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THE PHYSIOLOGICAL DEMANDS OF AMERICA'S CUP YACHT RACING

by

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A Doctoral Thesis

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ABSTRACT

The aim of this research was to report the physiological demands of America's Cup yacht racing. The nature of racing was quantified, specifically the activity pattern and exercise intensity, and the anthropometric, and fitness characteristics of the athletes documented. This included physiological assessment (aerobic power and anaerobic power) of the athletes during 'grinding' (standing arm-cranking) the primary activity of America's Cup sailing. The influence of crank velocity, crank length, crank-axle height and the role of the lower limbs were evaluated in order to determine the conditions for optimal power production during grinding. The acute thermoregulatory responses to racing were assessed, and the chronic responses to training in terms of upper respiratory infection (URI), salivary-immunoglobulin A (s-IgA) and subjective fatigue documented. The exercise intensity of racing was high, but intermittent, and influenced by how evenly matched the boats were and the role of the athlete. America's Cup sailors had the highest upper body aerobic power 4.7 $L \cdot min^{-1}$ and anaerobic power 1420 W values that have been reported during arm-cranking. The parabolic power-crank velocity relationship had an optima at 125 rpm. The optimal crank length for power production was 12.3% of arm-span (241 mm for a cohort of *grinders* and similar to the 250 mm cranks used in the America's Cup). The optimal crank-axle height was between 50 and 60% of stature (950-1150 mm in a cohort of *grinders* and substantially greater than the 850 mm height used on America's Cup yachts). Dynamic movement of the lower limbs reduced the physiological strain of grinding, indicating that involvement of the lower limbs was beneficial to grinding performance. B*owmen* were at risk of hyperthermia (peak T_{core} 39.2°C) and dehydration (sweat loss, 3.7% body mass), which may impair performance and could lead to heat illness. Downwind sailing resulted in greater cardiovascular and thermal strain than upwind sailing. The relationship between the group relative s-IgA concentration and the incidence of URI indicated that for the cohort relative s-IgA determined a substantial proportion of the variation in URI incidence. In summary, it is evident that the physiological demands of America's Cup yacht racing are high and varied, and the elite athletes studied are adapted and selected for the unique demands of this sport.

Keywords: Sailing; Thermoregulation; Immunology; Arm-cranking; Performance; Physiology; Anthropometry

CONFERENCE PROCEEDINGS

Neville V., Gleeson M., Folland J.P. (2008) *Salivary IgA can Help to Predict Upper Respiratory Infection in Athletes.* American College of Sports Medicine 55th Annual Meeting. Medicine and Science in Sports and Exercise, 40 (5):S15

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Neville V., Zaher N., Pain M.T.G., Folland J.P. (2009) *Lower Limb Influence on the Physiological Demands of Standing Arm-cranking ('grinding').* In review at: International Journal of Sports Medicine (at second review stage)

Neville V., Gant N., Folland J.P. (2009) *Thermoregulatory Demands of Elite Professional America's Cup Yacht Racing.* In review at: Scandanavian Journal of Medicine and Science in Sports (at second review stage)

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INTRODUCTION

1.1 Background to the Study

The America's Cup is one of the most prized and sort after trophies in sport. It boasts being the oldest trophy in modern day sport, predating the modern Olympic Games by 45 years. The America's Cup was first raced around the Isle of Wight, off the English south coast, in 1851 and was won by the American yacht, 'America', hence the origin of the name. To date there have been 32 Challenges for the America's Cup (Appendix 1) with the current winner, 'Alinghi', from Switzerland. The event is held approximately every three to four years between challenging yacht clubs, representing their respective countries (called 'Challengers') and the winner of the previous America's Cup (known as the 'Defender') who also hosts the event (Whiting 2007). The America's Cup is unique in that the format is still largely based on the original 'Deed of Gift', where the Defender is automatically in the final 'Match'. In other words, all the Challengers compete against each other in a Challenger series, where the winner then advances to race against the Defender in the final Match. Hence it is extremely difficult to win the coveted trophy.

Regarded as the pinnacle of sailing, the America's Cup has similarities to Formula 1 motor racing, with teams at the forefront of advancing yachting technology and requiring substantial financial support (budgets of up to US$ 300 million per campaign). The primary investment in resources and time has been in the research and development of the sailing technology and hardware. Some teams have as many as 40 professional designers developing the four main components of the racing yachts, namely, the hull, sails, mast and appendices (rudder, fin and bulb). The design process includes innovative science and technology, such as Finite Element Analysis (FEA), Computational Fluid Dynamics (CFD), computer modelling, wind tunnel and tank testing with scaled models as well as hundreds of hours of full-scale testing. The International America's Cup Class (IACC) version 5 rules, allow teams to build two new yachts for each event. The 24,000 kg, 26 m yachts are built from high performance materials, such as carbon fibre, kevlar, titanium, titanium alloys, nitronic steel and poly-phenylene-2,6-benzobisoxazole (PBO) fibre rigging. They have a fully adjustable 32 m carbon fibre mast, and a combined sail area of over 750 m^2 (Figure 1.1).

