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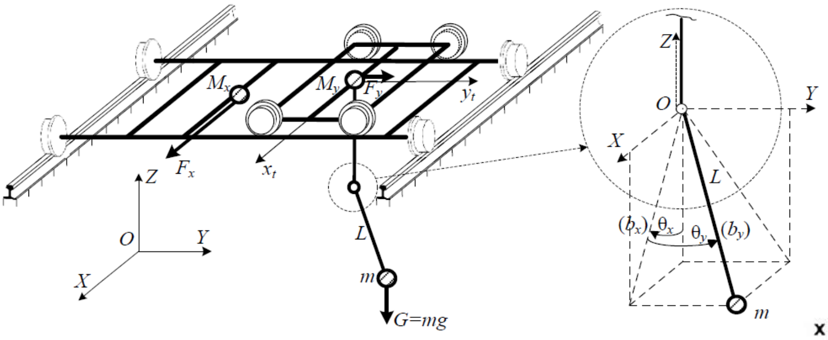

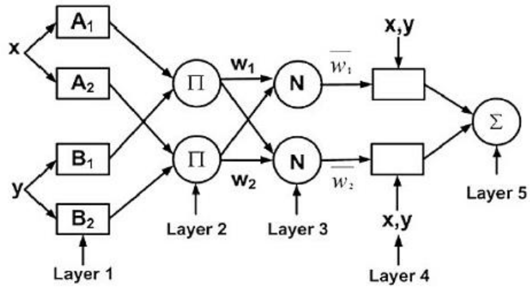

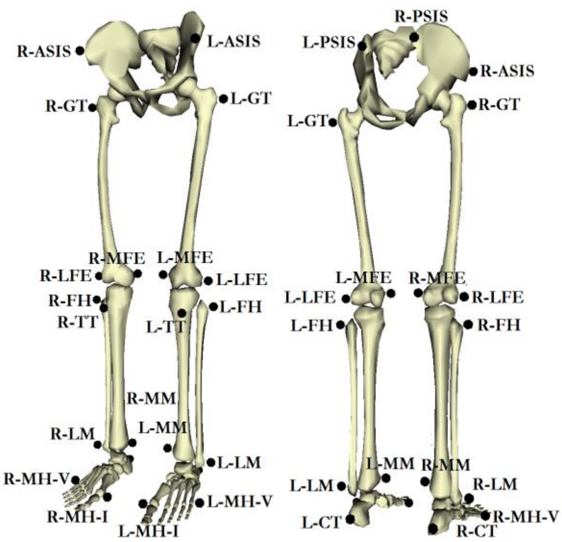

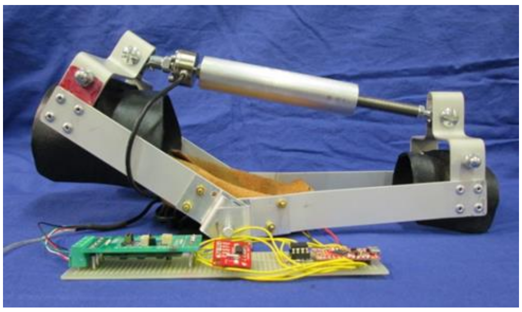

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International Journal of Mechanics and Control

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Preface for the special issue of the International Journal of Mechanics and Control (JoMaC) dedicated to BIOMECHANICAL ENGINEERING

Biomechanical Engineering applies principles of Engineering Mechanics to biological systems, and originates from the wider discipline of Biomechanics. Biomechanical Engineers work in a variety of fields including medicine, sports and rehabilitation.

Biomechanical Engineering can be declined into a variety of topics, for example biomechanics of human body, motion/equilibrium/postural analysis, articular kinematics, soft tissue mechanics, mechanics of fluid systems (cardio-circulatory, respiratory, …). Particular attention should be paid to human-machine interaction, comprising rehabilitation devices, orthoses, internal and external prostheses, exoskeletons, medical application of robotics, robotic surgery, and haptic systems.

The interest for Biomechanical Engineering has continuously increased in last years, and a large number of specialized journals populate the international editorial panorama. In addition, many international conferences, specifically devoted to Biomechanical Engineering, or including dedicated special sessions, are yearly organized.

It is worth reporting that a world organization such as IFToMM (the international federation for the promotion of mechanism and machine science) counts, among others, an especially dedicated Technical Committee for the Biomechanical Engineering. This TC has strongly grown up in the last period, evidencing an increasing interest in this discipline, and nowadays it counts 36 members from 20 Countries, spread over 4 Continents. In July 2018, the International Scientific Committee of MESROB (International Workshop on New Trends in Medical and Service Robotics) has deliberated to become the official conference of the IFToMM TC for Biomechanical Engineering.

JoMaC, the International Journal of Mechanics and Control, which is the official journal of IFToMM Italy, decided to dedicate in the current issue a special space to the Biomechanical Engineering.

Four valuable contributions, covering a wide range of biomechanical applications, have been invited and are here presented. Kristóf Rácz et al. propose new suitable standards to examine how a set of changes to a calibration protocol affects accuracy in gait analysis. Alberto Concu et al. evaluate the correlation between the mechanical and the metabolic energy, during the gait cycle of a subject equipped with and without energy storage devices called “Jump Stilts”. Wen Chih Wu et al. analyze changes in the metabolic power and energy cost, due to cardio-respiratory and metabolic adaption induced in a 52-aged élite sailor engaged in the Onestar Atlantic solo race from Plymouth (UK) to Newport (USA). Carlo De Benedictis et al. present an elbow static progressive brace equipped with special sensors, aimed at objective evaluation of the physiological response of the articulation during treatments for recovery of the functional range of motion.

I wish to express my sincere appreciation to all researchers having contributed to this special issue, for their valuable support to the growth of this fascinating discipline.

Carlo Ferraresi
Associate Editor of JoMaC
Chair of IFToMM TC for Biomechanical Engineering

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METABOLIC POWER AND ENERGY COST OF MECHANICAL WORK CARRIED OUT BY A SAILOR ENGAGED IN A SOLO OCEAN RACE: A CASE STUDY

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ABSTRACT

The purpose of this case study was to find fundamental information, concerning changes in the metabolic power and energy cost, due to cardio-respiratory and metabolic adaption induced in an aged 52 élite sailor engaged in the solo Atlantic race Onestar from Plymouth (UK) to Newport (USA), in 17 days. While sailing the participant wore an armband device to assess energy expenditure. The sailor also carried out incremental cardiopulmonary tests by a cycle-ergometer just before and after the race. During sailing the metabolic power per body mass unit ranged from 3.4 to 3.9 W kg^{-1}, while the corresponding metabolic cost to transport the body centre of mass inside boat ranged from 14.1 to 35.5 J kg^{-1} m^{-1}. After race stopped, the cardiopulmonary test showed that, at each step of work load, the oxygen consumption did not reduced with respect to the race beginning. Moreover, the index of aerobic efficiency was 0.23 and approached the theoretic maximum value of 0.25 more than that assessed before the race that was 0.21. It was concluded that several days of very hard sailing can induce specific adaptations in the cardio-respiratory, metabolic and endocrine systems in such a ways of maintaining the previous acquired aerobic capacity, thus generating a physical conditioning aimed at sustaining the high demanding of metabolic power despite occurring higher peak of energy costs.

