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Aerobic Power and Peak Power of Elite America's Cup Sailors

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ABSTRACT

Big-boat yacht racing is one of the only able bodied sporting activities where standing arm-cranking ('grinding') is the primary physical activity. However, the physiological capabilities of elite sailors for standing arm-cranking have been largely unreported. The purpose of the study was to assess aerobic parameters, VO_{2peak} and lactate threshold (OBLA), and anaerobic performance, torque- and power-crank velocity relationships and therefore peak power (P_{max}) and optimum crank-velocity (ω_{opt}), of America's Cup sailors during standing arm-cranking. Thirty-three elite professional sailors performed a step test to exhaustion, and a subset of ten *grinders* performed maximal 7 s isokinetic sprints at different crank velocities, using a standing arm-crank ergometer. VO_{2peak} was 4.7(0.5) L/min (range: 3.6-5.5 L/min) at a power output of 332(44) W (range: 235-425 W). OBLA occurred at a power output of 202(31) W (61% of W_{max}) and VO_2 of 3.3(0.4) L/min (71% of VO_{2peak}). The torque-crank velocity relationship was linear for all participants (r=0.9(0.1)). P_{max} was 1420(37) W (range: 1192-1617 W), and ω_{opt} was 125(6) rpm. These data are among the highest upper-body anaerobic and aerobic power values reported. The unique nature of these athletes, with their high fat-free mass and specific selection and training for standing arm cranking, likely accounts for the high values. The influence of crank velocity on peak power implies that power production during on-board 'grinding' may be optimised through the use of appropriate gear-ratios and the development of efficient gear change mechanisms.

Keywords: VO_2max; Oxygen uptake; Sailing; Grinding; Arm cranking; Hand cycling; Force-velocity; Power-velocity

INTRODUCTION

Standing arm cranking ('grinding') is the main physical activity performed during professional big-boat yacht racing, including the America's Cup. During America's Cup yacht racing, all manoeuvres are powered manually without the assistance of stored energy (Neville et al. 2006). There are four grinding pedestals on International America's Cup Class version 5 yachts, each manned by two athletes. The grinding cranks are manually driven by a cyclic upper body action whilst standing. This provides the mechanical power to turn the winches which in turn controls the sails and mast, and hence the manoeuvres of the boat (Whiting 2007). There are typically five or six designated *grinders* in the crew of 17, however, all athletes assist with grinding, with the exception of the *helmsman*. It has been suggested that America's Cup grinding utilises both anaerobic and aerobic energy systems, depending on the intensity of racing (Bernardi et al. 2007), but the physiological characteristics of America's Cup sailors are poorly understood and very little research has been published on standing arm cranking.

Arm cranking has received some scientific attention, due to its role in cardiovascular and injury rehabilitation (Carson 1989; Westhoff et al. 2008), as well as being an appropriate mode for assessing upper body athletes (Tesch 1983; Driss et al. 1998; Hubner-Wozniak et al. 2004; Pearson et al. 2007; Zagatto et al. 2008) and individuals with spinal cord injury or lower limb disability (Hicks et al. 2003; Goosey-Tolfrey et al. 2006; Valent et al. 2008). During upper body exercise, athletes trained for this type of work appear to be able to achieve a high proportion of their lower body VO_{2peak}, with seated arm cranking values of ~4.1 $L \cdot min^{-}$

^{1} being reported for elite upper body trained athletes such as wrestlers, kayakers, rowers and swimmers (Secher et al. 1974; Tesch 1983; Horswill et al. 1992). To date the majority of arm cranking research has been performed seated, with restricted lower limb involvement. The physiological responses to standing arm cranking have not been widely documented, with only a few reports on aerobic power (Vokac et al. 1975; Bernardi et al. 2007) and peak power (Vandewalle et al. 1989; Hubner-Wozniak et al. 2004; Bouhlel et al. 2007; Pearson et al. 2007) present in the literature. Standing arm cranking appears to elicit a similar cardiorespiratory response to seated arm cranking, but with a higher peak work load evident (13%)(Vokac et al. 1975). This indicates that cranking is more efficient when standing than when sitting. A recent report of a relatively inexperienced America's Cup team found an average VO_{2peak} of 4.1 $L\cdot min^{-1}$ (47 $ml\cdot kg^{-1}\cdot min^{-1}$)(Bernardi et al. 2007).

