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ORIGINAL ARTICLE

Assessment of energy demand in Laser sailing: influences of exercise duration and performance level

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Abstract In this study we analyzed the influence of both exercise duration and skill level on energy demand in Laser sailing. Twenty-three subjects volunteered for this study. The population is divided into two groups according to their skill level: 13 high (HS) and 10 low (LS). Every subject performed a 30 min upwind sailing test, with a tacking every 2 min. Heart rate (HR), gas exchange and respiratory parameters were analyzed throughout the trial, and measured blood lactate concentration ([La_{bl}] at rest and immediately after the exercise completion. Three, 4 min intervals were selected for analysis: 6–10 min (T10), 16–20 min (T20) and 26–30 min (T30). In contrast to previous studies, we found significantly progressive aerobic energy metabolism with sailing duration in the HS group (T10 = 45%; T20 = 61%; T30 = 68% $\dot{V}O_{2max}$, $P < 0.05$), whereas this demand remained stable, and significantly lower in LS group (T10 = 45%; T20 = 52%; T30 = 51% $\dot{V}O_{2max}$, $P < 0.05$). This study shows that aerobic demand is significantly more important in LS than in HS subjects after 30 min regatta, and could be an important factor in Laser regatta performance. We need further studies to confirm and explain this difference.

Keywords Oxygen uptake · Heart rate · Skill level · Laser sailing

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Introduction

Apart from tactical or strategic aspects, performance in dinghy sailing relates directly to the capacity of the sailor to overcome the external forces imposed on the boat. Indeed, the total force applied to the sail by the lift of the wind on the horizontal plane can be divided into two normal components: a lateral one, perpendicular to the main axes of the boat, which tends to capsize her; a second one, which is used during close-hauled to advance. Thus, the only means of keeping the boat upright requires the sailor to create a righting moment by leaning the upper body out of the boat, with feet under straps attached to the bottom of the hull. This hiking position is schematically represented in Fig. 1.

From a performance standing point, when the wind intensity increases, the sailor must increase the righting moment to preserve the boat flat. Indeed, the more upright the boat, the higher the rate of travel on water. The sailor's skill level can be expressed as the capacity to maintain the higher righting moment throughout the race in order to obtain the highest boat speed. In Laser (a single handed Olympic dinghy of 4.23 m), the sailor has to carry out this work alone, which constitutes the principal cause of muscular fatigue (Vogiatzis et al. 1996). In this hiking position, three principal points of contact between the sailor and side-deck can be identified (Maïsetti et al. 2002). These are the restraint of the ankles by the strap, the contact of the posterior face of the legs on the internal boat side-deck and finally the contact of the posterior face of the thighs on the external side-deck of the boat. The role of the upper limbs is to control the tension of the mainsheet and regulate the wind pressure in the sail.

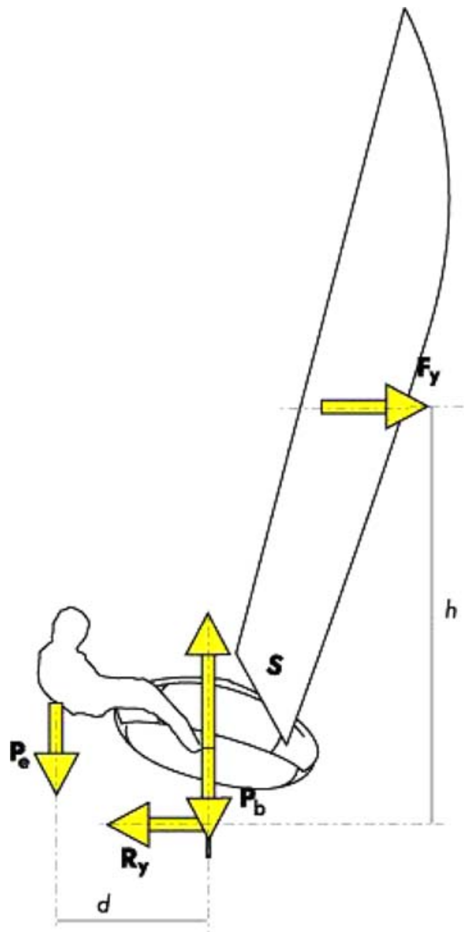

Fig. 1 Representation of the external forces acting on dinghy in navigation (modified according to Uklanski and Wolf 1986)

