.00	9.12	<0.001	0.78	1.23
	1st VMG upwind	7.31	2.00	0.58	3.64	<0.001	3.28	11.35
	2nd VMG upwind	-7.58	1.54	-1.07	-4.91	<0.001	-10.68	-4.48
	2nd VMG beam reach	1.81	0.63	0.51	2.87	0.006	0.54	3.08
Strong wind	Constant	15.01	3.83		3.91	<0.001	7.41	22.61
	First-leg ranking	0.71	0.06	0.70	11.33	<0.001	0.58	0.83
	2nd VMG beam reach	-0.75	0.23	-0.20	-3.21	<0.001	-1.21	-0.28

Note: Method used: forward stepwise. ᶜStatiscally significant association. *B* = linear regression coefficient. *β* = standardised partial regression coefficient. Std: standard. VMG: velocity made good. Light wind: >8–≤12 knots. Moderate wind: >12–≤15 knots. Strong wind: >15 knots.

Table 5 presents the results of the multiple linear regression analysis using the forward stepwise method for girls' group across light, moderate, and strong wind conditions with ranking in the race as the dependent variable. The model obtained in light wind conditions showed a linear relationship of 88% and goodness-of-fit or R2 = 0.78 (Durbin-Watson = 1.50). This model includes constant, firs-leg ranking, 1st VMG upwind, 2nd VMG broad reach and 2nd VMG beam reach. For moderate wind conditions, the model obtained showed a linear relationship of 0.84% and goodness-of-fit or R2 = 0.72. The value of Durbin-Watson was 1.95. The variables included in this model were: constant and first-

leg ranking. In strong wind conditions, the result showed a linear relationship of 82% and goodness-of-fit or R2 = 0.67. The value of Durbin-Watson was 1.63. This model includes constant, firs-leg ranking and 2nd VMG upwind.

Table 5. Linear regression coefficients for the girl´s group with ranking in the race as the dependent variable

		Non-standardized coefficients		Typified coefficients			Confidence interval 95% for *B*	
	Model	*B*	Std. Error	*β*	t	Sig.	Lower Bound	Upper Bound
Light wind	Constant	86.60	12.75		6.79	<0.001	61.16	112.05
	First-leg ranking	0.45	0.08	0.45	5.30	<0.001	0.28	0.62
	1st VMG upwind	-8.68	1.91	-0.40	-4.54	<0.001	-12.49	-4.87
	1st VMG broad reach	-4.39	2.05	-0.15	-2.13	0.03	-8.49	-0.29
	2nd VMG broad reach	-6.12	1.67	-0.27	-3.66	<0.001	-9.45	-2.78
	2nd VMG beam reach	-2.31	0.68	-0.22	-3.39	0.001	-3.67	-0.95
Moderate wind	Constant	1.86	0.93		1.99	0.05	-0.00	3.72
	First-leg ranking	0.86	0.06	0.84	13.74	0.000	0.73	0.98
Strong wind	Constant	10.88	2.98		3.65	0.000	4.94	16.83
	First-leg ranking	0.70	0.07	0.70	9.51	0.000	0.56	0.85
	2nd VMG upwind	-0.59	0.20	-0.21	-2.94	0.004	-1.00	-0.19

Note: Method used: forward stepwise. [c]Statiscally significant association. *B* = linear regression coefficient. *β* = standardised partial regression coefficient. Std: standard. VMG: velocity made good. Light wind: >8–≤12 knots. Moderate wind: >12–≤15 knots. Strong wind: >15 knots.

Table 6 shows the results of the multiple linear regression analysis using the forward stepwise method for boys' group across light, moderate, and strong wind conditions with first-leg ranking as the dependent variable. For light wind conditions, the model obtained showed a linear relationship of 64% and goodness-of-fit or R2 = 0.42 (Durbin-Watson = 1.17). The variables of this model were constant and 1st VMG upwind. The model obtained in moderate wind conditions showed a linear relationship of 69% and goodness-of-fit or R2 = 0.47. The value of Durbin-Watson (0.83) indicates that our error variance is not independent; therefore, it would not be appropriate to use a linear model. In strong wind conditions, the result showed a linear relationship of 76% and goodness-of-fit or R2 = 0.58. The value of Durbin-Watson (2.01) indicates that our error variance is independent; therefore, it would be appropriate to use a linear model. This model includes constant, 1st VMG upwind, 1st distance upwind and 1st maneuvers upwind.