The peak velocity of grinding during America's Cup racing has been reported to be between 120 and 150 revolutions per minute (Bernardi et al 2007), but the optimum velocity for power production and the nature of the torque-velocity and power-velocity relationships during standing arm cranking have not been determined. This may have an important bearing on the selection of gear ratios and the optimisation of power production during big-boat sailing. During elite sprint cycling a polynomial power-velocity relationship has been described (Martin et al. 1997; Dorel et al. 2005; Gardner et al. 2007), and contrary to the hyperbolic force-velocity relationship of isolated muscle (Wilkie 1949), the relationship between torque and velocity appears to be linear (Martin et al. 1997; Dorel et al. 2005; Gardner et al. 2007; Sprague et al. 2007). Similar results have been found during seated arm cranking (Vandewalle et al. 1989; Vanderthommen et al. 1997).

This study aimed to describe two important components of physical performance in elite America's Cup sailors during standing arm cranking ('grinding'). The first objective was to report key indices of aerobic endurance performance (aerobic power and lactate threshold) and to determine any differences between crew positions. The second was to document the torque-crank velocity and power-crank velocity relationships, and thus determine the peak power and optimum crank velocity, of America's Cup *grinders*.

METHODS

Participants

Thirty-three elite professional male America's Cup sailors participated in the study. Their physical characteristics are shown in Table 1. All athletes sailed for a team ranked in the top three during the 32nd Americas Cup. Their combined sailing experience included 8 Olympic medals and 98 America's Cup campaigns. Informed consent was obtained from all athletes, and the study was approved by the University's Ethical Advisory Committee.

Table 1. Anthropometric characteristics of America's Cup sailors [mean ± SD]

Position	N	Age [y]	Stature [m]	Body Mass [kg]	Σ 7 Skinfolds [mm]	Body Fat [%]	Fat Free Mass [kg]	Body Surface Area [m^2]
Grinders	10	36 ± 7	1.88 ± 0.05[a]	105 ± 6[b]	77 ± 15	13 ± 4	91 ± 5[e]	0.23 ± 0.01[f]
Utilities	6	34 ± 6	1.83 ± 0.06	94 ± 9[c]	99 ± 16	17 ± 3	77 ± 6	0.22 ± 0.01
Bowmen	6	35 ± 6	1.79 ± 0.02	84 ± 5	67 ± 19[d]	11 ± 4[d]	74 ± 4	0.20 ± 0.01
Trimmers	5	34 ± 6	1.80 ± 0.08	82 ± 5	68 ± 14	12 ± 3	72 ± 6	0.20 ± 0.01
Afterguard	6	40 ± 7	1.84 ± 0.04	88 ± 4	78 ± 10	14 ± 2	75 ± 4	0.21 ± 0.01
All	33	36 ± 6	1.84 ± 0.06	92 ± 11	78 ± 18	14 ± 4	79 ± 9	0.22 ± 0.02
Range		[25 to 47]	[1.66 to 1.95]	[74 to 117]	[48 to 126]	[7 to 22]	[63 to 96]	[0.18 to 0.25]

[a] Grinders taller than Bowmen (P=0.01) and Trimmers (P=0.04)
[b] Grinders heavier than all other positions (P<0.01)
[c] Utilities heavier than Trimmers (P=0.05)
[d] Bowmen less than Utilities (P<0.05)
[e] Grinders greater than all other positions (P<0.001)
[f] Grinders greater than all other positions (P<0.03)

Experimental design

All athletes visited the laboratory for an initial test where anthropometric measurements were taken prior to the athletes performing a step test to exhaustion to determine peak oxygen uptake (VO_{2peak}) and lactate threshold. A sub-group of ten athletes (*grinders*) then returned to the laboratory one month later to perform four maximal 7 s isokinetic sprints, at different velocities of arm cranking in a randomised order, for the measurement of peak torque and power at each crank velocity.