Keywords: Ocean sailing, metabolic power, metabolic cost, Armband metabolic device, cardiopulmonary testing

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1 INTRODUCTION

The “solo” ocean sailing can be considered like as an extreme sport since it greatly stresses several homeostatic mechanisms in the athlete’s body, so involving a high degree of risk. In fact, during long lasting sailing the occurrence of hyperglycemia, hypoalbuminemia and even altered blood electrolytes has been observed [1]. Moreover, the activity of critical enzymatic processes such as the monoamine oxidase, the creatine phosphokinase and the lactate dehydrogenase appeared as reduced [1].

In these sailing people all the latter occurrences may have not negligible consequences on the intimate functioning of cellular dynamics in nervous, cardiac and striate muscle tissues, but also on the water content in the body with serious risk of hypovolemia and therefore maintenance of normal blood pressure values. A study by Lewis et al. [2], where sailors were exposed in the sea to an average temperature of 7 ° C and wind speed of 24 km/h, confirms this latter occurrence since these Authors showed that after 2.5 hours of sailing there was a significant reduction in body mass, caused by water loss, with reduced blood concentrations of Na, K and Cl. Another condition of strong homeostatic disturbance, lamented by many ocean sailors, is the breaking of the normal sleep/wake rhythm which often slips from a continuous to a fragmented sleep condition. In fact, in sailors crossing in solitary the pacific ocean, Hagin et al., [3] found that the average sleep time was only 5.4 hours per day and was characterized by considerable fragmentation over 24 hours with sleep periods ranging from a minimum of 20 minutes to a maximum of 2 hours. This condition agreed with an increase in the anxiety levels since in these sailors the marked fragmented sleep pattern correlated with a significant increase in reaction times to visual stimuli [4]. All these occurrences, of course, may increase the risk of accidents in boat. As is well known, lack of sleep together with high levels of anxiety reduce the efficiency of the immune system [5, 6, 7]. In this regard the study of Zheng and co-workers [8] has shown that, after 20 days of non-stop sailing, the microbiota of the oral cavity varied dramatically with an increase of about 70% of the presence of Streptococcus pneumonia. Despite these alarming occurrences and though the participants in oceanic sailing competition are constantly increasing, studies aimed at better clarify the systemic adaptations, the metabolic power engaged and risks faced by these solitary navigators are few and the data obtained are not yet well matched. In this paper we report a case study of an élite ocean sailor who participated to an Atlantic Ocean race, with the aim of the maximum possible information on his body adaptations due to the race. We have dedicated particular attention especially concerning the metabolic power released and the corresponding energy cost of the mechanical work while sailing, in such a way to link these purely mechanical variables with the cardiopulmonary and metabolic adaption due to the long lasting oceanic sailing. In this light, in the sailor we monitored these variables before his departure from England, during Atlantic navigation and a few days after his arrival in USA.

2 METHODS

2.1 THE PARTICIPANT

The participant at the present study is a very experienced male ocean sailor and, at the race beginning, he aged 52 years and weighted 70 kg. He began to race in sailing competitions from the age of six and he won the last edition of the prestigious Onestar (OSTAR) ocean sailing cup in June 2017, from Plymouth in England to Newport in the USA, and this was the object of our investigation. But he had previously won the same cup in 2013 and the Twostar edition in 2012. Moreover, already in 2010 he was the winner of another prestigious solo Atlantic regatta: *La Route du Rhum*, from Saint Malo in France to the Guadalupa in the Caribbean. The sailor provided written consent to participate in the investigation. The case study and the protocol were in agreement with the declaration of Helsinki concerning ethical principles for medical research involving human subjects.

2.2 THE BOAT

The boat is named *Vento di Sardegna* and is an Open 50 that was built on a project largely indicated by the participant himself. It is 15.24 meters long (plus 1.45 of bowsprit), has a maximum beam of 4.73 and weighs 7 and a half tons. Made under vacuum by the Dolphin Shipyards of Rome and SC Latina, in Italy, it has a PVC and Kevlar sandwich hull and a carbon and PVC blanket. The sails, designed by the participant, were the first in the world made with the sk99 low crimp yarn, a fibre 50% stronger than kevlar and 30% more resistant than carbon, as well as being very light and almost immune to stretching. Another substantial change concerns the sunroof, also designed by the participant, which had a geodetic shape that allowed to staying in the cockpit even in the cold and in the storm. For the onboard power supply, two Efoy fuel cells (FNC Energy, Germany) were used which through the combustion of methanol guaranteed a total of 16 amps 24 hours a day. The Automobili Lamborghini Spa participated in the boat building offering its expertise in carbon fibre composite materials through the advanced research centre of the car company of Sant'Agata Bolognese (Italy). This research center has followed the design and construction of a new carbon fibre canard, a movable bow drift that improved the boat's hydrodynamics, fundamental in upwind sailing for keep the route and go up the wind avoiding the natural drift to which boats are subject. On Vento di Sardegna the engine was a Lombardini Marine 1404 S-Drive with 40 HP (Italy), which transmits to a titanium propeller with adjustable blades from the Ewol Company (Italy).

2.3 THE RACE

The OSTAR is a singlehanded Trans-Atlantic Race: the oldest a solo race in the world and it consists of 3,000 miles against prevailing winds and currents. Since the first edition in 1960, nearly 800 people have started this race, but almost a third failed to finish. It's the ultimate challenge for amateur sailors. The regatta traces the historical route of the Mayflower sailing ship with on board the first pilgrim fathers who, the September six of 1620, left Plymouth in England directed towards the new world, and they landed on the shores of the Rhode Island in the North America, eleven months ago. The OSTAR 2017 began the May 29 and participants were 21. Already on June 1, *Vento di Sardegna* was at the head of the race with a route oriented far north compared to other boats, reaching 55° of latitude, and June 3th touched the latitude peak of 58° north and then it starts the descent towards Newport. Around June 6th, *Vento di Sardegna* approached the line of the orthodromic route, but meantime began a strong storm. That was a perfect storm during which 6 boats had left the race. By utilizing a commercial application programming interface (API) for weather information (Weather API, Meteomatics GmbH, Switzerland) during the storm raging, we were able to know the following weather variables: relative humidity at 2 meters above the sea level, wave height, water temperature, wind speed, temperature of air at 2 meters above the sea level and atmospheric pressure.

Data were acquired from June 9th to June 15th with a cadence of 15÷30 minutes. When on June 13th the storm ceased *Vento di Sardegna* was still at the head of the race and had reached around 45 ° north latitude. Then it continued towards Newport where attacked to the pier the following 15th. Only other 5 boats finished the race with the sixth that arrived in Newport on July 3th while the second, compared to *Vento di Sardegna*, had a delay of about 4 days. So our participant concluded the OSTAR 2017 race in 17 days 4 hours 6 minutes and 19 seconds.

2.4 EXPERIMENTAL PROTOCOL

We tested the participant in the following three experimental conditions: (A) before the race beginning, in Italy, (B) during the race through the Atlantic Ocean, (C) at the race end, in USA. The specific procedures of each experimental condition are described below.

