Research article

Analysis of sailing variables and performance of laser sailors with different rankings under the condition of certain wind speed

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ABSTRACT

Objective: The aims of this study were to describe the characteristics of sailing variables and differences between different ranking sailors under the condition of certain wind speed, and predict the variables that affect performance.

Methods: Five regatta's data of the 2019–2020 Hempel World Cup Series and Tokyo 2020 Olympic Games for a total of 63 races were analyzed in this study. The wind speed was defined as light wind below 8 knots, medium wind at 8–12 knots and strong wind above 12 knots. Sailors were divided into top 10 and other ranked groups based on their performance for each race.

Results: 1) The race time of Laser class was about 50 min. The sailing distance traveled, VMG, percentage of upwind time, and the number of downwind maneuvers increased with an increase in the wind speed, while upwind maneuvers decreased increasing wind speed. Under the same wind speed, the VMG of reaching legs was the highest, followed by downwind and upwind legs in same wind speed. (2) The top 10 sailors had a high VMG, less race time, upwind/reaching legs' time and distance compared to other ranked sailors in all categories of wind speed (p < 0.05). There was no significant difference in the number of maneuvers among sailors of different rankings (p > 0.05). (3) There was a moderate to high correlation between first upwind mark position of sailors and the race ranking (r ranging 0.762–0.851, p < 0.01), and the top 10 sailors' first upwind ranking was close to the race performance.

Conclusions: Wind speeds affect sailing variables and race characteristics. VMG and time and distance in upwind and reaching legs are important variables for differentiating sailors' level. Regardless of the wind speed, the first upwind mark position of sailors can be used as an effective factor in predicting the performance of the race.

1. Introduction

Dinghy sailing is considered to be a dynamic and challenging water sport. Driven by the wind, the participants drive the boat to sail in a specific direction by adjusting the sail, rope, tiller and body position. Changes in wind speed directly affect the application of sailing techniques and tactics, the selection of sailing routes and physical fitness requirements of sailors, which are closely related to the results of the competition [1, 2].

Olympic class sailing is a fleet racing in which sailors must round the marks in the course as fast as possible to reach the finish line. The large-scale regatta usually consists of 10–12 races. A scoring system is implemented where for first position 1 point is awarded, second position 2 points, and so on. Finally, the top ten sailors with fewer points after the preliminary heats enter the final, so it is important to defeat the opponents reaching the finish line first [3, 4]. The course of Laser class sailing includes upwind, downwind and reaching (broad reach) legs. During upwind leg, it is not possible to sail directly into the wind as the sail would stall, in order to move towards the direction of the incoming wind, the boat performs zigzag-type maneuvers, called tacking, each leg of which comprises a turn of the bow against the wind [5, 6]. Sailing downwind will be produce a powerful sideways force on the sails causes the boat to heel, which increases its resistance and decreases speed. To prevent the boat from capsizing and improve performance, sailors use their body as a lever to create a righting moment that correct the position of the boat, this movement is termed hiking [7, 8]. Sailing downwind leg,
the boat is turned away from the wind, in order to cope with the change of wind direction and drive air into the sail, sailors adjust the direction of the boat by “gybing” and “bearing away” maneuvers [9]. Sailing reaching, the wind blowing from the port or starboard side, and the sails produce both forward and sideways force, which also requires sailor hiking to balance the boat. Different legs require different abilities of sailors, the physical load of each leg varies according to the wind intensity [8, 10]. The upwind and reaching sailing performance are associated with physical fitness, requiring high strength endurance and a good level of aerobic capacity [11]. Sailing downwind requires well maneuver skills, balance and dynamic stability [12]. In addition, since upwind leg does not sail in a straight line, the position and number of tacking and sailing distance during the sailing process are important factors that affect the sailing time and race ranking.

Few studies have focused on the sailing variables characteristics, and the relationship between sailing variables and performance of high-level Laser class sailors. We also cannot differentiate elite sailors by their rankings in a regatta, as the speed and direction of the wind are constantly changing and the environmental conditions have a considerable impact on sailing. Researches also need to consider the differences in sailors training and competing in different wind conditions. The current study analyzed the data of 63 races according to a certain wind speed range. All the races were from World Cup and Olympic Laser class regattas which represent the world’s top level of competitive sailing. The purposes of this study were to further explore the sailing characteristics of high-level Laser races in a certain wind speed range, and compare the sailing parameters of sailors in different rankings, so as to predict the race performance and guide the daily sailing training. In addition, studies have shown that the position of the first upwind mark is important to the competition performance [13]. Therefore, we further discussed the relationship between the first upwind mark’s position and race ranking in different wind speed conditions.