Anthropometry

All measurements were taken in accordance with the prescribed methods of the International Society for the Advancement of Kinanthropometry (Marfell-Jones et al. 2006). Nude body mass was measured with a digital scale to the nearest 0.1 kg (Tanita BWB-800, Tokyo, Japan) and height was measure with a stadiometer to the nearest 0.005 m. Skinfold thickness was measured in duplicate at seven sites (biceps, triceps, subscapular, supraspinale, abdomen, thigh, calf) using Harpenden skinfold calipers (Baty International, West Sussex, UK). Body fat % was calculated from the sum of seven skinfolds (Siri 1961; Jackson and Pollock 1978). Body surface area (BSA) was calculated using the Mosteller formula (Mosteller 1987):

$$BSA = \sqrt{((\text{height x body mass})/3600)}.$$

Equipment

All tests were performed on an adjustable SRM electronically-braked scientific ergometer (Schoberer Rad Meßtechnik Scientific, Jülich, Germany), which was specifically modified for standing arm cranking (Fig. 1). The centre of the ergometer handles were 0.44 m apart (medio-lateral displacement), and the crank arm length was kept constant at 0.25 m for all measurements. Torque was recorded continuously at 200 Hz (SRM torque software) and averaged over 360°. Crank velocity was measured every revolution. The SRM Powercrank was calibrated daily according to the manufacturer's guidelines. Pulmonary gas exchange was measured breath-by-breath, using an automated on-line gas analysis system (Oxycon Pro, Jaeger, Hoechberg, Germany). The athletes wore a nose clip and breathed through a sealed low-resistance mouthpiece and impeller turbine digital sensor (TripleV, Jaeger) that measured inspired and expired gas volumes, and was connected to the analysis system via a capillary line. The gas was analysed for O_2 and CO_2 concentrations using paramagnetic and infrared analysers, respectively. The analysers were calibrated automatically before each test with gases of known concentration and the volume sensor was calibrated using a 3-L syringe. The on-line values were calculated by the Jaeger computer software (IntelliSupport). Heart rate (HR) was monitored every 5 s with a telemetric HR monitor (Polar S720, Finland).

Fig. 1 Image of the modified SRM arm ergometer used for America's Cup grinding performance analysis. Crank length was 0.25 m and the distance between the handles was 0.44 m.

Aerobic Power

Each athlete was able to self select the height of the arm ergometer axis, which was typically ~50% of stature. A step protocol (Washburn and Seals 1983; Smith et al. 2004) was adopted with up to eight, 4 min stages each consisting of 3 min of constant work, followed by a 30 s rest interval and a 30 s ramp up to the next step. The initial power output was 75 W which was increased by 40, 45 or 50 W at each step, based on the athletes previous response to a laboratory aerobic power test, and with the aim of reaching exhaustion after 6 or 7 steps. The athletes were required to maintain a constant velocity of 80 rpm (Smith et al. 2001), and the test was terminated when the athlete was no longer able to maintain a velocity above 75 rpm despite verbal encouragement. Earlobe blood samples (~25 µL) were taken during each 30 s rest interval and immediately analysed for the lactate concentration using an automated blood lactate analyser, YSI 2300 Stat (Yellow Springs Instruments Inc., Ohio, USA). A further blood sample was analysed 3 min post exercise. The rating of perceived exertion (Borg scale) was also recorded at the end of each step. The cardiorespiratory variables were averaged over the final 30 s of each step, and the highest 30 s average oxygen uptake was taken to be the VO_{2peak}. An absolute blood lactate [BLa] concentration of 4.0 $mmol{\cdot}L^{-1}$, also referred to as the 'onset of blood lactate accumulation' (OBLA) (Sjodin and Jacobs 1981) was used to determine lactate threshold (Heck et al. 1985). Heart rate, VO_2 and work load at OBLA were calculated using linear interpolation between the relevant data points.

