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ORIGINAL ARTICLE

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The physiological demands of sail pumping in Olympic level windsurfers

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Abstract This study investigated the physiological effects of sail pumping (PB) – a manoeuvre often adopted to provide additional propulsion to the board – in Olympic Class Windsurfing, following relaxation of the "no-pumping" rules by the International Federation. Fifteen Olympic-level windsurfers (10 men) from nine different countries volunteered for the study, which was performed during two international Olympic regattas. The measurements were carried out during actual sailing when both PB and not-pumping (NPB) using a portable metabolimeter. Windsurfing, when PB, elicited a dramatic increase in cardiorespiratory responses compared to NPB. Mean (SD) values for oxygen uptake and heart rate during NPB for the men and women were: 19.2 (4.4) and 15.7 (3.3) ml·kg^{-1}·min^{-1}, and 110 (10) and 122 (12) beats·min^{-1}, respectively, whereas the values in PB were: 48.4 (5.7) and 40.2 (4.2) ml·kg^{-1}·min^{-1}, and 165 (12) and 172 (13) beats·min^{-1}, respectively. All the PB parameters, with the exception of heart rate (HR), were significantly higher in the men than in the women but no differences were observed between the sexes in NPB with the exception of HR, which was higher in the women. Our results suggest sail pumping is as physically demanding as most aerobic sporting activities. In the context of the need to deal with a highly demanding athletic branch of sailing as part of an Olympic regatta, recommendations are made on how best to make physical and dietary preparations.

Keywords Windsurfing · Energy cost · Blood lactate · Sail pumping

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Introduction

Sail pumping (PB) in windsurfing is a manoeuvre in which the surfer pulls and pushes the sail rhythmically so that it acts as a wing, thus providing the board with additional propulsion. In windsurfing, PB is considered particularly effective at wind velocities up to 15 knots (7 m·s^{-1}). At higher wind speeds this action loses its efficacy or physically it becomes too demanding.

De Vito et al. (1997) were the first to measure the energy cost of PB during actual sailing conditions on a cohort of Italian windsurfers. Their findings revealed that PB required a strenuous aerobic effort as shown by the fraction of the maximum oxygen uptake ($\dot{V}O_{2max}$) that was employed during actual sailing (75% of $\dot{V}O_{2max}$) in male participants. Other studies, which used blood lactate concentrations and heart rate (HR) (Guevel et al. 1999) or just HR (Dyson et al. 1996) measurements during actual windsurfing conditions, confirmed that PB is physically demanding.

Windsurfing was, until recently, considered as a moderately intense activity (Plyley et al. 1985; Mclean and Chad 1992). This is probably due to the fact that early studies were conducted at a time when sailors were not allowed to pump, as the International Sailing Federation (ISAF) only introduced the Mistral One Design board as an Olympic Class, and made PB in windsurfing *legal*, in 1993. Due to that change in windsurfing regulations, the ISAF requested its Medical Commission to investigate the physical demands of PB during Olympic Class Windsurfing in order to be able to issue event organisers with sport specific guidelines and provide competitors and coaches with recommendations on how best to make physical and dietary preparations for competition.

The purpose of this study was therefore threefold. First, to provide an insight into the physiological demands of PB by comparing responses while sailing with or without PB . Second, as the race equipment for male and female competitors is standard, we aimed at evaluating whether PB places differing demands on the two sexes. Third, as several up-wind and down-wind legs make up the racing course, we wished to assess the effects of PB on both of these legs and to compare the body's physiological responses during the up- and down-wind legs.

Methods

Subjects

The study was carried out during the Rome International Regatta in Anzio and the European Windsurfing Championship in Athens. A group of 15 windsurfers (10 men and 5 women) from nine different countries volunteered for the study, which was approved by the University Ethics Committee before its commencement. To ensure that the results of the study were reliable and applicable to Olympic standard competition it was decided to invite a few of the most highly ranked athletes in the official ranking list of ISAF for Olympic Classes. The sample included the world's number one male and female windsurfers at that time, as well as two Olympic medallists from both the Atlanta and the Sydney Olympic Games. The ages and physical characteristics of the 15 participants are given in Table 1.

Study protocol

All measurements were made during the regatta days before competition commenced. While ashore the subjects were instrumented with a portable metabolimeter (K4 RQ, Cosmed, Italy). To reproduce the actual conditions of a regatta and to allow sufficient time for achieving steady-state conditions, without interfering too much with the daily performance of the athlete, the following protocol was adopted.