2. Methods

This study was based on retrospective analysis of the global positioning systems (GPS) data regarding Laser sailors competing in the 2019–2020 World Sailing World Cup series and the 2020 Olympic Games. The data is available through online platforms https://www.spsailing.com and https://tokyo2020.sailing.org. Sailors were divided into two groups based on their performance level (ranking) for each race: top 10 and other rankings.

In total, 63 races were included for analysis (excluding medal race), and date on sailors whose results were cancelled due to breaking the rules were not included. There was one race from Hempel World Cup Series 2019 Miami (Race 11, silver) that was not included as the GPS data was not available (Table 1). Analysis data included the range of wind speed during a race, time and distance, the number of maneuvers, VMG, as well as sailor’s position at first upwind mark in each race.

Sailors have different hiking positions with the change of wind speed. Studies show that below 8 knots wind speed, sailors usually hold sitting hiking position, sitting on the boat through the body’s forward and backward movement to keep balance. In 8–12 knots wind speed, sailors keep upright hiking, leaning back their body to hike over the side. Above 12 knots wind speed, sailors remain extended hiking, opening the hip joint to extend the body out of the boat as much as possible [11, 14]. In this study, the wind speed is defined as light wind below 8 knots, medium wind at 8–12 knots and strong wind above 12 knots, all regattas’ wind speeds range from 3.8 to 19.9 knots.

Statistical analysis was performed with the SPSS Statistics V26.0 (IBM Corporation, Armonk, NY). The data are presented as means (M) and standard deviations (SD). The level of significance was set at p < 0.05. The U Mann-Whitney test was applied to analyze differences in the race time, distance, the number of maneuvers and VMG by ranking for three wind categories. Spearman rank correlation was used to analyze the relationship between the position of the first upwind mark and race ranking.

3. Results

Table 2 shows sailing variables data of sailors with different rankings for three wind speed conditions. It was observed that the laser level competition time was a bout 50 min, and the race distance ranges from 5453.0 ± 1195.6 m to 9551.0 ± 788.7 m. The sailing distance traveled, VMG, percentage of upwind time, and the number of downwind maneuvers increased with an increase in the wind speed, while upwind maneuvers decreased increasing wind speed. Under the same wind speed, The VMG of reaching legs was the highest, followed by downwind and upwind legs in same wind speed.

Figure 1 (a-d) shows that the top 10 sailors had less race time, upwind/reaching legs’ time and distance compared to other ranked sailors in all categories of wind speed (p < 0.05). When the wind speed was higher than 12 knots, the top 10 sailors had a shorter race distance (p < 0.01).

Figure 2a shows that the top 10 sailors’ upwind/reaching legs VMG, downwind VMG below 8 wind speeds were higher than other rankings. There was no significant difference in the number of maneuvers among sailors of different rankings (Figure 2b) (p > 0.05).

Table 3 shows there was a moderate to high correlation between first upwind mark position of sailors and the race ranking (r ranging 0.762–0.851, p < 0.01), and the top 10 sailors’ first upwind ranking was close to the race performance (ranking), Figure 3.

4. Discussion

The purpose of this study was to use the GPS data from the 2019–2020 Hempel World Cup Series and 2020 Tokyo Olympic Games to explore the sailing characteristics of high-level Laser races, compare the sailing variables of sailors with different rankings in a certain wind speed range, so as to predict the race performance and guide the daily sailing training. Furthermore, this study investigated the relationship between the first upwind mark’s position and race ranking in different wind speed conditions.