Peak Power

The height of the arm ergometer's central axis was set at 0.9 m from the ground. The ergometer's isokinetic mode (constant velocity) was adopted for the sprints. After an initial 5 min self paced warm-up, athletes performed four maximum effort isokinetic sprints at different crank velocities in a randomised order, from a range of six crank velocities: 80, 90, 100, 110, 120 and 140 rpm. Each sprint was 7 s in duration with a 10 min rest interval between trials. A 10 s countdown was given to the start of the sprint during which time a velocity of 50 rpm was maintained with no resistance. Verbal encouragement was given throughout the test. Torque and angular velocity were recorded throughout each sprint and analysed off-line. Once the prescribed velocity for each sprint was achieved, the highest torque and power values (over 360°) were calculated.

Power was determined as the product of torque (T) and crank velocity (ω) expressed in radians$\cdot$s^{-1}. Linear regression of the torque-crank velocity relationship was used to determine maximal torque (T_{max}) and maximal crank velocity (ω_{max}) by extrapolation to the respective intercepts. For each individual, maximal power (P_{max}) was determined as the apex of the power-crank velocity relationship, and optimal crank velocity (ω_{opt}), the crank rate at which P_{max} occurred.

Statistical analysis

Anthropometric, aerobic power and OBLA data for the different crew positions were compared with one-way ANOVA. When significant main effects were found, a Bonferroni post hoc test was used to determine differences between positions. Pearson product-moment correlation coefficients were calculated to assess bivariate relationships. Statistical analyses were performed with SPSS version 14.0 for Windows. Statistical significance was set at $P \leq 0.05$, and data are presented as mean ± SD.

RESULTS

The anthropometric characteristics of the sailors are shown in Table 1. G*rinders* were heavier than all other positions ($P<0.01$), while *bowmen* had a lower body fat percentage than *utilities* ($P=0.05$).

For all the athletes VO_{2peak} was 4.69 ± 0.50 L$\cdot$min^{-1} (range: 3.58 to 5.48 L$\cdot$min^{-1}), which occurred after 26 min 29 s ± 2 min 27 s of the step test at a power output of 332 ± 44 W. G*rinders* achieving a higher power output than the *afterguard* (369 ± 35 *vs*. 297 ± 50 W, $P=0.01$) and *bowmen* had a higher relative VO_{2peak} than *grinders* (56 ± 6 *vs.* 48 ± 4 ml$\cdot$kg$^{-1}\cdot$min^{-1}, $P=0.04$; Table 2). Figure 2 shows the BLa response to increasing VO2 as a percentage of VO2peak.

For the whole crew the lactate threshold (OBLA) occurred at a power output of 202 ± 31 W (61 ± 6% of W_{max}) and VO_2 of 3.34 ± 0.04 L$\cdot$min^{-1} (71 ± 5% of VO_{2peak}), with *grinders* having greater power output than *trimmers* at OBLA (227 ± 7 *vs.* 177 ± 28 W, $P=0.01$**;** Table 3).

For each of the *grinders* the relationship between torque and crank velocity during the isokinetic sprints was linear ($r=0.94 \pm 0.06$). The torque-crank velocity relationship for this cohort of grinders was expressed by the following equation: $T = -0.8421\ \omega + 211.68$ ($r=-0.99$, $P<0.001$), with predicted Tmax, 212 Nm and xmax, 251 rpm (Fig. 3).

Table 2. Maximal physiological responses of America's Cup sailors during a standing arm cranking ('grinding') step test [mean ± SD].