Each athlete sailed to the regatta field and this phase was adopted as the warm-up period. Following 5 min of rest during which baseline variables were recorded and a blood sample was taken for blood lactate analysis, the sailors were instructed to sail for 8 min on the upwind leg. During the first 4 min, sailors were asked to keep their bodies still while not sail-pumping (NPB), whereas during the remaining 4 min sailors were instructed to PB as frequently and for as long as they could. Following the completion of the 8 min upwind leg, sailors were asked to stop and rest until their physiological responses had returned to pre-test conditions; within the first 3 min into the recovery a second blood sample was drawn for analysis. Following 15 min of rest sailors were asked to sail down-wind for 8 min; during the first 4 min using NPB followed by 4 min with PB. At the end of this final leg the subjects stopped and a third blood sample was drawn within the 3 min following the end of the test. An additional blood sample was collected for analysis from each subject immediately after the end of the race on the same day of the actual test session and therefore in similar weather conditions. Of 15 tests 12 were carried out in light to moderate wind velocities that ranged from 4 to 6 m·s^{-1}. Only 3 tests were conducted in stronger winds that ranged from 7 to 8 m·s^{-1}.

Table 1 Age and physical characteristics of the participants. Data are means (SD)

Variable	Men ($n=10$)	Women ($n=5$)
Age (years)	22.9 (4.3)	24.7 (3.8)
Stature (m)	1.78 (0.05)	1.65 (0.01)
Body mass (kg)	68.7 (4.0)	57.5 (3.9)
Body surface area (m^2)	1.85 (0.08)	1.63 (0.05)

On-water measurements

The following cardiorespiratory variables were recorded by the K4 at 15 s intervals: oxygen uptake ($\dot{V}O_2$), carbon dioxide output ($\dot{V}CO_2$), pulmonary ventilation ($\dot{V}_E$) and HR, and transmitted by radio to a receiver unit located in a motor boat following behind the windsurfer. The samples for the determination of blood lactate concentration were drawn from an earlobe and were analysed immediately using a portable lactate analyser (Accusport, Boehringer, Germany).

Measurements ashore

To estimate the fractional use of $\dot{V}O_{2max}$ by the windsurfers on water, 8 male windsurfers performed an incremental exercise test on a cycle ergometer (Monark model 810) to the point of exhaustion. The pedal frequency was 60 rpm and the intensity was increased by 25 W each minute from an initial value of 50 W. Cardiorespiratory variables were recorded using the K4 as described above.

Statistical analysis

We used the 1 min of data corresponding to the last minute (3–4) of each 4 min of sailing when NPB or PB for the purpose of analysis. All data are presented as means (SD). Differences between up-wind and down-wind data on the same subject were tested using paired Student's *t*-tests. Since comparisons of the values between the two sailing-legs revealed no significant differences, it was decided to present in this report the responses recorded from the down-wind leg only. To determine the effect of PB on body responses four sets of data were considered: NPB and PB in women, and NPB and PB in men. A two-way ANOVA (sex and sailing condition) was conducted and followed, where appropriate, by either paired or unpaired-Student's *t*-tests to determine differences between-trials (PB compared to NPB) and between-sexes, respectively. The α level was set at $P<0.05$ for all calculations.

Results

Mean values for $\dot{V}O_{2max}$ and HR responses from all 15 competitors while sailing up-wind and down-wind using PB or NPB are shown in Fig. 1.

Mean values of the cardiorespiratory variables measured during actual windsurfing are shown in Table 2. For both sexes, it is evident that PB resulted in a dramatic elevation in all reported variables compared to NPB. The $\dot{V}O_2$, $\dot{V}CO_2$, $\dot{V}_E$ and HR were significantly higher using PB compared to NPB ($P<0.001$).