2.4.1 Experimental Condition A

Before race, the sailor reached the obesity centre of the medical faculty, at the University of Cagliari, Italy, where he was submitted to an accurate and polispecialistic medical and psychological examination. After this, he reached the laboratory of respiratory physiopathology, at the Cardiovascular Intensive Care Unit of the same University, where he performed an incremental, cardiopulmonary exercise at the cycle ergometer (CPX, 20 W min-1 of incremental ramp) up to exhaustion [9]. During the CPX the sailor was connected to a metabolic unit (Ergostik, Germany) by means of a face mask, thus several values of cardiopulmonary variables were assessed breath-by-breath and beat-by-beat. Incremental test ceased when the participant was no longer able to maintain the pedalling rhythm of 60 ÷ 70 revolutions per minute. In the participant the 12 led ECG was continuously monitored and the systolic and diastolic arterial blood pressures were also assessed at each step of load by means of a brachial sphygmo-manometer [10].

2.4.2 Experimental Condition B

During the ocean sailing the participant was equipped whit a metabolic sensor device, i.e. the “SWA” (Sense Wear Armband, Body Media Inc, Pittsburgh, USA). This is a wireless, non-invasive, multi-sensor activity monitor that was worn from the participant on the left triceps muscle.

The SWA integrates data from five sensors including a three axis accelerometer, an heat flux sensor, a galvanic skin response sensor, a skin temperature sensor, and a near-body ambient temperature sensor, with the aim of estimate energy expenditure under free-living conditions [11, 12]. The software created by the manufacturer calculates the energy expenditure using a patented algorithm [13] that combines acceleration, heat flow, and other parameters. The SWA had the advantage of being able to quantify the energy expenditure at rest [14, 15], for very low-intensity activities or during static exercises that do not require walking or running [16], as sometime was the case of our ocean sailor. Moreover, it has been found that this device also gives reliable values of energy expenditure up to ten METs intensity of physical activity [17]. Recently, Koehler and Drenowatz [18] had published a meta-analysis concerning the applications and limitations of the SWA. They concluded that this device consents to accurately estimate energy expenditure corresponding to the distance travelled while walking as well as at rest and, in general, during light to moderate physical activities, as resulted from the comparison of the SWA to both the methods of the indirect calorimetry [19] and the doubly labelled water [20]. In addition, the sailor had with him an automatic brachial sphygmomanometer (Omron M2, the Netherlands) for the self measurement of arterial blood pressures and heart rate. Moreover, by means of strips for urine analysis (Combi Screen, Analyticon Biotechnologies, Germany), semi-quantitative measurement of the urinary concentration of several variables were also carried out by the participant. Obviously, all these energy, blood and urine measurements have been made by the sailor when the navigation conditions allowed this. However, in order to acquire data as much as possible indicative of any stable functional adaptations resulting from the sailing activities related to the race performance, we asked our participant to wear as much as possible the SWA device.

2.4.2 Experimental Condition C

On the fourth day after his arrival in USA, after having recovered in the meantime his proprioceptive sensitivity to walking on the mainland, the participant travelled by taxi to the Rhode Island Hospital in Providence (about 34 miles from Newport), and at the heart station of the hospital he performed a second CPX by a cycle-ergometer which applied the same ergometric protocol as in the previous condition A, and in which were assessed the same cardiometabolic variables by a respiratory gas exchange device (Medgraphics, Breeze VO2000, USA).

2.5 DATA ANALYSIS

From each of the two CPX performed by the participant in the A and C experimental conditions, it has been taken into consideration the following variables respectively assessed at the rest before the test, at the workload corresponding to the anaerobic threshold (AT) [21] and at the maximum work rate considered:

- workload (W) in watt;
- oxygen consumption per minute (VO_2) as referred to the whole body mass: in l min^{-1}, and to body mass unit: in ml kg^{-1} min^{-1};
- carbon dioxide production per minute (VCO_2) in l min^{-1};
- respiratory exchange ratio (RER) as the VCO_2/ VO_2 ratio;
- expiratory pulmonary ventilation (V_E) in l min^{-1};
- respiratory tidal volume (V_T) in l;
- respiratory rate per minute (RR) in breaths min^{-1};
- heart rate per minute (HR) in beats min^{-1};
- oxygen pulse (OP) as the VO_2/HR ratio in ml $beats^{-1}$;

Moreover, to better understand the systemic integrative responses to the long lasting ocean sailing, were calculated also the following other variables:

- excess of carbon dioxide production (VCO_{2Exc}) as [VCO_2 - (RER_{Rest} x VO_2)] in l min^{-1} [22], which, stoichio-metrically, correlates with the blood lactate concentration at the W_{180}, thus indicating the maximum level of engagement of the anaerobic lactacid mechanisms for the muscle fuel [23].
- rapid shallow breathing index (RSBI) as the RR/V_T ratio measured as breaths $min^{-1}l^{-1}$ [24], which indicates the relative contribution to the respiratory impedance due to the air flow rate (the viscous component) and to the pulmonary stiffness (the elastic component);
- aerobic efficiency index (E_{Oxy}) as the ratio between the energy output at the cycle-ergometer (in kcal) and the corresponding aerobic energy expenditure, obtained by multiplying VO_2 by the equivalent caloric value which was considered as 5 kcal per each litre of oxygen consumption [25].

In the experimental condition B, where the participant was engaged in the race through the Atlantic Ocean, among the variables provided by the SWA tool were chosen those following:

- daily time of wearing the SWA (W_{SWA}) in hours (h);
- daily time of physical activity inside the boat (PA) in hours (h);
- daily time of sleeping (Sleep) in hours (h);
- daily distance travelled by the sailor body centre of mass (BCoM) inside the boat (TD) in meters (m);
- daily energy spent to transport the BCoM inside the boat environment during the PA (EE_{PA}) in kcalories.

Even in this experimental condition, some other critical variables were extrapolated from those released by the SWA, which are shown as follows:

- daily mean metabolic power output per kg of body mass (W_{Met} = W kg^{-1}), which was calculated by dividing EE_{PA} by body mass (kcal kg^{-1}) and multiplying it for the joules equivalent per each kcal (4.18 KJ), therefore, this value of metabolic energy was divided for the PA expressed in seconds [26];
- daily mean velocity of transport of the BCoM in the environment inside boat (V_{Tran} = ms^{-1}), obtained by dividing TD by PA: V_{Tran} = TD/PA.
- daily mean metabolic cost of transport of the BCoM in the environment inside boat (C_{Tran} = J $kg^{-1}m^{-1}$), defined as the ratio between the metabolic power and the corresponding motion velocity of BCoM of sailor inside the boat environment, i.e. $C_{Tran} = W_{Met} / V_{Tran}$ [27, 28].

Where it was appropriate, regression equations were calculated, and graphically represented, among data from CPX made by the participant before and after the ocean race [29]. Assessed data during the ocean sailing have been graphically represented as box and whiskers plots [30, 31]. In this latter case to compare differences among data groups was chosen the Mann-Whitney non parametric unpaired test and a $P < 0.05$ was considered as statistically significant.