Wind speed is an important factor in determining sailors’ internal and external load as well as performance in dinghy sailing race [3, 15, 16]. In our study, the race time was similar for three wind categories while the
Table 2. Sailing variables data of sailors with different ranking under three wind speed conditions.

| Variables       | Group     | <8 (knots) | 8-12 (knots) | >12 (knots) |
|-----------------|-----------|------------|--------------|-------------|
|                 |           | Upwind     | Downwind     | Reaching    | Upwind      | Downwind     | Reaching    | Upwind      | Downwind     | Reaching    |
| Race time (min) | G1        | 47.57 ± 7.13** | 47.56 ± 5.07** | 48.55 ± 4.22** |
|                 | G2        | 50.01 ± 7.42 | 50.11 ± 5.28 | 51.40 ± 4.19 |
|                 | AVG       | 49.36 ± 7.38 | 49.41 ± 5.28 | 50.51 ± 4.27 |
| Race Distance (m) | G1        | 5402.7 ± 1174.9 | 6828.6 ± 908.4 | 9420.3 ± 837.4** |
|                 | G2        | 5466.1 ± 1201.2 | 6930.7 ± 928.3 | 9631.6 ± 790.8 |
|                 | AVG       | 5453.0 ± 1195.6 | 6806.1 ± 924.3 | 9551.0 ± 788.7 |
| Time (min)      | G1        | 23.56 ± 2.51** | 25.47 ± 3.35** | 25.47 ± 3.15** |
|                 | G2        | 25.27 ± 4.17 | 27.05 ± 3.47 | 27.05 ± 3.47 |
|                 | AVG       | 25.08 ± 4.15 | 26.48 ± 3.46 | 26.48 ± 3.46 |
|                 | %         | 50.7 ± 4.5 | 53.9 ± 4.6 | 53.9 ± 4.6 |
|                 |           | 35.3 ± 3.8 | 35.4 ± 2.2 | 35.4 ± 2.2 |
|                 |           | 14.0 ± 5.6 | 10.6 ± 4.0 | 10.6 ± 4.0 |
|                 |           | 5.4 ± 1.6 | 65.2 ± 4.9 | 65.2 ± 4.9 |
|                 |           | 3.3 ± 1.1 | 27.9 ± 12.2 | 27.9 ± 12.2 |
|                 |           | 11.0 ± 11.3 |            |            |
| Distance (m)    | G1        | 1864.0 ± 701.4 | 872.6 ± 335.4* | 872.6 ± 335.4* |
|                 | G2        | 2098.2 ± 592.3 | 918.0 ± 302.9 | 918.0 ± 302.9 |
|                 | AVG       | 2028.0 ± 588.8 | 908.6 ± 310.3 | 908.6 ± 310.3 |
|                 | %         | 53.5 ± 5.5 | 54.0 ± 5.4 | 54.0 ± 5.4 |
|                 |           | 29.2 ± 7.7 | 31.8 ± 7.8 | 31.8 ± 7.8 |
|                 |           | 17.3 ± 6.4 | 14.2 ± 5.6 | 14.2 ± 5.6 |
|                 |           | 5.4 ± 1.6 | 47.7 ± 10.2 | 47.7 ± 10.2 |
|                 |           | 3.3 ± 1.1 | 36.9 ± 6.3 | 36.9 ± 6.3 |
|                 |           | 11.2 ± 6.1 |            |            |
| VMG (knots)     | G1        | 2.7 ± 0.4** | 3.4 ± 0.6* | 3.3 ± 0.3** |
|                 | G2        | 2.5 ± 0.4 | 3.2 ± 0.4 | 3.2 ± 0.4 |
|                 | AVG       | 2.5 ± 0.4 | 3.2 ± 0.4 | 3.2 ± 0.4 |
|                 | %         | 2.7 ± 0.4** | 3.4 ± 0.6* | 3.3 ± 0.3** |
|                 |           | 3.2 ± 0.4 | 3.2 ± 0.4 | 3.2 ± 0.4 |
|                 |           | 4.7 ± 0.6 | 4.7 ± 0.6 | 4.7 ± 0.6 |
|                 |           | 5.7 ± 1.1 | 5.7 ± 1.1 | 5.7 ± 1.1 |
|                 |           | 7.8 ± 1.1 | 7.8 ± 1.1 | 7.8 ± 1.1 |
| Maneuvers (number) | G1        | 17.7 ± 7.6 | 27.6 ± 15.2 | 14.1 ± 5.4 |
|                 | G2        | 17.9 ± 7.7 | 28.9 ± 14.9 | 15.2 ± 5.2 |
|                 | AVG       | 17.9 ± 7.7 | 28.6 ± 15.0 | 15.0 ± 5.3 |