Several studies, including electromyographic recording (EMG), have shown that hiking imposes essentially static stresses on quadriceps, abdominal and other muscle groups for periods of several minutes with only few short periods of rest (Vogiatzis et al. 1996). Within this framework, the developed forces at the hiking strap and in the mainsheet seem to be proportional to the intensity of the wind, and range respectively between 166 and 843 N (Newton) (15–77% maximum voluntary contraction—MVC) and between 43–289 N (13–90% MVC), (Mackie et al. 1999).

Only little attention has been paid to the influence of these mechanical constraints, imposed during the regatta, on both the local muscular and general physiological adaptations. In experimental conditions, the energy expenditure imposed by dinghy sailing is assessed by four parameters, namely, minute ventilation ($\dot{V}E$), heart rate (HR), oxygen uptake ($\dot{V}O_2$) and blood lactate concentration ($[La]_b$).

To our knowledge, only Vogiatzis et al. (1995a, 1996) have measured the myoelectric symptoms of muscular fatigue during the maintenance of the hiking position. In these studies, the EMG activity was recorded on rectus femoris and biceps brachii muscles during repetitive bouts of isometric exercise in simulated sailing. In this study, $\dot{V}O_2$ was also recorded to examine the relation between mechanical and physiological adaptations in dinghy sailing. The authors suggest that the development of muscle fatigue is accompanied by increasing hyperventilation. Previous studies made under actual sailing conditions reported that, in addition to high HR, $\dot{V}E$ was also disproportionately high in relation to $\dot{V}O_2$ (Vogiatzis et al. 1994, 1996). The authors suggest that the hyperventilation accompanying isometric exercise may be due to reflexes arising from the exercising muscles and central command.

Few studies have examined real sailing condition. In such studies, maximum values for VE, HR, $\dot{V}O_{2max}$ and $[La_{bl}]$ range between 50 and 63l min^{-1}, 135 and 153 beats min^{-1}, (69–79% HR_{max}), 19 and 23 ml kg^{-1} min^{-1} (37–44% $\dot{V}O_{2max}$), 1.6 and 3 mmol l^{-1} (Vogiatzis et al. 1994, 1995a, b, De Vito et al. 1996).

It seems, therefore, that during Laser sailing, the energy demand is mainly sustained by the aerobic metabolism, as indicated by the reduced level of oxygen uptake (≈35% $\dot{V}O_{2max}$), but with high level of HR (≈75% HR_{max}). This phenomenon has been explained as the results of the specific isometric effort component which characterizes the hiking position. Indeed, muscle perfusion is impaired by mechanical compression by the contracting skeletal muscles (Kilbom and Brundin 1976; Vogiatzis and Roach 1993; Blackburn 1994; Legg et al. 1997; Felici et al. 1999). Within this framework, published reports relative to simulated sailing investigation (Harrison et al. 1988; Spurway and Burns 1993) show that relatively large increases in mean arterial blood pressure and heart rate are accompanied by modest increments in oxygen uptake.

However, some methodological aspects can explain these observations. Studies on Olympic sailing did not reproduce the racing conditions met by the athletes during a regatta. In these studies, the mean exercise duration of exercise on-water varies from 10 to 15 min, whereas regattas last from 30 to 45 min, and no information is given about the tacking frequency. Tacking has been reported to stress the cardio-respiratory response (De Vito et al. 1996) and thus it could be considered that tacking could increase energy expenditure. Finally, during a regatta, the sailors continuously adapt their position in order to maintain the optimal hiking position as long as possible. Skilled sailors adapt their position more frequently than moderately trained sailors do in order to maintain the optimal boat speed. Thus, we can hypothesize that during a 30 min regatta, the constant adaptation of the hiking position induces an increased energy expenditure especially in a high level performers. Within this framework, the principal objective of our work is to analyze influence of both exercise duration and skill level on energy demand in Laser sailing by measuring HR, $\dot{V}O_2$, $\dot{V}E$ and $[La_{bl}]$ during a 30 min on-water sailing task.