3 RESULTS

Table I shows maximum and minimum values of the chosen weather variables acquired during the OSTAR race, along the route travelled by *Vento di Sardegna*. It can easily be observed that the weather conditions that our participant's boat encountered during the regatta were particularly arduous, and he said that he had been strenuously engaged in ruling sails in such a way of keeping the right route as well as in avoiding the risk of the body hypothermia.

Table I - Minimum and maximum values of the assessed weather variables from June 9th to June 15th, 2017 along the route travelled by *Vento DI Sardegna*.

Weather Variables	Values
relative humidity at 2 meters above sea level	60÷80%
wave height	2÷6 meters
water temperature	+1° C÷-1.5° C
wind speed at 10 meters above sea level	18÷63 km/h
air temperature at 2 meters above the sea level	0° C÷-10° C
atmospheric pressure	98.4÷100.4 kPa

When the sailor reached the heart station at the Providence hospital, in USA, to perform the second CPX, his body mass was of 63.5 kg or about 9% lower than before the race beginning. In the experimental condition A the time up to CPX exhaustion of the participant was 10 minutes, corresponding to 10 incremental ramps of 20 W increase in workload, while in C the test lasted of only 8 minutes and corresponded to 8 incremental ramps. Regarding this latter test, it should be considered that the test was interrupted by the physicians of the Providence Hospital just before the athlete’s exhaustion, due to the occurrence of dyspnoea and cough as well as by an elevated blood pressure (the systolic arterial pressure reached 220 mmHg and the diastolic one reached 104 mmHg).

However, as early as the fifth minute of recovery from the CPX, arterial pressures returned to normal values (122/70) and also the breathing returned as a normal. Due to this, in C the W-max reached at the end of the CPX was lower (187 watt) than in A (205 watt).

Table II - Values of functional variables assessed at Rest, at anaerobic threshold (AT) and at the 180 watt of exercise workload (Ex_{180}) from the CPX performed during each of the experimental condition A and C, are represented.

Variables	Condition A			Condition C		
	Rest	AT	Ex_{180}	Rest	AT	Ex_{180}
VO_2(ml kg^{-1}min^{-1})	4.1	21.4	31.2	4.1	27.8	33.1
VO_2(l min^{-1})	0.29	1.50	2.14	0.26	1.77	2.10
VCO_2(l min^{-1})	0.24	1.49	2.52	0.21	1.92	2.43
CO_{2Exc}(l min^{-1})			0.79			0.75
RER	0.80	1.01	1.18	0.80	1.09	1.16
V_E(l min^{-1})	11	40	77	8	53	72
V_T(l)	0.69	2.11	3.35	0.80	2.42	2.55
RR(breaths min^{-1})	16	19	23	10	22	28
RSBI(br. min^{-1} l^{-1})	23.0	9.0	6.9	12.5	9.0	11.0
HR(beats min^{-1})	86	128	155	79	139	142
PO_2(ml beats^{-1})	3.4	11.7	13.8	3.3	12.7	14.8
E_{Oxy}			0.218			0.233

To uniform data comparison among the two CPX, relative peak values were considered as reached when W reached 180 Watt (W_{180}) in both incremental tests. Table II shows that, with respect of the condition A, which was considered as the pre-race reference one, in condition C the VO_2 at W_{180} was of about 2 ml kg^{-1}min^{-1} higher. Interestingly, the anaerobic threshold was reached at 73% and 84% of the W_{180}, respectively in the A and C experimental conditions.

The following equation concerns to the linear regression which has been calculated among copies of data concerning the VO_2 per body mass unit assessed during each workload step in both A and C cycle ergometer incremental test:

$$VO_2(C) = 1.7955 + 1.0023\, VO_2(A) \tag{1}$$

The regression equation (1) is highly significant ($P < 0.0001$), and the corresponding straight line with the spread of points is shown in the Figure 1. In this figure is clearly shown that the regression line is parallel to the equity line, which latter, however, falls inside the lower limit of the prediction interval of the regression. In addition to this, the almost total identity among VO_2 values assessed during the CPX of C whit the ones of A is also reinforced by the value of the angular coefficient in the equation (1) which is practically unitary. Table II also shows that, in comparison with the condition A, in condition C the maximum values of VCO_2 and of CO_{2Exc} were a little lower, and in the same way behaved V_E. Nevertheless, the breathing patter observed at the W_{180} in C was noticeably different than in A. In fact, with respect to the CPX made before race, the CPX made after race showed a wide fall of V_T (- 0.8 l), which was quasi compensated by the increase of 5 breaths min^{-1} in RR when the W_{180} was reached. Because of this, in C the value reached by the RSBI, at the W_{180}, was very high (+ 4.1 breaths min^{-1}l^{-1}) than in A.

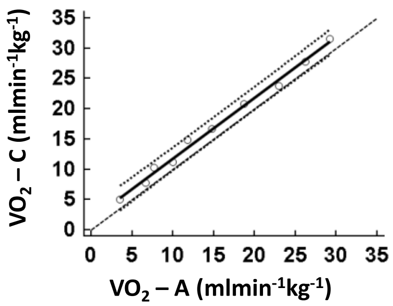

Figure 1. Relationship among the oxygen consumption per body mass unit (VO_2) assessed during the CPX of experimental condition C versus the experimental condition A, is represented as a the linear regression (continuous line). Dotted lines delimit the 95% of prediction interval while the dashed line is the equity line for x = y. Empty circles represent couples of considered A and C values.

Regarding variables that referred about the cardio-pulmonary linkage, Table II shows that, at W_{180}, the HR of C was 13 beats min^{-1} lower than in A and, on the contrary, the capacity of oxygen transport from the chest towards the peripheral organs, i.e. the OP, had a little gain. The E_{Oxy}, or the oxidative efficiency index, showed in the condition C a value that was only 7% lower than 0.25 (this latter is the theoretic maximum value of the E_{Oxy} in the muscle machinery [32]). In A this index was 15% lower than the theoretical value. Table III shows the daily behaviour of the chosen variables among those released from the SWA during the experimental condition B. Collected data were subdivided in the following three groups: group I concerning the three days just after the start of the OSTAR; group II concerning the last three days when a storm, that began June 6th and finished the 13th, was still raging; group III concerning the three days just prior to arrival at Newport and, meantime, the storm had ceased.

This table shows that, during the race, the participant wore the SWA for nine days (corresponding to about 50% of the total days of race), and in six of these days practically he wore the device for 24 h.

However, it can be seen that only in Group II, while the storm raged, the sailor spent most of daily time for the physical activity inside the boat (up to 18 hours in the June 10th). In any case the sailor slept very few in the 9 days monitored, i.e. a maximum of 5 hours the June 15th but practically he did not sleep the May 30th and June 13th.

Figure 2 shows daily changes occurred in W_{Met} in each of the three groups of days monitored. Not significant difference was found among days of groups I and II since both the medians in the respective box and whiskers plots reached 3.9 W kg^{-1} as well as among group I and group III (median = 3.4 W kg^{-1}). On the contrary, the group III showed W_{Met} values that were significantly lower than those of group II.