Table 6. Linear regression coefficients for the boy´s group with first-leg ranking as the dependent variable

		Non-standardized coefficients		Typified coefficients			Confidence interval 95% for *B*	
	Model	*B*	Std. Error	*β*	t	Sig.	Lower Bound	Upper Bound
Light wind	Constant	59.51	5.85		10.15	<0.001	47.86	71.17
	1st VMG upwind	-15.94	2.07	-0.64	-7.70	<0.001	-20.05	-11.82

Moderate wind	Constant	51.63	8.21		6.28	<0.001	35.16	68.11
	1st VMG upwind	-7.38	1.28	-0.59	-5.76	<0.001	-9.95	-4.81
	1st maneuvers upwind	2.55	1.14	0.23	2.24	0.029	0.26	4.84
Strong wind	Constant	-4.34	16.62		-0.26	0.79	-37.28	28.60
	1st VMG upwind	-4.05	0.90	-0.39	-4.50	<0.001	-5.84	-2.26
	1st distance upwind	0.01	0.00	0.28	3.33	0.001	0.00	0.02
	1st maneuvers upwind	1.68	0.40	0.28	4.21	<0.001	0.89	2.48

Note: Method used: forward stepwise. [c]Statiscally significant association. *B* = linear regression coefficient. *β* = standardised partial regression coefficient. Std: standard. VMG: velocity made good. Light wind: >8–≤12 knots. Moderate wind: >12–≤15 knots. Strong wind: >15 knots.

Table 7 displays the forward stepwise multiple linear regression results for girls' group, using first-leg ranking as the dependent variable under light, moderate, and strong wind conditions. In light wind conditions, the model obtained showed a linear relationship of 51% and goodness-of-fit or R2 = 0.27. The value of Durbin-Watson was 1.34. This model includes constant and 1st VMG upwind. For moderate wind conditions, the result showed a linear relationship of 64% and goodness-of-fit or R2 = 0.41. The value of Durbin-Watson (1.84) indicates that our error variance is independent. The variables included in this model were: constant, 1st VMG upwind and 1st VMG broad reach. In strong wind conditions, the result showed a linear relationship of 60% and goodness-of-fit or R2 = 0.35 (Durbin-Watson = 1.34). This model includes constant and 1st VMG upwind.

Table 7. Linear regression coefficients for the girl´s group with first-leg ranking as the dependent variable

		Non-standardized coefficients		Typified coefficients			Confidence interval 95% for *B*	
	Model	*B*	Std. Error	*β*	t	Sig.	Lower Bound	Upper Bound
Light wind	Constant	42.80	5.69		7.51	<0.001	31.54	54.15
	1st VMG upwind	-11.12	2.14	-0.51	-5.19	<0.001	-15.40	-6.85
Moderate wind	Constant	27.88	3.27		8.51	<0.001	21.35	34.41
	1st VMG upwind	-11.62	1.72	-1.51	-6.72	<0.001	-15.07	-8.18
	1st VMG broad reach	4.06	0.77	1.18	5.24	<0.001	2.52	5.61
Strong wind	Constant	42.80	4.70		9.10	<0.001	33.44	52.17
	1st VMG upwind	-5.51	0.86	-0.60	-6.40	<0.001	-7.22	-3.79

Note: Method used: forward stepwise. [c]Statiscally significant association. *B* = linear regression coefficient. *β* = standardised partial regression coefficient. Dependent variable: first-leg ranking. Std: standard. VMG: velocity made good. Light wind: >8–≤12 knots. Moderate wind: >12–≤15 knots. Strong wind: >15 knots

4. Discussion

The present study investigated the biomechanical and tactical determinants of performance in Olympic RS:X sailing across a broad spectrum of wind conditions, using high-frequency GPS data to quantify VMG, distance covered, maneuver frequency, and in-race positioning. Across all analyses, first-leg ranking consistently emerged as the strongest predictor of final race outcome for both men and women, independent of wind intensity. This finding aligns with previous research indicating that early tactical

positioning exerts a disproportionate influence on subsequent race dynamics, particularly in classes where course geometry, windward congestion, and limited overtaking lanes constrain tactical flexibility [10]. The strength of these associations in the present dataset (r = 0.75–0.84) reinforces the decisive role of the opening upwind leg in shaping competitive trajectories.