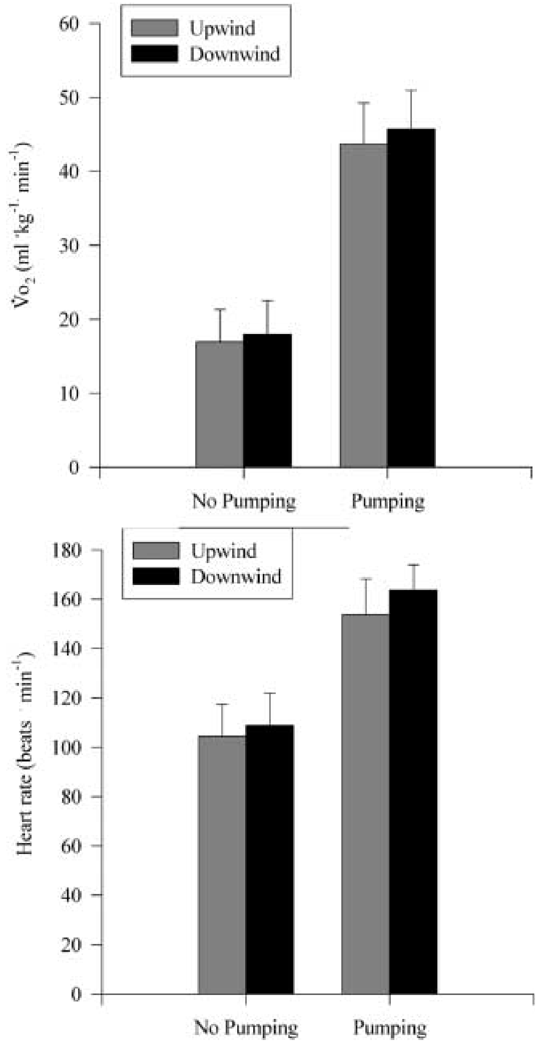

Fig. 1 Comparison of the 15 sailors' oxygen uptake ($\dot{V}O_2$) and heart rate responses during up-wind and down-wind legs with or without sail-pumping. Data are means and SD

In addition, Fig. 2 shows for a typical subject the trend of the main cardiovascular parameters (HR, $\dot{V}O_2$, $\dot{V}CO_2$) measured during the test procedures in both upwind and down-wind legs, during NPB and PB.

During both PB and NPB, the women exhibited higher HR values than the men (Table 2), although only during NPB was this difference statistically significant ($P < 0.01$). By contrast, the men showed significantly higher values than the women in all the other variables, $\dot{V}O_2$, $\dot{V}CO_2$ and $\dot{V}_E$ during PB (Table 2).

The maximal values for $\dot{V}O_2$ and HR of the 8 male windsurfers in the offshore incremental test on the cycle ergometer, as well as their mean $\dot{V}O_2$ and HR responses (in absolute and relative to maximal values) recorded on-water during NPB and PB sailing conditions are given in Table 3.

The blood lactate concentrations measured during both the up-wind and down-wind sailing tests and during actual races are shown in Fig. 3. No significant differences were observed between the first and second leg or between the two legs and the end of the race conducted in the same sea/weather conditions.

Table 2 Cardio-respiratory variables measured during actual down-wind sailing, during both sail-pumping (*PB*) and not sail-pumping (*NPB*) conditions and in both sexes. Data are mean and SD

	Men	Women
Oxygen uptake ($ml \cdot kg^{-1} \cdot min^{-1}$)		
NPB	19.2 (4.4)	15.7 (3.3)
PB	48.4 (5.7)[a]	40.2 (4.2)[a,b]
Carbon dioxide production ($ml \cdot kg^{-1} \cdot min^{-1}$)		
NPB	15.0 (2.7)	12.6 (2.4)
PB	42.8 (7.0)[a]	37.3 (5.7)[a,b]
Minute ventilation ($l \cdot min^{-1}$)		
NPB	31.1 (5.6)	26.6 (6.2)
PB	90.8 (19.9)[a]	65.8 (12.9)[a,b]
Heart rate ($beats \cdot min^{-1}$)		
NPB	110 (10)	122 (12)[b]
PB	165 (12)[a]	172 (13)[a,b]

[a]Difference statistically significant between sailing conditions
[b]Difference statistically significant between sexes

Concerning the respiratory exchange ratio (*R*) no statistical differences were observed between the sexes, however, in all subjects *R* values measured during PB were greater than those during NBP ($P < 0.01$).

Discussion

This is believed to be the first time ever that 15 highly ranked international competitors have had their energy costs and cardiorespiratory responses measured during actual windsurfing during both PB and NPB.

The present results corroborate previous findings obtained by De Vito et al. (1997) and expand on their observations by showing that PB, when it is performed by Olympic-standard international competitors, is a highly demanding aerobic activity. Furthermore, the mean $\dot{V}O_2$ values [48.4 (5.7) and 40.2 (4.2) $ml \cdot kg^{-1} \cdot min^{-1}$ for men and women, respectively] indicate that PB is as physically demanding as other aerobic sporting activities, such as cross-country running and rowing (Reilly and Secher 1990). The $\dot{V}O_2$ and HR responses when expressed as percentages of maximal values on a subgroup of 8 male windsurfers amounted to 77% and 87%, respectively, these figures being very similar to those (75% $\dot{V}O_{2max}$ and 92% maximal HR) reported by De Vito et al. (1997). In addition, the mean HR values recorded from our male and female competitors during PB are comparable to those obtained either from the National Team of French Olympic windsurfers (Guevel et al. 1999) or from the National Team of British windsurfers during actual races (Dyson et al. 1996). On the contrary, NPB was shown to be a low-demand physical activity, thus confirming previous results obtained using HR measurements alone at the time when PB was sanctioned at the standard of Olympic competition (Shephard 1997).