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Table III - Data assessed daily from the SWA device worn by the participant while he sailed and concerning: time of wear of the SWA (W_{SWA}), time of physical activity (PA), inter-night time of sleep (Sleep), distance travelled inside the boat (TD), energy expenditure for physical activity inside boat (EE_{PA}). In the left column are indicated the days in which the registrations were made. Group I concerns the first 3 days just at beginning of race, Group II concerns the 3 days in which the boat had been fully engaged in the storm, Group III concerns the 3 days just before arrival.

Days	W_{SWA} (h)	PA (h)	Sleep (h)	TD (m)	EE_{PA} (kcal)
Group I					
May 30	24:00	12:37	00:10	10200	2355
June 01	14:50	07:21	00:38	9500	1768
June 04	24:00	09:01	01:07	6400	2111
Group II					
June 10	24:00	17:51	01:22	6700	3786
June 11	24:00	12:55	06:06	5000	2782
June 12	23:09	15:53	03:49	9400	3486
Group III					
June 13	11:48	10:58	00:00	7100	2042
June 14	24:00	14:35	02:00	10300	2999
June 15	13:45	04:21	05:07	2800	792

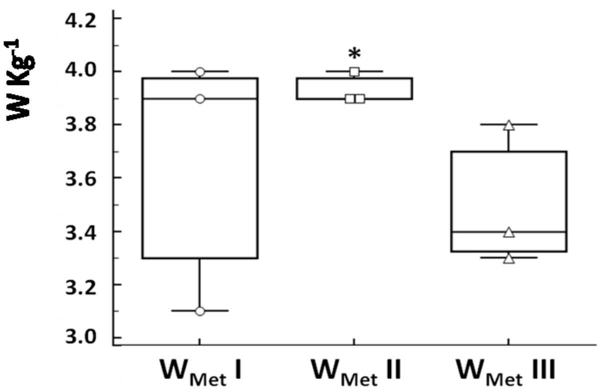

Figure 2. Box and whiskers plots with the points spread concern mean metabolic power spent in each of the first 3 days of race (W_{Met} I), in the 3 days while storm raged (W_{Met} II) and in the last 3 days of race (W_{Met} III). Straight line within each box represents the statistical median above which the first quartile is positioned while below it is placed the third quartile concerning the distribution of the points represented. Vertical lines external to the interquartiles box are the whiskers which reach the upper and down extreme values and represent the fourth quartile.
(*) $P < 0.05$ with respect to W_{Met} III.

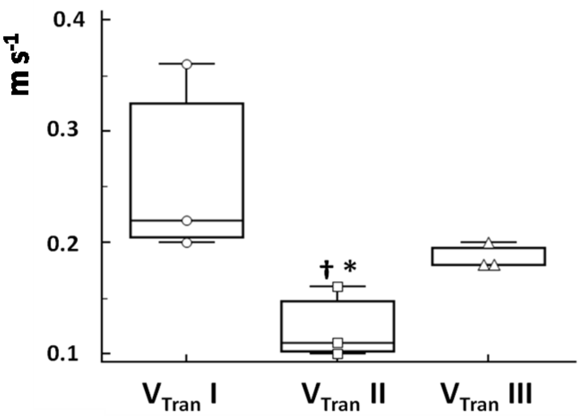

Figure 3. Box and whiskers plots with the points spread concern mean velocity of transport of the sailor body centre of mass into boat environment in each of the first 3 days of race (V_{Tran} I), in the 3 days while storm raged (V_{Tran} II) and in last 3 days of race (V_{Tran} III). Straight line within each box represents the statistical median above which the first quartile is positioned while below it is placed the third quartile concerning the distribution of the points represented. Vertical lines external to the interquartiles box are the whiskers which reach the upper and down extreme values and represent the fourth quartile.
(†) $P < 0.05$ with respect to V_{Tran} I; (*) $P < 0.05$ with respect to V_{Tran} III.

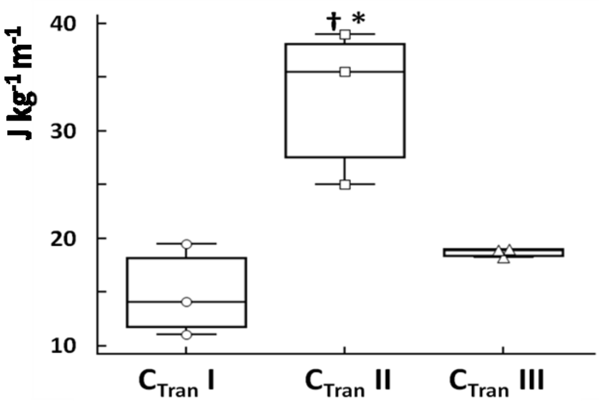

Figure 4. Box and whiskers plots with the points spread concern mean metabolic cost of transport of the sailor body centre of mass into boat environment in each of the first 3 days of race (C_{Tran} I), in the 3 days while storm raged (C_{Tran} II) and in last 3 days of race (C_{Tran} III). Straight line within each box represents the statistical median above which the first quartile is positioned while below it is placed the third quartile concerning the distribution of the points represented. Vertical lines external to the interquartiles box are the whiskers which reach the upper and down extreme values and represent the fourth quartile.
(†) $P < 0.05$ with respect to C_{Tran} I; (*) $P < 0.05$ with respect to C_{Tran} III.

Table IV - The values of the variables assessed from the urine analysis, by the participant while he sail, are represented together with values of systolic (SABP), diastolic (DABP), mean (MABP) arterial blood pressures and heart rate (HR).

Variables	May 30 (h19:22)	June 07 (h16:42	June 13 (h 11:22)
leukocites	neg.	25-75 μl^{-1}	neg.
specific gravity	1030	1030	1030
pH	5	5	5
nitrite	neg.	neg.	neg.
red blood cells	5-10	5-10	5-10
protein	100mg dl^{-1}	trace	neg.
glucose	norm.	norm.	norm.
ketones	neg.	neg.	neg.
urobilinogen	norm.	35µmol l^{-1}	norm.
bilirubin	neg.	neg.	neg.
SBAP(mmHg)	140	182	143
DBAP(mmHg)	93	160	78
MBAP(mmHg)	109	167	100
HR(beats min^{-1})	84	88	78

The daily changes occurred in V_{Tran} are shown in the box and whiskers of figure 3. The medinan of V_{Tran} in the box corresponding to group II, or in that days in which the participant was still fighting the storm, was halved (0.11 ms^{-1}) respect to the median concerning the days preceding the storm (group I, V_{Tran} = 0.22 ms^{-1}), and this reduction of speed was statistically significant.

In the days after the storm cessation (group III) the median of V_{Tran} rose anew until 0.18 ms^{-1}, a value that was not statistically different of that of group I, but it increased (about 1.5 times) with respect to that of in group III in a statistically significant manner. Respective changes of the C_{Tran}, occurred in each of the three groups of monitored days, are shown in the box and whiskers of figure 4. It can be seen that in the group II of days (median = 35.5 J $kg^{-1}m^{-1}$) the metabolic cost to transport the BCoM of the sailor inside boat increased significantly (about 2.5 times) with respect to the one of group I (median = 14.1 J $kg^{-1}m^{-1}$). It is of interest that while C_{Tran} of group III (median = 18.9 J $kg^{-1}m^{-1}$) resulted not different from the group I one, this variable was significantly lower (about a half) than that of group II. Table IV shows the reading of sticks for urine analysis. Data concerned measurements made at the OSTAR beginning (May 30th) and during the sailing race (June 07th and 13th). Leukocytes were present in the urine at the June 7th. It is well known that urinary leukocyte concentration higher than 20 μl^{-1} somewhat indicates bacteria infection somewhere in the urinary tract. Interestingly, in each tested day the urine specific gravity was positioned in the superior extreme limit of its specific scale, or borderline with a condition of dehydration. Urinary pH was maintained at the constant value of 5 or at the extreme inferior physiological limit for this variable.