A second major finding concerns the central importance of VMG during the first upwind leg, which emerged as the most influential technical variable across nearly all wind categories. Upwind VMG integrates multiple performance components—tactical decision-making, hydrodynamic efficiency, sail trim, and pumping effectiveness—making it a comprehensive indicator of technical proficiency. The stronger correlations observed in women suggest that performance variability in this group may be more sensitive to upwind efficiency, potentially reflecting differences in body mass, sail-handling strategies, or risk-taking behavior compared with men [21–23].

Wind intensity modulated the relative importance of specific performance indicators. Under medium winds, both men and women relied heavily on VMG in upwind and downwind legs, consistent with the mixed metabolic demands of pumping and transitions between displacement and planning modes. In very strong winds, however, VMG during the beam reach became a decisive factor, particularly among men. This shift reflects the hydrodynamic characteristics of the RS:X board, which achieves its highest speeds on reaching legs when fully powered; under these conditions, small differences in board trim, balance, and control can produce disproportionately large performance gains [3,24]. The results also highlight the analytical value of GPS-derived metrics for performance assessment in elite sailing. VMG, distance, and maneuver counts provided objective, high-resolution insights into tactical and biomechanical strategies, reinforcing the utility of GPS-based analytics for identifying key performance determinants. The consistency of the regression models across wind categories further supports the robustness of these indicators and their relevance for applied performance monitoring (Table 4-7).

The parallel drawn with middle-distance running underscores a broader principle of race strategy: early positioning acts as a structural filter that shapes the probability of success. Just as the first 200 meters of an 800-m race determine tactical freedom and metabolic efficiency, the first upwind leg in RS:X racing establishes the tactical landscape for the remainder of the race [12–15,25]. Athletes who secure a strong early position reduce exposure to disturbed airflow, minimize tactical constraints, and preserve physiological resources for later segments.

Future research should explore whether integrating physiological data—such as heart rate, power output, or sail-pumping frequency—with GPS metrics could further clarify how athletes manage the interplay between biomechanics, tactics, and fatigue across varying wind conditions. Such multimodal datasets may enhance the predictive value of performance models and provide deeper insight into the physiological cost of tactical decisions.

Several limitations should be considered when interpreting the findings. First, the use of publicly available GPS data restricted the analysis to the variables provided by the SAP-Sailing® platform. Although the system offers high-frequency positional information, it does not include complementary biomechanical or physiological metrics, limiting the ability to fully characterize internal load or fatigue-related performance changes. Second, wind conditions were classified based on average race values; short-term fluctuations within each leg were not analyzed, potentially masking micro-tactical adaptations that influence VMG and ranking. Third, the study did not examine sex-specific biomechanical or tactical strategies beyond statistical comparisons. Although men and women competed on identical equipment, differences in body mass, strength, and technique may influence VMG and maneuvering efficiency in ways not captured by the current variables.

Addressing these aspects in future research could deepen the understanding of performance determinants in Olympic windsurfing and improve the precision of GPS-based analytics.

5. Conclusions

Across all wind categories and in both sexes, first-leg position exhibited the strongest association with final race ranking, with correlation coefficients ranging from 0.75 to 0.84. The regression analyses confirmed that this variable alone accounted for the majority of the explained variance in performance, indicating that the competitive outcome is largely shaped during the opening upwind leg. This segment represents the phase of greatest tactical density, where fleet congestion, disturbed airflow, and restricted overtaking lanes amplify the strategic value of early positioning.

Upwind VMG during the first leg emerged as the only technical variable consistently associated with both first-leg ranking and overall performance across all wind conditions. This finding establishes upwind VMG as the primary technical key performance indicator (KPI) in RS:X racing. Among women, the influence of this variable was even more pronounced, suggesting that upwind efficiency constitutes the most sensitive and discriminative performance factor within this group.

These findings underscore the critical influence of early-race dynamics and upwind technical proficiency in determining competitive success within Olympic RS:X windsurfing. Consequently, training programs should prioritize technical development on the upwind leg—specifically emphasizing the initial beat—given its decisive impact on overall race outcomes.

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