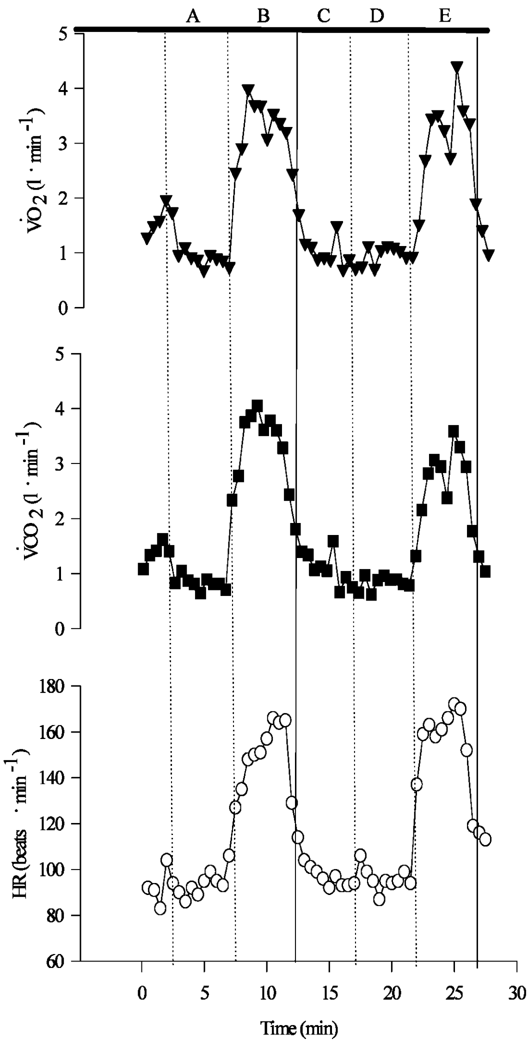

Fig. 2 Oxygen uptake ($\dot{V}O_2$), carbon dioxide output ($\dot{V}CO_2$) and heart rate (*HR*) values (averaged every 30 s) measured during the actual race simulation in one typical male windsurfer. The *vertical dotted lines* demarcate the phases of the different tests, which are also indicated by the *letter above* each period: *A* non pumping up-wind, *B* pumping up-wind, *C* pause, *D* non pumping down-wind, *E* pumping down-wind. Refer to Methods for more details about the protocol

The use of the cycle ergometer for the measurement of the sailors' $\dot{V}O_{2max}$ could be a limitation of the present study, as it did not impose stresses similar to the demands of windsurfing. On the other hand, only a windsurfing simulator capable of reproducing the activity of the whole-body musculature during PB would represent a valid solution to this problem. To our knowledge, such a simulator is not yet available. Moreover, in the present study, to facilitate the recruitment of top level athletes, the $\dot{V}O_{2max}$ measurement was not conducted in a laboratory setting but in the proximity of the regatta field. For all of these reasons it was preferred to use a standard cycle ergometer, which was easy to transport to the sailing venue, and presented an exercise task that was readily performed by the windsurfers.

Table 3 Oxygen uptake ($\dot{V}O_2$, maximal oxygen uptake ($\dot{V}O_{2max}$) and maximal heart rate (HR_{max}) responses measured during the incremental cycle ergometer test and actual sailing, in both pumping (*PB*) and not pumping (*NPB*) conditions in eight male windsurfers. Data are presented as absolute values and as percentages of maximal values (%max)

	Mean (SD)	%max (SD)
$\dot{V}O_{2max}$ (ml·kg^{-1}·min^{-1})	63.0 (6.2)	–
NPB $\dot{V}O_2$ (ml·kg^{-1}·min^{-1})	19.0 (4.2)	30 (3)
PB $\dot{V}O_2$ (ml·kg^{-1}·min^{-1})	48.7 (5.3)	77 (8)
HR_{max} (beats·min^{-1})	187.0 (13)	–
NPB HR (beats min^{-1})	105.0 (10)	56 (5)
PB HR (beats·min^{-1})	163.0 (12)	87 (8)