Materials and methods

Subjects

A total of 23 male Laser sailors, 13 high skilled (HS) and 10 low skilled (LS) sailors volunteered for the study. The University Ethics Committee gave its approval. All HS subjects are competing at international sailing level and train 4 h day^{-1}, 5 times per week. All LS subjects are members of regional sailing teams. Age, physical and performance characteristics of all subjects appear in Table 1. Physiological characteristics of participants appear in Table 2.

To estimate the fractional use of $\dot{V}O_{2\ max}$ by the sailor on water, each subject performed an incremental exercise up to volitional exhaustion followed within 3 days by a test simulating regatta conditions on the water.

Laboratory measurements

$\dot{V}O_{2max}$ values were recorded during an incremental running exercise performed on a treadmill (Jaeger, LE 6000, Wuerzburg, Germany). Expired gases were collected at rest for 3 min, and after an 8 min warming up run at 8 $km.h^{-1}$, the speed was increased by 0.5 $km.h^{-1}$ every minute until volitional exhaustion. The following criteria were used to define the maximum values for the exercise: a respiratory exchange ratio (RER) > 1.1, an increase in running speed without a $\dot{V}O_2$ increase, a $[La_{bl}] > 7$ mmol l^{-1} and attainment of the theoretical HR_{max} value (220-age), (Astrand and Rodahl 1986). Gas and respiratory parameters were calculated breath-by-breath during the whole test by the software provided in the equipment (Jaeger Oxycon Pro®, Wuerzburg, Germany) previously validated (Carter and Jeukendrup 2002). Minute ventilation ($\dot{V}E$, l min^{-1}), oxygen consumption ($\dot{V}O_2$, ml kg^{-1} min^{-1}), carbon dioxide excretion ($\dot{V}CO_2$, ml kg^{-1} min^{-1}), respiratory rate (f_R, br min^{-1}) and respiratory exchange ratio (RER) were calculated. Blood lactate concentration ($[La_{bl}]$) was measured using an enzymatic method, YSI 2300 Stat®, (Yellow Springs Instruments, Ohio, USA) from 25 µl samples of blood taken from the earlobe at rest and immediately after the exercise.

From these values ventilatory threshold (T_{vent}) was calculated according to the method proposed by Wasserman et al. (1973).

On-water measurements

After a 3 min rest aboard, subjects sailed for 30 min as close as possible to the direction from which the wind was blowing (upwind sailing). A tack was programmed every 2 min. Before starting, a 5 µl blood sample was taken, and used it as reference. A second blood sample was taken immediately after the 30 min sailing period (Fig. 2).

Respiratory gas and cardiac parameters were continuously recorded during the whole sailing period. Three measurement periods were chosen for analysis: 6–0 min (T10), 16–20 min (T20) and 26–30 min (T30). When the wind strength varied by more than 20% during the 30 min sailing period, we excluded the test from analysis. Gas and respiratory parameters were recorded using a telemetric analyzer VmaxST® was (SensorMédics, Linda, USA) recently validated (Prieur et al. 2003). VmaxST® is a lightweight system composed of a measurement module (size: 120 × 110 × 45 mm, weight: 650 g) and a battery module (size: 120 × 110 × 45 mm, weight: 260 g). The two parts are secured to the chest with a harness. Expired volume was measured using a turbine driven flow-meter (Triple® V, digital). O_2 and CO_2 concentrations were derived from an electrochemical cell and an infrared

Table 1 Age and physical characteristics of participants

	Age (year)	Body mass (kg)	Body fat (%)	Height (cm)	Sailing (h. $week^{-1}$)
HS (n = 13)	21.3 ± 3.3	74.2 ± 4.3	14.8 ± 2.2	178.4 ± 3.5	20.1 ± 1.75*
LS (n = 10)	22.9 ± 1.29	73.8 ± 4.52	15.8 ± 2.79	179.0 ± 2.8	8.5 ± 3.31*

Values are presented as means ± SD

n Number of subjects, *HS* high skill sailors, *LS* low skill sailors

*Significant difference between the two population ($P < 0.05$)