Position	N	HR max [beats·min^{-1}]	VO_{2peak} [L·min^{-1}]	VO_{2peak} [ml·kg^{-1}·min^{-1}]	V_E [L·min^{-1}]	Peak Power [W]	BLa [mmol·L^{-1}]
Grinders	9	186 ± 8	5.04 ± 0.41	48 ± 4	199 ± 22	369 ± 35[b]	11.3 ± 1.3
Utilities	6	191 ± 8	4.74 ± 0.35	51 ± 4	184 ± 20	332 ± 19	11.7 ± 1.2
Bowmen	6	187 ± 7	4.63 ± 0.39	56 ± 6[a]	189 ± 25	328 ± 35	12.0 ± 2.4
Trimmers	5	190 ± 9	4.50 ± 0.50	55 ± 5	186 ± 15	311 ± 45	13.2 ± 2.0
Afterguard	6	181 ± 10	4.18 ± 0.66	49 ± 6	179 ± 10	297 ± 50	10.6 ± 2.4
All	32	187 ± 9	4.69 ± 0.50	51 ± 6	189 ± 20	332 ± 44	11.7 ± 1.9
range		[167 to 201]	[3.58 to 5.48]	[41 to 62]	[152 to 229]	[235 to 425]	[8.2 to 15.9]

[a] Bowmen greater than Grinders (P=0.04); [b] Grinders greater than Afterguard (P=0.01)

Table 3. Physiological responses at lactate threshold of America's Cup athletes, during standing arm cranking ('grinding') [mean ± SD].

Position	**N**	**Power** [W]	**HR** [beats·min^{-1}]	**VO_2** [L·min^{-1}]	**VO_2** [ml·kg^{-1}·min^{-1}]	**VO_2** [% of VO_{2peak}]
Grinders	9	229 ± 21[a]	159 ± 10	3.67 ± 0.33[a]	34.7 ± 3.6	73 ± 4
Utilities	6	197 ± 23	168 ± 9	3.34 ± 0.33	35.9 ± 2.4	71 ± 6
Bowmen	6	198 ± 22	163 ± 5	3.26 ± 0.33	39.2 ± 2.7	70 ± 6
Trimmers	5	177 ± 28	155 ± 5	3.10 ± 0.56	37.7 ± 6.2	68 ± 6
Afterguard	6	192 ± 36	158 ± 10	3.13 ± 0.46	35.3 ± 4.9	72 ± 4
All	32	202 ± 30	161 ± 9	3.34 ± 0.43	36.3 ± 4.2	71 ± 5
range		[136 to 261]	[139 to 180]	[2.46 to 4.00]	[28.7 to 44.1]	[61 to 79]

[a] Grinders greater than Trimmers (P=0.01)

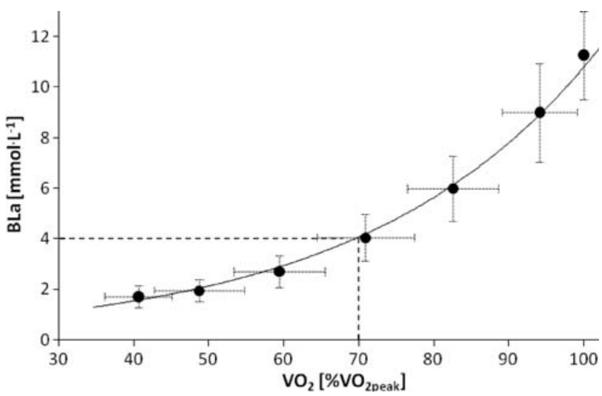

Fig. 2 Blood lactate concentration (BLa) with increasing VO2 as a percentage of VO2peak during each stage of an incremental step testing to exhaustion on a standing arm-crank ergometer (n = 33). Data are mean ± SD.

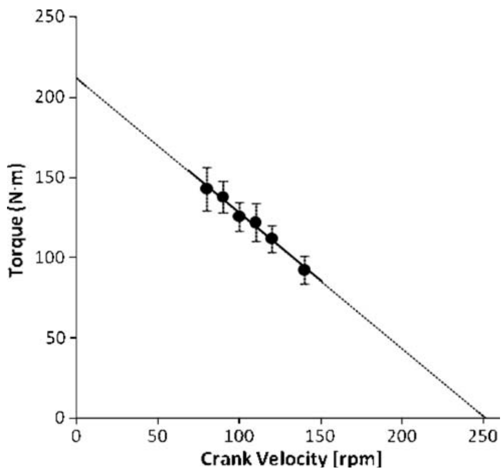

Fig. 3 Torque and crank velocity relationship during standing arm cranking ('grinding') (r = -0.99, P<0.01, n = 10).