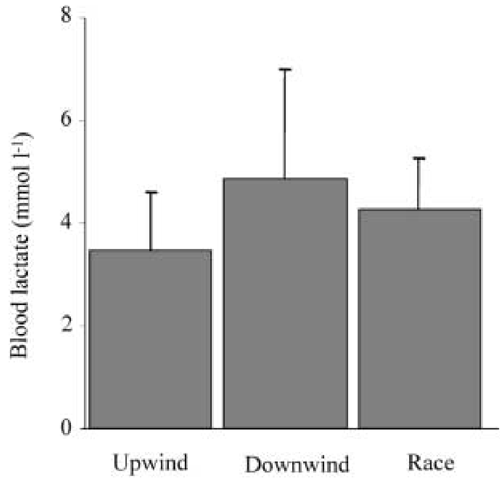

Fig. 3 Blood lactate concentrations in blood samples taken after the first leg (up-wind), and second leg (down-wind) of the race simulation, and at the end of a race in a true regatta (race). Data are means and SD

The significant differences shown on the recorded respiratory responses between male and female athletes during PB deserve some reflections. As the on-water test conditions were not identical for everybody and the number of female participants was smaller than that of male it is hard to make comparisons between male and female responses. However, the lower $\dot{V}O_2$ values recorded in women during PB may reflect their reduced ability to generate as high a level of power on the sail as their male counterparts. When metabolic cost $\dot{V}O_2$ is expressed relative to body mass the effect of the sex dismorphism was reduced but not completely removed. A greater percentage of body fat could partially account for this difference (Forbes 1972), together with a reduced haemoglobin concentration (Woodson 1984). In contrast to the respiratory demands the women exhibited significantly higher HR values during NPB. In NPB a quasi-isometric effort is required (Van Gheluwe et al. 1988) which can induce the typical cardiovascular adjustment, i.e. an increase of blood pressure and HR not proportional to the muscle mechanical effort (Schönle and Rieckert 1983). This phenomenon is even more pronounced because of the involvement of the upper arm muscles (Pendergast 1989). In this respect, NPB can be compared to the *hiking* effort in dingy sailing. Studies have shown that hiking elicits cardiac work that is disproportionate to the $\dot{V}O_2$ requirement (Vogiatzis et al. 1995; Marchetti 1999). In the present study the higher HR response observed in the women, during NPB, could be ascribed to an anticapsising effort. Although female athletes are disadvantaged in term of muscle mass, stature and body mass, when compared to their male counterparts, they still have to produce the same anticapsising effort because the size of the sail is the same for both male and female competitors.

Comparisons of the windsurfers' $\dot{V}O_2$ and HR responses between up-wind and down-wind legs, during both PB and NPB, revealed no significant differences. Such observations are in accordance with the data obtained on 14 Italian windsurfers (7 men and 7 women) by De Vito et al. (1997), but are in contrast to those obtained by Guevel et al. (1999) who observed a statistically significant difference in mean HR response between down-wind and up-wind legs.

The *R* and blood lactate concentrations during PB (typically in the range of 0.90–0.95 and 3.5–4.5 $mmol \cdot l^{-1}$, respectively) suggest discernible involvement of anaerobic metabolism, given the length of time that PB was performed. The lactate values observed in the present study during up-wind and down-wind legs were very similar to those measured following the actual race (Fig. 3) and are in good agreement with those reported by Guevel et al. (1999) and De Vito et al. (1997) held in similar wind conditions. Based on this observation it is likely that during a typical race, lasting 40 min, lactic acidosis might present a limiting factor to muscle performance, especially in the relatively small but hard working muscles of the upper body. It is therefore advisable to windsurfers to set PB frequency at or only slightly above the exercise intensity that represents the lactate threshold. The accessibility of portable lactate analysers and HR monitors has led to an increased interest by coaches and sailors in using the lactate threshold approach (during sea or dry-land training) to achieve optimal adaptations and maximise performance (personal observation).

The precise estimation of the fractional use of carbohydrate from the *R* values might be inappropriate due to the high lactate concentration. Nevertheless the high *R* values obtained during PB are indicative of an increased rate of carbohydrate use. In addition, the high $\dot{V}_E$ values measured during PB suggest a significant water loss from the lungs. The sweat loss can also contribute to the dehydration of the athletes. Therefore, fluid supplements must be provided especially in hot and humid environments. The second consideration, which is of course linked to the first, regards the need to allow sufficient rest in between races to guarantee a proper recovery and an optimal replenishment of fluids and nutrients.

In conclusion, this study showed that windsurfing can encompass both leisure and competitive aspects of sport, and that PB is the factor that demarcates the two conditions. These results confirm that NPB is a low cost activity compared to PB and can be generally practised safely at a recreational level. By contrast PB is a very demanding activity which requires a high level of physical fitness and which necessitate a stricter sports medicine supervision in term of both training and nutritional strategies.

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