Table 2 Maximal values of physiological parameters reach during the incremental exercises

	$\dot{V}E_{max}$ (l min^{-1})	HR_{max} (bpm)	$\dot{V}O_{2max}$(ml kg^{-1} min^{-1})	T_{vent} (% $\dot{V}O_{2max}$)	RER	$Lactate_{max}$ (mmol l^{-1})
HS (n = 13)	115.2 ± 8.6	192 ± 4.3	58.2 ± 4.7	57.3 ± 3.2 %	1.18 ± 0.02	8.4 ± 1.5
LS (n = 10)	117.4 ± 9.4	189 ± 4.52	55.9 ± 6.9	55.8 ± 4.6 %	1.15 ± 0.05	9.1 ± 2.8

Values are presented as means ± SD

n Number of subjects, *HS* high skill sailors, *LS* low skill sailors

analyzer respectively. HR values were averaged over 5 s intervals using a Polar 4000® Sport Tester (Kempele, Finland). [La_{bl}] was measured using a Lactate Pro (Akray, Kyoto, Japan) which was recently validated (Pyne et al. 2000).

Statistical analyses

Results are presented as population means and standard deviations (σ). Differences in physiological characteristics and sailing conditions between the two groups were tested using the Student's t tests for unpaired groups, and used Pearson's product moment to show the relationship between wind intensity and energy expenditure. A repeated measures ANOVA, skill × duration on $\dot{V}E$, HR, $\dot{V}O_2$, values were used to analyze the effects of exercise duration and skill level. The Tukey post-hoc test analysis established the significance of any differences. We set the significance level at $P < 0.05$.

Results

As indicated in Tables 2 and 3, there were no differences between the two groups, concerning the anthropometric and cardio-respiratory parameters measured in the laboratory. In general terms the only difference concerned the sailing time per week, which was indeed higher in HS sailors compared to LS sailors ($P < 0.05$). The mean wind intensities for HS and LS are 11.6 + 4.6 and 12 + 7 knots, respectively.

Moreover, in both groups, a linear relationship was also demonstrated between wind intensity and energy demand ($r = 0.85$, $P < 0.01$; Fig. 3)

We saw a significant interaction effect between exercise duration and skill level (Table 4). In the high skill group only, we noted a significant increase in the energy demand with exercise duration, whereas the demand remained stable in the low level group. At the end of exercise the HS group attained 68.3% and the LS group 51.2% of $\dot{V}O_{2max}$.

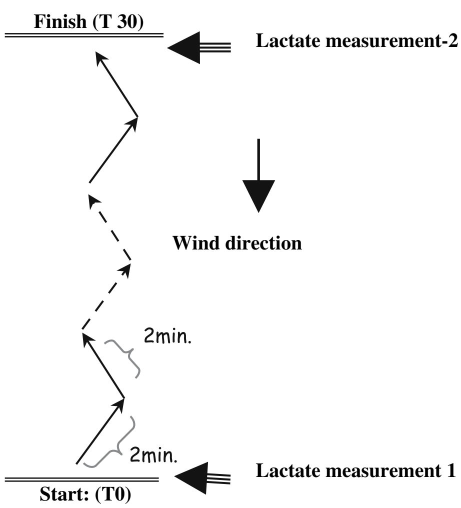

Fig. 2 On-water protocol

Discussion

The main result of the present study is that energy demand increases with exercise duration in a high skilled population, indicating the role of aerobic metabolism for these subjects. This result contradicts previous reports that indicated a relatively low aerobic contribution during sailing with estimated mean values of ≈40% $\dot{V}O_{2max}$ (estimated from De Vito et al. 1996; Vogiatzis et al. 1994, 1995a, b).

However, this contradiction may be explained by differences in experimental protocols. Indeed, in these early studies, wind intensity never exceeded 20 knots, and sailing duration always remained shorter than 15 min. De Vito et al. (1996) reported an exercise duration of 15 min and Vogiatzis et al. (1994; 1995a, b) reported durations varying from 10 to 15 min or around 10 min. When we compare these previous results with our results obtained over a similar time, i.e., the first period of measurement (T10) and the same wind conditions (n = 19), our results are in agreement with the literature whatever the group. Indeed those results show aerobic contribution and a blood lactate concentration lower than 4 mmol l^{-1} if wind intensity is lower than 20 knots and during the first 10 min of sailing (Table 5).