G1: top 10 sailors; G2: other ranking sailors; AVG: average; %: percent; *significant difference to G2 sailors, p < 0.05, **significant difference to G2 sailors, p < 0.
distance was different significantly, which was related to race rules and course setting of the sailing. The rules specify that the Laser race’ time limit is 75 min, and time to reach the first upwind mark is within 25 min after start. The competition organizing committee needs to set the race courses according to wind speed, wind direction and waves [17]. The course distance varies with the wind speed, but no matter what the wind speeds conditions, more successful sailors always reach the finish line using the shortest time. For race distance, there was no difference between two groups of sailors in different rankings for light and medium wind. However, when the wind speed was higher than 12 knots, the top 10 sailors had a less race distance compared to other ranked sailors, which was mainly affected by course selection and course-keeping ability. More successful sailors complete the courses over a shorter distance, and maintain their course with some maneuver skills even in highly unstable environments [18].

From the perspective of different legs, the upwind leg time increased from 50.4 % to 65.4 % with the increase of wind speed. However, the percentage of upwind leg distance did not change significantly. This might be due to an increase in wind speed, increasing the boat's the tilting moment [11]. Sailors have to pay more efforts to hike to keep the boat's stability, and the same proportion of the distance took an increased percentage of time. Previous studies have shown that the time spent on upwind and reaching leg is an important variable for differentiating sailors’ level, high-level sailors have less time to complete upwind and reaching legs, a short upwind sailing distance compared to low-level sailors [2, 18, 19]. In this study, the top 10 sailors had significantly shorter upwind/reaching legs' time and distance of than those of other ranking sailors for the same wind speed., which may be affected by the following three reasons: (1) Course selection and maneuver skills. The decisions the sailors make as to how they chose to sail around the course are dependent on the sailors' skill at understanding and foreseeing the

Table 3. The correlation between sailors' first upwind leg ranking and race ranking under three wind speeds conditions.

| Wind speed (knots) | R    | p value |
|-------------------|------|---------|
| < 8               | 0.788| <.001   |
| 8–12              | 0.762| <.001   |
| > 12              | 0.851| <.001   |

Figure 1. Comparison of times (a, b) and distance (c, d) at different legs between top 10 sailors and other ranking sailors under three wind speed conditions (* indicates significant difference between top 10 sailors and other ranking sailors).

Figure 2. Comparison of VMG (a) and maneuvers (b) between top 10 sailors and other ranking sailors under three wind speed conditions (* indicates significant difference between top 10 sailors and other ranking sailors).
weather conditions as well as their technical and tactical understanding of the sport [20]. The more successful sailors’ sailing routes are more scientific and well-developed maneuvers [14], so that their course distance is shorter. Even if they choose the same course as other sailors, or slightly longer one, they can steer the boat with great thrust and less resistance through better sailing skills. (2) Boat position. Sailors with higher ranking will be more forward in sailing position, the upwind tacking and course selection are less interfered by other boats, so they could have the opportunity to choose a suitable course. (3) cognitive difference. Sailing performance is affected by many external environmental factors, sailors’ cognition and processing ability to different environments affect their decision-making procedure and motor behavior pattern [19, 21].

VMG is based on the function of sailing speed and wind direction angle, which is calculated by multiplying the boat speed by cosine of the angle to wind direction, taking into account the vertical component of the speed relative to the wind direction, and this speed is the best combination of speed and sailing angle. A higher VMG means that a sailor is sailing towards their destination at a faster speed and shorter distance, reflecting boats’ ability to sail against wind as well as sailors’ ability to make use of wind [19, 22]. This study found that the VMG in reaching legs was the highest, followed by downwind and upwind legs for the same wind speed, and VMG increased with the increase of wind speed, which is consistent with the research results of other sailing classes [23, 24]. On an upwind course, sailors resist heeling force on the boat and sideways force on the sails that will push the boat sideways through the water. When sailing downwind, there is less sideways and heeling force, with more concentrated forward drive, the boat should be able to sail faster. Sailing reaching, there is enough sideways force to keep the boat stable, and airflow over sides of mainsail drives the boat at higher speed [9]. In addition, in our study, the VMG of the top 10 sailors on the upwind/reaching legs was higher, which may be related to sailors’ course choice and physical fitness. Top level sailors have a better departure and the orientation toward the upwind mark and the most suitable course during the race. And sailing on the upwind/reaching legs need different extent hiking, which requires good strength and endurance in core and lower extremity, the efficiency of hiking is closely related to the boat speed [25, 26]. Previous studies have also shown that VMG is considered as an important variable in a regatta, more successful sailors have higher VMG in both upwind and downwind legs [13, 27]. This study further pointed out that VMG can be used as a predictor of race performance regardless of wind speed.