It may be that in the race time span the sailor had a diet excessively rich in proteins and low in carbohydrates. Proteins were almost always present in the urine of the sailor, even if they had reached values up to 100 mg dl^{-1} only at the race beginning. All these increased urinary values could indicate one or several of the following possible causes: dehydration, emotional stress, exposure to extreme cold, strenuous exercise. In fact, several of these facts had been happen to our sailor while he raced in the OSTAR cup. Finally, both urinary increases of blood red cells and urobilinogen shown the June 7th could be related with an excessive physical exertion since in that day the sailor was engaged against the storm (see also the blood arterial pressures detected on that day which were very high), and for this reason haemolysis could be happen. Other variables assessed from the urine sticks did not show any significant changes in those days chosen by the sailor for measurement.

4 DISCUSSION

To our knowledge, this is the first time that such a quantity of cardio-respiratory and metabolic measurements are carried out for prolonged times in a sailor engaged long lasting in a solo ocean race. In this study were also assessed several variables concerning the functionality of these organs while the participant performed two CPX: the former before and the second after the race. The availability of these information consented us of weigh up the magnitude of the metabolic and biomechanical variables detected during different phases of sailing through their comparison with what resulted from the two CPX. In fact, data from the two CPX indicate that during the ocean sailing the participant did not suffer for a race-induced aerobic deconditioning, i.e. a condition that could happen due to the reduced possibility of motion inside the boat because of the restricted environment [33].

4.1 METABOLIC POWER FOR OCEAN SAILING

Box and whiskers representations in fig. 3 show that medians concerning daily W_{Met}, showed from the participant while he was engaged in the OSTAR, ranged from 3.4 to 3.9 W kg^{-1}. This latter value of W_{Met} was almost double than 2.1 W kg^{-1}, a value previously observed [34] as a mean obtained from VO_2 gross values in six subjects walking on a level treadmill at a constant speed of 0.2 ms^{-1} (a speed into the range of those of this study). Moreover, in both groups of 12 subjects aged 20.8 years and of other 12 aged 77.4 years, respectively, which walked on a level treadmill, the respective W_{Met} were of about 4.2 W kg^{-1} and 4.5 W kg^{-1} [35]. The latter mean values of metabolic power approached the medians of those assessed in our participant, but the walking speed (0.98 ms^{-1}) was from 5 to 10 times higher than in the actual experiment. On the other hand, when a group of runners [36] walked 5 min on a 30° inclined treadmill at a constant velocity of about 0.2 ms^{-1}, or a speed near those actually scheduled, their gross value of W_{Met} was about 6.5 W kg^{-1} or quasi two times higher than the metabolic power medians of the sailor. Interestingly, Osniach and Di Prampero [37] found that in elite soccer athletes the average of overall energy expenditure during a match which last 90 min corresponds to an O_2 consumption of about 25.2 ml kg^{-1} min^{-1}. In considering that 1 ml O_2 has an energy equivalent of about 21 J, therefore their averaged net metabolic power about is 8.8 W kg^{-1}. Soccer can be considered as a situational sport in which the outcome of the action does not depend exclusively on the technical gesture and physical performance, but on the ability to find the right responses to adapt to different stimuli. In the same way it can be considered also an oceanic sailing race. In that case it is reasonable to assume that, in our participant, the average metabolic power output during the Atlantic race, net of the value of the base power that about could be 0.9 W kg^{-1} [38], was quasi one third of the average metabolic power supplied by elite soccer players during a game. From the above considerations, it can be reasonably concluded that, in our participant, the metabolic power of 3.9 W kg^{-1} could be evaluated as the maximum expression of the metabolic energy contribution to hard sailing engagement.

It is quite interesting to consider that even at the beginning of the race (group I of days) was required to our sailor the maximum contribution of aerobic energy. In fact, also in the latter condition the W_{Met} was 3.9 W kg^{-1} and this most likely for the reason that the race beginning had required the maximum effort to our participant in such a way of gaining the head position. It is Also notable the fact that in the days of group III, when the sailing returned to be less harsh, the W_{Met} was significantly reduced with respect to the days in the group II, and this is a confirmation of a linkage between metabolic power released and intensity of mechanical work output carried out.

4.2 METABOLIC COST OF OCEAN SAILIN

Despite the W_{Met} was the same in both groups I and II of sailing days, data from the actual study shows that the V_{Tran} of group II was reduced to a half of group I. This was because in the days in which the storm raged the C_{Tran} had rose more than two times of that of the previous days of group I. In other words, the storm required a lot of metabolic power to be spent for overcoming several body activities that did not contribute to the transport of the BCoM in the environment inside of the boat and, since W_{Met} could not be further increased, on the basis of the following equation that links together these three biomechanical variables [39]:

$$W_{Met} = V_{Tran} \times C_{Tran} \tag{2}$$

The increase in the energy cost was mandatory at the expense of speed. Concerning the human locomotion, Cavagna & Franzetti [40] stated that in a linked, multi-segmental system, i.e. the human body, the internal work is done by the movements of single segments with respect to the BCoM. In this light, in subjects that walked on a treadmill at the ground level, it has been found that the internal work about oscillated from 0.2 J kg^{-1} m^{-1} [41, 42] to 0.4 J kg^{-1} m^{-1} [43].

Indeed, the physical activity for ruling the sails is characterized by movements of the various body segments with respect to the BCoM, which are more complex than those related to walking along a straight line at the ground level. In fact, in volleyball players engaged in a field game, i.e. these latter are situational athletes which are comparable to oceanic sailors, Laconi et al. [25] utilized a rotational mechanical model, based on photogrammetric surveys, to evaluate also the rotational mechanical work of the bust. They found that this movement could reach about 10% of the total mechanical work spent in a game action in which the athlete jumps, rotates bust and hits the ball with his hand as hard as possible. In this latter experiment was evaluated that during a volleyball action lasting 90 s the average O_2 consumption was of about 21 ml kg^{-1} min^{-1} which corresponded to a gross metabolic power of 7.3 W kg^{-1}, hence the internal work spent in rotating the upper body was of about 0.7 W kg^{-1}. Summarizing all the above experimental evidences, and admitting that the latter ones can be extrapolated into the internal work of a sailor, it is clear that these cover only a minor part the energy cost of our participant engaged into the storm. As the participant told us, during the storm there were continuous postural threats, which response to reduce the risk of falling required an additional muscle effort and thus carried an additional metabolic load respect that concerning only the transport of the BCoM inside boat. In healthy subjects walking on a ground level treadmill, IJmker and colleagues [44] applied to the pelvis unexpected sideward pull and projected on the belt of treadmill sudden images of restrictions of the path width along which the subjects were invited to pass. These postural treats produced up to 13.6% increase in the energy cost of walking due to increased activity of several postural muscles. It must also be considered that when postural perturbations do occurs then the joints stability is guaranteed by the co-activation of antagonistic muscles while the agonistic ones are in activity on such joints, i.e. the so called muscle co-activation [45].