Peak power during the 7 s sprints is displayed in Fig. 4. Peak power at 120 rpm was significantly greater (17%) than at 80 rpm (P=0.03, Fig. 4a), as was relative peak power (P=0.01, Fig. 4b). Peak power was significantly correlated to body mass (r = 0.58, P = 0.04). The power-crank velocity relationship was a parabola described by the equation: $P = -0.1206\omega^2 + 29.201\omega - 361.73$ (r=0.73). P_{max}, the apex of the power-crank velocity relationship, was 1420 ± 37 W (range: 1192 to 1617 W), and when normalised for body mass was 13.7 ± 1.0 $W \cdot kg^{-1}$ (range: 12.0 to 15.4 $W \cdot kg^{-1}$). ω_{opt} occurred at 125 ± 6 rpm (range: 114 to 133 rpm).

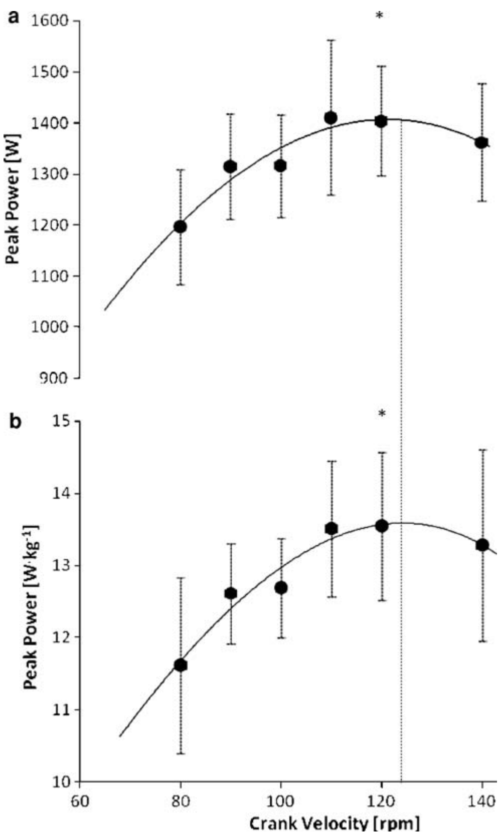

Fig. 4 Relationship between a Peak Power and Crank Velocity during standing arm cranking ('grinding') (r = 0.73, n = 10). Asterisk 120 significantly greater than 80 rpm (P = 0.03); b Relative peak power and crank velocity (r = 0.81, n = 10). Asterisk 120 significantly greater than 80 rpm (P = 0.01).

DISCUSSION

The main findings of this study were that America's Cup sailors are characterised as having high absolute upper body aerobic and anaerobic power. To the best of our knowledge no other cohort of athletes has achieved an average VO_{2peak} for arm cranking of 4.7 L·min^{-1} (51 ml·kg^{-1}·min^{-1}) that we have found for a whole crew of America's Cup sailors, or the P_{max} of 1420 W (13.7 W·kg^{-1}) for a sub-group of *grinders*. America's Cup grinding is unique in that it is one of the only able bodied sporting activities where arm cranking is the primary physical activity.