As regards maneuvers, which include tacking, gybing and bearing away skills. The quality of maneuvers affects the boat speed, so sailors must apply appropriate maneuvers and complete it efficiently to reduce the loss of boat speed [25]. Previous research has shown that the wind speed may be related to number of tacks completed in upwind legs, and when races with similar average wind speeds were compared, there was a similar number of tacks [3]. Further investigation in this study revealed that the number of tacks in light wind was higher than that in medium and strong wind, but there was no significant difference among different ranking sailors. The main reason is that the boats will be squeezed in one area when the wind is light, which will cause problems in the race such as covering and right of away, the sailors try to get more propulsion by tacking to complete the pass, gain right of away, and make the sail wing more fully exposed to wind. Tacks in upwind leg increase the energy expenditure of sailors [28], but it also has some benefits. Hiking will produce “quasi-isometric” stress on the lower-body anterior muscles under the condition of moderate to strong wind, resulting in muscle blood flow restrictions. Tacking maneuvers reduce the muscle pressure and blood flow resistance caused by long hiking, so that the muscles of lower limbs can be temporarily relaxed as well as elevate blood flow and oxygen consumption [29, 30].

When sailing downwind, a sailboat could become prone to experiencing dynamic instability without warning signs, which makes it more difficult to maintain balance [12]. And the wind direction is not fixed, as the wind shift changes, sailors need to adjust the heading or the sail’s angle in order to get the best wind direction angle. In this study, the number of downwind maneuvers increased with the increase of wind speed (including gybing and bearing away). In the process of downwind bearing away, the bow rotates along the wind, and the wind direction angle becomes larger and larger until the boat reaches the stern wind state. Sailors deliberately alter body weight within the boat, so that the boat constantly alternates from heeling to windward to leeward, which increases downwind speed. The sailboat is more maneuverable to alter the wind direction and the sail’s angle in order to get the best wind direction angle. In this study, the number of downwind maneuvers increased with the increase of wind speed. Research showed that there was no significant difference in the number of maneuvers performed by sailors with different rankings [2]. According to Hagiwara [18], the number of maneuvers cannot be used as a variable to distinguish sailors’ performance in light wind.

Sailing race spends most of the time in the upwind and downwind legs, reaching time is very short, the upwind time accounted for more than half of the total race time, so the performance on upwind greatly affects the final competition results [2, 31]. The first leg of dinghy sailing
is always upwind, and elite sailors have better rankings on first upwind mark [17]. This study indicated that the first upwind mark ranking was closely related to race performance, which would be used as an effective factor to predict the performance of Laser class sailors regardless of speed precision. When sailing upwind, hiking maneuver is required because the action of the wind on the sails causes the boat to heel, making the use of hiking to keep the balance of the boat. Long-term sailing training may lead to certain specific adaptability, high-level sailors have more efficient hiking technique, which results in less friction between boat and water and therefore more speed [8]. In addition, sailors’ performance is affected by the rivals. The sailor must anticipate his rivals and capture as much information as possible from them to carry out the most appropriate actions according to each circumstance condition [32]. The sailors who have a better position in the first upwind leg take less account of the rivals, focus more on the environmental information to increase the boat speed and perform their technique and tactics without interference from rivals [33, 34].

5. Conclusions and recommendations

Based on the above, it seems clear that wind speed affects sailing course setting and race characteristics. VMG, upwind/reaching legs time and distance are the important variables to distinguish the sailors’ level. The first upwind mark position of sailors would be used as an effective factor to predict the race performance regardless of wind speed.

Specifically, recommendations for future training follows the recent developments in sailing as described above: (1) The performance of the upwind leg has an important influence on competition results of the Laser race. (2) More attention should be paid to how to obtain a good position on first upwind legs, reasonably arrange the proportion of windward/downwind/reaching training in different wind speeds, and improve the courses selection ability and VMG of sailors. (3) VMG is a variable to distinguish the level of sailors, which can be used as a reference for talent selection.

Declarations

Author contribution statement

Dandan Pan: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Wrote the paper.
Kaiyang Sun: Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

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The authors declare no conflict of interest.

Additional information

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