Obviously, the additional contraction of antagonistic muscles to ensure postural stability of an articulation, could add in our participant a supplement of metabolic power dissipation. This had been confirmed in the experiment from IJmker and co-workers [44] since they observed an increase in the co-contraction indices of the antagonistic couples of muscles composed of the gastrocnemius medialis with tibialis anterior (+11.7%) and rectus femoralis with biceps femoralis (+6.9%). All these increases in postural muscle activity certainly played a not negligible role in increasing the energy cost of our sailor engaged in the Atlantic storm.

However, the participant reported that, especially in the days in which storm raged, he was continuously and intensely engaged in the sailing maneuvers like as side hiking or fast sequences of tacking and gybing, by grinding on a winch, to set the sails. All these maneuvers could spent a lot of energy but they do not contribute to transporting the BCoM inside the boat.

In fact, Bernardi et al. [46] found that during a tacking manoeuvre performed by a group of 6 elite grinders inside a sailing boat, the grinding effort required an oxygen expenditure peak which corresponded to about 1 kJ per kg of body mass. Since each grinding effort lasted about 60 s, then the metabolic power engaged was of about 17 W kg^{-1}. Furthermore, Bourgois et al. [47] had tested 10 elite sailors on a sailing ergometer while they emulated upwind sailing exercise in > 15 knots. The test consisted of 18 hiking bout each lasting 90 s, interspersed with 10 s of rest, to change position on the boat simulator, for resemble tacking. Authors found that, in the latter simulation, the aerobic mean expenditure of energy was of about half a kJ, hence the corresponding mean metabolic power ought reach about 6 W kg^{-1}. Resuming what above reported, it may be concluded that several kinds of mechanical work made by the participant, and that did not contribute to the transport of the BCoM while he sailed in the storm, could concur together in increasing the metabolic cost of sailing observed in the group II of days, so resulting in a reduction of the velocity in travelling the BCoM into the boat environment. Ortiz et al. [36], in their experiments concerning the metabolic cost in subjects walking on a up 30-degree inclined treadmill, at a speed of 0.3 $ms^{-1,}$ found a C_{Tran} of about 29 J kg^{-1} m^{-1}. This latter result could consent us to assume that the C_{Tran} due to the hard sailing into an ocean storm is comparable to that of people engaged in the so called vertical kilometre performance that is a foot race in which runners reach 1000 m of elevation over a course length of less than 5000 m [48]. Interestingly, in the three days of group III, just before race stopped and during which the storm had been over, C_{Tran} was decreased up to reach values not significantly different than in the days of group I or before storm took place. In the same time the V_{Tran} had been increased. This event highlighted a close and quantifiable relationship between the worsening of the ocean's atmospheric conditions and the increase in the energy cost of the sailing and vice versa.

4.3 CARDIOPULMONARY TESTING

As revealed the comparison between data from the CPX performed by the concurrent just after he won the OSTAR race versus data from the CPX performed before the race, several factors concerning specific adaptations of cardio-respiratory and metabolic systems, played such a role in inducing like a sailing race-dependent aerobic training. and the main changes are discussed in depth as follows:

A) Few days after the race finished the CPX carried out by the participant at the hospital heart station in USA showed that the sailing race had not induced in the participant a reduction in the oxidative contribution for power supply to muscle activities. This implies that the participant had maintained a good endurance capacity;

B) With respect to the condition A, in the C one at W_{180} the CO_2 did not rise as well as the $CO_{2Excess}$. This confirmed a maintained capacity of use aerobic energy sources when the sailor finished the ocean race. This metabolic adaptation was also clearly highlighted by the observed high value reached by the workload at which occurred the AT in the C test and, in turn, it avoided to increase the recruitment of the anaerobic sources of energy to supply the exercising muscle. This could result in a muscle glycogen savings by exchanging the energetic support from glucidic substrate to lipidic one, that is, turning away the onset of muscular fatigue;

C) In experimental condition C the breathing pattern was favourably adapted since at W_{180} there was a dramatic fall of -24% in V_T, even if compensated by + 22% in increase of RR. This shift from an inotropic to a chronotropic modality in the breathing pattern, strongly pointed out by the 59% increase in the RSBI with respect to the condition A, could reflect a training induced adaption of the brain stem centre for breathing control [49]. In fact, it has been suggested that relative hypocapnia (note that the CO_{2Exc} was lowered in C with respect to A) as happens when workload progressively increases overcoming the AT, and a respiratory super-compensation takes place with the purpose of avoiding a fall of the blood pH [50], could induce an enhancement of the excitability of pulmonary stretch receptors [51]. For this, the effect of the nervous reflex that enhanced the sensitivity in these receptors is that of cutting short the inspiration [52], thus producing a reduction in both inspiratory volume and duration of breaths which may be reflected in a reduction of V_T and an increase in RR, respectively [53]. This possible respiratory adaption, observed in the participant after a long lasting sailing period, could have the purpose of reduce the stretch of the inspiratory muscles, with a lesser mechanical work to be made from these muscles, i.e. a not negligible aerobic energy saving;

D) In C, the capacity of oxygen transport from the chest towards the peripheral organs, i.e. the OP, at W_{180} was practically maintained when compared to the OP value of the condition A.

In considering the following equation of the Fick principle:

$$VO_2 = SV \times HR \times \Delta O_{2a-v} \tag{3}$$

where SV is the left ventricle stroke volume and $\Delta O_{2a\text{-}v}$ is the artero-venous difference in oxygen concentration, one can write:

$$VO_2 / HR = SV \times \Delta O_{2a-v} \tag{4}$$

or

$$OP = SV \times \Delta O_{2a-v} \tag{5}$$

Since it has been reported that, during an incremental test in healthy and moderately trained subject the SV increase is very low [54, 55], therefore OP can be considered as an index of the $\Delta O_{2a\text{-}v}$ [56]. Hence, we could reasonably assume that, in our participant, notwithstanding the adverse sailing condition, an important mechanism which is the one related to the arterio-venous oxygen concentration difference, was maintained at a constant value. Thus the ocean race had preserved in the participant a good oxygen flow from capillaries to muscle cells, or a good cellular delivery of O_2.

E) In C the E_{Oxy} at W_{180} assumed a value that was 7% higher than in A, and approached (- 7%) the value of 0.25 that, as the Nobel Prize Archibald Vivian Hill already had reported in his paper of 1964, is the theoretic E_{Oxy} maximum value in the muscle machinery [32]. It may be that this increase in oxidative efficiency, occurred just after the race, reflected a training enhanced mitochondrial respiratory capacities of muscle. This possibility has been confirmed in a very recent study of Konopka et al. [57] about an athlete engaged in the 5 days cycling at the 2016 Colorado Trail Race (up to 24 h/day between altitudes of 1,675 and 4,025 m to complete 800 km and 21,000 m of elevation gain). In his vastus-lateralis muscle this athlete achieved mitochondrial respiratory capacities among the highest published for humans, due to greater mitochondrial protein synthesis which may contribute to the improved mitochondrial respiration and serve as a mechanism to resist cellular energetic stress.