The P_{max} produced by *grinders* in this study was substantially more than that previously reported during arm cranking. To our knowledge, no other study has reported a cohort of athletes to have P_{max} greater than 1000 W during arm cranking. A recent study also on America's Cup *grinders* performing standing arm cranking, found P_{max} of 929 ± 100 W (Pearson et al. 2007). Other studies of standing arm cranking have reported P_{max} values of 720 to 732 W (8.5 to 9.6 W·kg^{-1}) in javelin throwers and elite wrestlers (Hubner-Wozniak et al. 2004; Bouhlel et al. 2007) and 700 W (10.6 W·kg^{-1}) during seated arm cranking in elite gymnasts (Jemni et al. 2006). In addition, the peak aerobic power values observed during this study are the highest reported during arm cranking exercise. Slightly lower results have been reported during seated arm cranking by elite rowers (4.4 L·min^{-1} (Secher et al. 1974)) and elite sprint kayakers (4.3 L·min^{-1} (Tesch 1983)), both activities requiring substantial upper body aerobic power. The impressive peak power and aerobic power values in this study are characteristic of the unique requirements of this cohort of athletes, that are selected and trained for the specific activity of standing arm cranking. The large body size (and fat-free mass) of these elite sailors would certainly be expected to contribute to the high absolute values recorded. In fact the *grinders*, who recorded the highest absolute aerobic power (5.0 L·min^{-1}) and produced P_{max} values more than 40% above any previously documented, had a significantly greater fat free mass (91 kg) than all other crew positions. However when normalising for body mass, *bowmen* had the greatest relative VO_{2peak} (56 ml·kg^{-1}·min^{-1}). Similar results have been reported previously with *grinders*, 4.7 L·min^{-1} and *bowmen*, 52 ml·kg^{-1}·min^{-1} (Bernardi et al. 2007). This disparity between positions is likely due to differences in body mass between roles, with *grinders* ~20 kg heavier than *bowmen* as a result of their high power requirements. In addition, the nature of activities typically performed by the *bowmen* are more prolonged with shorted recovery periods than *grinders*. The high aerobic power seen in all crew positions, indicates the importance of upper body aerobic power for this sport. Although the activity profile of most crew roles is considered to be intermittent with the most intense periods during manoeuvres, the prolonged nature of racing (~100 min), the high number of work bouts and the relatively short rest intervals suggests a heavy reliance on aerobic energy metabolism (Gaitanos et al. 1993) that may explain the high aerobic power values of these athletes.

Compared to seated arm cranking, where the involvement of the lower limbs is restricted, standing arm cranking has a greater contribution from the proximal kinetic chain in force production, hence, one might expect a higher performance during standing than seated arm cranking. Although it has previously been reported that the maximal cardiorespiratory response is unaffected by the type of arm cranking (Vokac et al. 1975). Other factors likely to influence performance during standing arm cranking are crank length, ergometer height and the distance between the crank handles, which are seldom reported in the literature. In this study, these were all similar to that typically employed on America's Cup racing yachts, but the greater crank length and handle separation compared to standard arm ergometers, likely facilitates a greater range of movement and involvement of a larger muscle mass.

A discontinuous step test protocol was selected for the current study in order to determine both aerobic power and the lactate threshold. Although it has been suggested that maximal arm crank tests of aerobic power should be short in duration (<14 min) in order to avoid local fatigue (Goosey-Tolfrey et al. 2006), this has not been confirmed, and no significant differences have been observed in any measured variables during arm cranking between step and ramp protocols despite a 3-fold difference in test duration (Washburn and Seals 1983; Smith et al. 2004).

The OBLA has repeatedly been found to be an important determinant of endurance performance (Sjodin and Jacobs 1981; Mujika and Padilla 2001). The mean VO_2 at OBLA of the sailors in the present study was 71% of VO_{2max} which is less than that typically reported in elite cyclists (~86% (Mujika and Padilla 2001)) and well trained kayakers (81% (van Someren and Oliver 2002)). The nature of grinding during America's Cup yacht racing is highly intermittent and characterised by short bouts of maximal effort interspersed by longer rest intervals (Bernardi et al. 2007; Neville 2008). This intermittent activity profile may explain the lower OBLA of *grinders* compared to the continuous activities of cycling and flat water kayaking. Unfortunately there is almost no comparable data for lactate threshold during arm cranking. One observation of elite paraplegic wheelchair athletes reported as high as 75% of maximum power and 80% of HR_{max} at OBLA during seated arm cranking (Schmid et al. 1998), however the numerous physiological differences between able bodied and disabled athletes, makes it difficult to compare these findings.