Table 3 Environmental conditions for each group during the sailing test

	Air temperature (C°)	Water temperature (C°)	Wind intensity (knots)	Atmospheric pressure (mmHg)
HS (n = 13)	11.7 ± 2.79	13.5 ± 0.94	11.6 ± 4.65	1013.3 ± 15.2
LS (n = 10)	12.8 ± 3.33	14.0 ± 0.67	12.0 ± 7.09	1014.5 ± 14.82

Values are presented as means ± SD

n Number of subjects, *HS* high skill sailors, *LS* low skill sailors

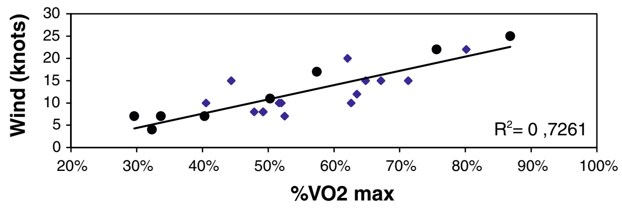

Fig. 3 Relationship between wind intensity and energy demand (% $\dot{V}O_{2max}$)

Furthermore, in contrast with other studies we have seen neither the increasing hyperventilation, where $\dot{V}E$ was disproportionately high in relation to $\dot{V}O_2$, nor a greater % HR_{max} than % $\dot{V}O_{2max}$ as reported by Vogiatzis et al. (1994, 1996). They suggest that the hyperventilation accompanying isometric exercise may be due to reflexes arising both within the exercising muscles and central command. In our study, subjects tacked every 2 min and $\dot{V}E$ and HR increased proportionately to $\dot{V}O_2$. We suggest that tacking regularly creates dynamic muscle contraction which can explain the lower $\dot{V}E$ values recorded in our study. Relatively few studies have investigated the effect of tacking on physiological response. Within this framework, even if tacking could be considered as an additional stress, De Vito et al. (1996) did not observe an increase in oxygen uptake even during a series of tacks at 15 s cadences. Further studies are needed to explain the role of tacking strategies on physiological adaptation during a regatta.

One interesting result of our study is that the energy demand increase is seen only in highly skilled subjects. To the best of our knowledge, no previous studies have analyzed the effect of skill level on physiological demand. De Vito et al. (1996) focused on ‘‘experienced athletes’’ in one study and on ‘‘national or international ranked athletes’’ in another; Vogiatzis et al. (1995b) mentioned that sailors were ‘‘member of the Scottish National Squad’’. Our results reveal a relatively low anaerobic component, $[La_{bl}] < 4$ mmol l^{-1}, and the importance of the aerobic contribution for skilled sailors during a 30–45 min regatta. By contrast, the aerobic contribution in the low skilled group was always lower. This observation is confirmed by the difference in $\dot{V}O_2$ values when expressed in percent of T_{vent}. In the skilled sailors, $\dot{V}O_2$ values at the end of the test represent 119% of T_{vent} whereas in low skilled subjects this value represents only 95% of T_{vent}.

There were no significant differences in treadmill $\dot{V}O_{2max}$ between the two groups (HS 58.2 and LS 55.9 ml kg^{-1} min^{-1}). Thus, the difference in energy contribution during sailing between these two populations can be explained by the inability of our less-skilled subjects to use a high percent of their $\dot{V}O_{2max}$ or HR_{max}. However, there is no substantial information available on the relation between $\dot{V}O_2$ recorded on a treadmill and $\dot{V}O_2$ on water, but as Astrand and Rodahl (1986) suggest, measurements recorded in the laboratory are not always transferable to field work; this is especially so when muscle actions are different.