5 CONCLUSIONS

The main conclusion arising from this case study was that in a healthy and moderately trained sailor, but very skilled in sailing techniques, several days of very hard physical work, as was the 2017 edition of the Atlantic OSTAR competition, can induce specific adaptations in both systems cardio-respiratory and metabolic in such a way of maintain his aerobic capacity, thus generating a physical conditioning aimed at sustaining the metabolic power demand from the muscle efforts that are specific to this extreme sport. Another critical help that comes from this study concerns the type of experimental protocol used. In fact, it is evident that a strict time linkage among data assessed during laboratory incremental tests and data assessed by the devices worn from the athlete while he sails, could result strategic to optimize his training protocol in the light of a best ocean sailing race performance, and reducing life threatening risks. However, pitfalls can be lurking due to conditions of immune-suppression/inflammation [8] as well as malnutrition [58], dehydration [2] and reduced sleep [3], which can be linked to the long permanence at sea while atmospheric conditions may give rise to prohibitive situations for sailing, with a very high metabolic cost and risk of dramatic reduction in the availability of metabolic power for surmounting these critical issues. The fact that our sailor did not complete CPX after his arrival to Newport because of the occurrence of dyspnoea, cough and high blood pressure, can be considered as an alarm signal that during the ocean sailing he was overreaching his capacity of adjust physiological responses to avoid homeostatic failures. The 9% reduction of the participant body mass at the race end together with the borderline condition of dehydration as well as the relative proteinuria and the not negligible presence of urinary leukocytes, blood red cells and urobilinogen, assessed by the participant during the ocean race, could confirm the possibility of the establishment of a hypothalamic-pituitary-adrenocortical (HPA) hypertonum. This latter suggestion has been supported by previous findings concerning board sailors which carried out a 30 min exercise of hard sailing at a wind surfing simulator [59]. At the end of the test these athletes showed a blood concentration of cortisol that was more than doubled with respect to the pre test value [60]. A similar eventuality could have taken place in our sailor from which could result a state of subclinical immune-depression with an increased risk of infections in the upper respiratory tract and in the urinary tract. The adaptive response to a stressor, that involved the HPA axis, recently termed as reactive homeostasis [61], leads to increase changes for survival [62]. A longer extension of magnitude in stressor's events inversely leads to homeostatic overload [61] with detrimental effects on fitness [63]. Sleep deprivation [64] and cold exposure [65] that shaped that oceanic performance, could sustain the dysregulation of HPA axis.

Interestingly, it has been found that when the AT was overcame during a cycle-ergometer incremental test, studied subjects showed a dramatic reduction in the rate of increase of blood concentration of natural killer (NK) cells that inversely correlated with the CO_{2Exc} [10]. This “open window” to pathogens entering in the elite athletes upper airways lasts about 70 h. This phenomenon has been interpreted as a cortisol-dependent shift towards an anti-inflammatory/performance-preserving condition. In our participant, this occurrence by the one hand could consent to maintain the shown high values of W_{Met} to sustain strong values of C_{Tran} but, by the other hand, it could expose the sailor to serious risk of contracting pathogens. Moreower, the lack of sleep and high levels of anxiety could reduce the efficiency of his cognitive function, decision making, vigilance and executive functions [66] with suffering of the microarchitecture of the white matter [67]. So, it may be concluded that long lasting oceanic sailors must be accurately monitored, especially concerning the metabolic power demand and the energy cost of mechanical work during the shipping. However, also the indicators of possible cortisol induced immune-suppression must be monitored, in such a way of preventing serious risk to run into situations that may endanger the life of the sailor.

6 STUDY LIMITATIONS

The most important limitation of this case study was the impossibility, from the sailor, of assess the measurements with the SWA during the entire period of sailing. Obviously, this lack of information partly reduces the possibility of an exhaustive evaluation of the adaptive effects played, on the participant, from the long staying at sea. However, what has been possible to detect in this study represents a reasonable basis of information to hazard a hypothesis of some quantitative relationship between the psychophysical stress due to the sailing competition and the functional adjustments implemented by the sailor in order to respond effectively to the increase of the demand of muscular power.

Another not negligible limitation of this study arises from the fact that the SWA device does not allow to distinguish between the energy spent to produce internal work, which is the work done to accelerate the body segments related to the centre of mass, and that outlay for the external work of the body moving in space. This impeded to evaluate the mechanical efficiency of our participant while he sailed. Unfortunately, there are still no technologies suitable for differentiating these two forms of mechanical energy in a moving athlete in free but very restricted spaces. Last but not least, some uncertainties in the measurement of cardiometabolic parameters during CPX performed by the participant could not be underestimated. In fact, some inaccuracies in the differences between the same variables assessed during the two incremental tests could be occurred due to the fact that the two gas analyzer devices used were built by different companies, as well as the two cycle ergometers. Besides, there was not any dietary control in the energy intake by the participant during the race, and this could have influenced the differences in RER and $CO_{2Excess}$. However, we can reasonably conclude that, thanks to the agreement in this sense among the large amount of data obtained, the aerobic capacity of our participant was not depressed as a consequence of his participation to the Atlantic regatta OSTAR.

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TEMPLATE FOR PREPARING PAPERS FOR PUBLISHING IN INTERNATIONAL JOURNAL OF MECHANICS AND CONTROL

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ABSTRACT

This is a brief guide to prepare papers in a better style for publishing in International Journal of Mechanics and Control (JoMaC). It gives details of the preferred style in a template format to ease paper presentation. The abstract must be able to indicate the principal authors' contribution to the argument containing the chosen method and the obtained results. (max 200 words)

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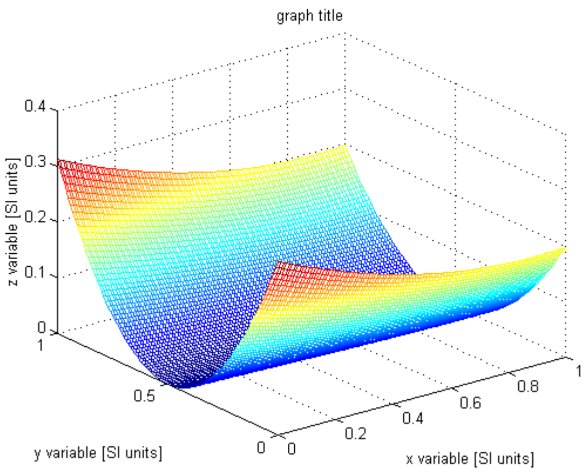

Figure 1 Simple chart.

Table VII - Experimental values

Robot Arm Velocity (rad/s)	Motor Torque (Nm)
0.123	10.123
1.456	20.234
2.789	30.345
3.012	40.456

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$$W(d) = G(A_0,\sigma,d) = \frac{1}{T}\int_0^{+\infty} A_0 \cdot e^{-\frac{d^2}{2\sigma^2}} dt \qquad (1)$$

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