It is generally acknowledged that substantial differences exist between arm cranking and lower body exercise, such as cycling. For example, the maximal aerobic capacity of the upper body in untrained subjects seems to be limited by peripheral factors, including a small involved muscle mass, a greater proportion of type II fibres (Johnson et al. 1973), a low density of capillaries (Turner et al. 1997; Calbet et al. 2005) and mitochondria (Turner et al. 1997), and a greater peripheral resistance (Stenberg et al. 1967). In addition, arm cranking exercise results in greater physiological stress (RPE and HR) at the same VO_2 (Leicht 2008) when compared with cycling in untrained subjects. Despite these physiologic and energetic disadvantages the current study demonstrates the exercise capacity of trained elite upper body athletes.

The torque- and power-crank velocity relationships of elite upper body trained athletes have received little attention, with the few reports in the literature indicating a linear relationship between torque and velocity (Vandewalle et al. 1989; Vanderthommen et al. 1997; Driss et al. 1998), similar to that in cycling. The parabolic power-crank velocity relationship seen in this study emphasises the influence of crank rate on peak power. The optimum velocity for maximum power output was 125 rpm, which is surprisingly similar to the ω_{opt} during elite track cycling (~ 129 rpm (Dorel et al. 2005; Gardner et al. 2007)). The relatively short upper limbs and greater crank length of grinding compared to cycling (250 *vs* 170 mm (Dorel et al. 2005)) would be expected to lead to a greater joint excursion during each revolution with grinding. Hence for a given crank velocity, considerably greater joint angular velocities would be expected with grinding compared to cycling. It is surprising therefore that ω_{opt} of the two activities appears so similar, and may be indicative of a greater proportion of type II fibres in the upper body musculature of elite *grinders* compared to the leg musculature of cyclists. There is some evidence, that the upper body muscles tend to have a greater proportion of type II fibres compared to the lower body (Johnson et al. 1973).

The only documented evidence of crank velocity during America's Cup racing reported peak velocity of between 120 and 150 rpm (Bernardi et al. 2007). From the results of the current study it seems that a narrow range of crank velocities between 115 and 135 rpm would be beneficial for optimising power production. This has considerable implications for the design of winch gear ratios and gear selection during big-boat sailing. The on-board winch systems typically have up to eight gears, which are usually changed by either stopping the crank rotation for the newly selected gear to engage, or by changing the direction of crank rotation (i.e. grinding backwards). Both of these gear changing techniques result in a loss of momentum and a velocity substantially outside of the optimum range whilst the *grinders* are striving to exert maximum power during a manoeuvre. In addition, grinding backwards elicits substantially less power (~17%) than grinding forwards (Pearson et al. 2007). Therefore, it would be highly beneficial if it were mechanically possible to maintain momentum (within the optimum crank velocity range) in the forward direction during gear change; i.e. to change gear while grinding forwards without stopping, such as the use of a 'crash-box' gear change system.

Taken together the results of this study underscore the unique nature of this cohort of elite athletes who have high levels of both anaerobic and aerobic upper body power. This poses a challenge to the conditioning of these athletes as both explosive power and endurance are required. Future research may look to investigate the influence of specific training interventions on upper body power and endurance. In addition, research should aim to investigate the physiological demands during competition, particularly the determination of the actual power output of *grinders* during racing.

Conclusions

The high P_{max} with concomitant high VO_{2peak} suggests that America's Cup *grinders* require substantial upper body anaerobic power in addition to high aerobic power. The elite nature of these athletes, their high fat-free mass, training and selection for standing arm cranking, as well as the mechanics of the 'grinding' ergometer used, may have contributed to their high values. In addition, the influence of crank velocity on peak power implies that power production during on-board 'grinding' could be optimised through the use of appropriate gear-ratios and development of efficient gear change mechanisms.

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Conflict of Interest:

The authors are not aware of any conflict of interest.

Ethical Standards:

The experiments comply with current laws.

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