Table 4 Values are presented as means ± SD of % $\dot{V}O_{2max}$, % T_{vent}, % HR_{max}, and % $\dot{V}E_{max}$ with exercise duration in the two experimental groups during the three exercises periods

		T10	T20	T30
% $\dot{V}O_{2max}$	HS	45.08 ± 1.02	61.53 ± 2.12^{+*}	68.35 ± 1.76^{+*}
	LS	45.43 ± 0.98	51.70 ± 1.05	51.29 ± 1.38
$\dot{V}O_2$ in % T_{vent}	HS	79 ± 1.8	107 ± 2.4^{+*}	119 ± 2.5^{+*}
	LS	76 ± 0.8	95 ± 3.2	95 ± 3.8
% HR_{max}	HS	64.65 ± 2.14	73.46 ± 2.02^{+}	78.53 ± 2.18^{+*}
	LS	65.22 ± 2.02	70.65 ± 2.65	70.70 ± 1.02
% $\dot{V}E_{max}$	HS	33.05 ± 1.67	43.301 ± 1.45^{+*}	46.51 ± 1.62*
	LS	33.12 ± 1.06	40.73 ± 1.74	39.07 ± 1.39

*Significant difference between the two populations. $P < 0.05$

$^{+}$ Significant difference with previous period (in HS). $P < 0.05$

Table 5 Values of physiological parameters for a sailing period of less than 15 min reported in the literature compared to those in our study

	n	Duration (min)	Wind (knots)	$\dot{V}O_2$ (ml min^{-1} kg^{-1})	HR (b min^{-1})	$\dot{V}E$(l min^{-1})	$\dot{V}O_{2max}$ (%)	HR_{max} (%)	Final lactate (mmol l^{-1})
Our study	19	10	7–25	23.8	124	42.8	42.5	64.3	3.3
Vogiatzis et al.	6	NA	11–13	20.9	145	56	NA	NA	NA
(1994)	6	NA	15–18	23.1	153	63.3	NA	NA	NA
Vogiatzis et al. (1995a)	6	10	7–20	20.3	145	NA	39	74	2.3
Vogiatzis et al.	8	10	8–16	19	135	NA	37	69	3
(1995b)	8	10	16–20	22	145	NA	42	79	2.3
De Vito et al. (1996)	6	15	5–8	23	144	50	44	78	NA
Mean	7.2	11	5–20	21.4	145	56.4	40.5	75.0	2.5

NA not available

On the other hand, this difference can also relate to differences in adaptation on the dinghy between the two groups. Indeed, there is a link between sailing performance and the need to preserve an optimal boat speed by keeping a horizontal position. A previous study (Larsson et al. 1996) showed a direct relation between skill level and the capacity to maintain a hiking position longer during simulation on specific sailing ergometer. Mackie and Legg 1999 showed that during sailing, highly skilled athletes continuously adjust their position on the boat in order to maintain an optimal righting moment. Our results suggest a link between the constant adjustment of this position and the energy expenditure. In an expert population, the continual adjustment of the posture and the maintenance of a maximal level of force on the hiking strap could explain the increase in the energy expenditure over time. In contrast, a non-expert population may be characterized by difficulty in maintaining an optimal hiking position and therefore optimal boat speed. This absence of maintained postural adaptation can explain the low, but stable energy demand during the 30 min on water exercise. Indirect evidence for this hypothesis has been reported in previous work in laboratory (Blackburn 1994). In this study the author showed a relationship between the variability of the force exerted on the straps during hiking and the energy expenditure ($\dot{V}O_2$). Furthermore, Vogiatzis and Roach (1993) have suggested that the hiking posture is sustained by a continuous increase in the muscular activation level (iEMG) of the isometrically contracting muscles of the legs. Such an increase requires recruitment of additional motor units as indicated by the increased amplitude, and can also be associated with an increase in demands on the cardiovascular and metabolic systems.

Conclusion

This study set out to analyze the influence of both exercise duration and skill level on energy demand in Laser sailing. Relatively little work has been conducted in this area, and little is known about the real energy demand during a whole regatta or its influence on sailing performance. The results show that aerobic demand in skilled subjects is not negligible after 30 min, and could be an important factor in Laser regatta performance. However, we need further studies to explain the relationship between hiking and tacking strategies and energy expenditure during prolonged races.

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