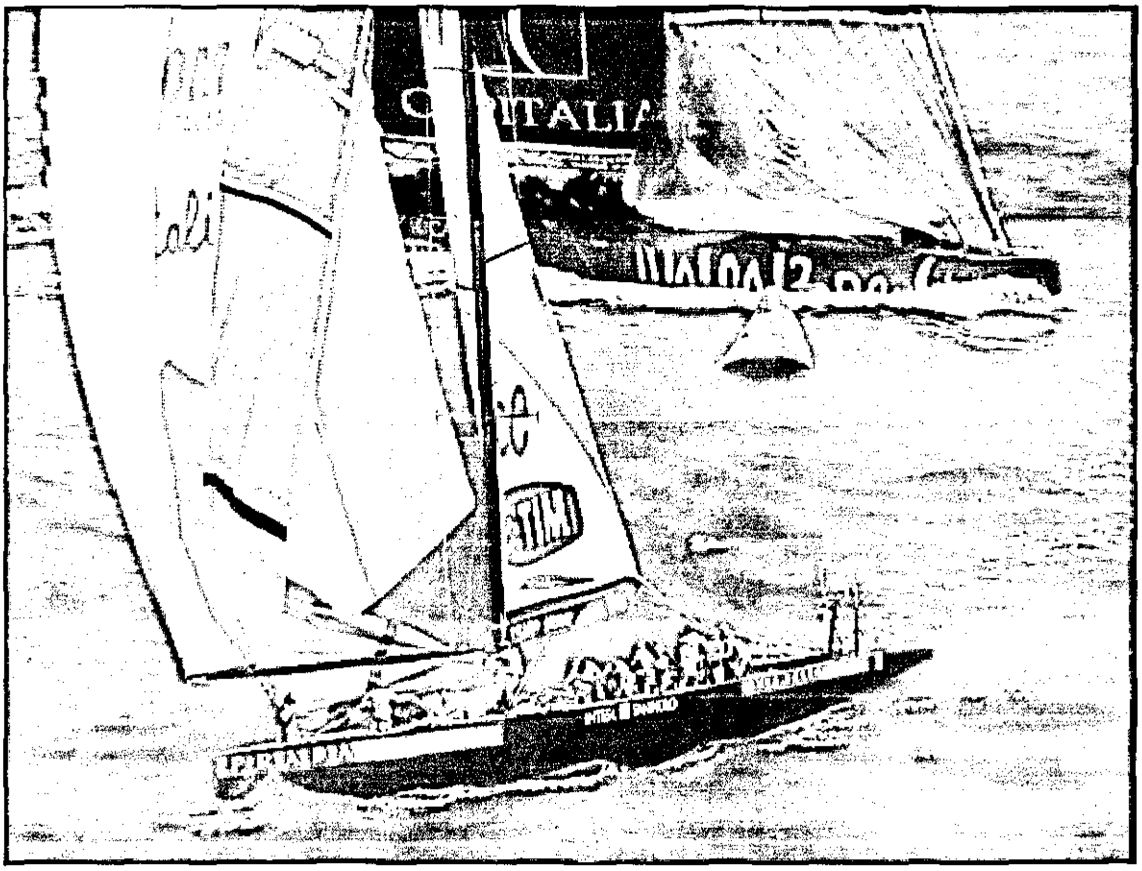


Figure 1.1 America's Cup (IACC version 5) racing yachts, showing the *bowmen* dropping the genoa (upwind foresail) after rounding the windward mark (courtesy of Luna Rossa © Luna Rossa Trademark Sarl)

The America's Cup is one of the largest sporting events in the World, over 2-million spectators attended the 32nd America's Cup in Valencia, Spain, and more than 100 million people from 150 countries watched the event on television (Sheahan 2007). In addition, US$ 2.6 billion was spent on the infrastructure to host the 32nd America's Cup in Valencia with an estimated economic benefit of ~ 40,000 new jobs as a result of the event (CNN 2007). Considering the profile of the event, very little scientific research has examined the physical role of the crew and optimising the performance of these professional sailors.

Preparation for the America's Cup usually entails 3 to 4 years of crew and yacht development, during which the professional athletes sail and train together on a full-time basis. The high estimated total daily energy expenditure for America's Cup sailors, in particular *grinders* (~ 5800 kcal) indicates a high physical work load (Bernardi et al. 2007a). During the 31st America's Cup, Challenging teams competed in up to 50 races over

22 weeks, with two races per day during the earlier rounds of the competition (Neville et al. 2006). America's Cup racing is a 'match-race' format (i.e. two boats at a time) around a two lap upwind and downwind course which typically lasts between 60 and 120 min. The racing crew on-board an America's Cup yacht comprises 17 skilled athletes. The physical requirements of each position are determined by the primary activities specific to the role (Blondelle and Simonnet 1984; Bertrand and Robinson 1985; Bessinger 2002). The athletes can be divided into five groups of similar physical and technical requirements, namely; *grinders, bowmen, trimmers, utilities* and *afterguard* (Allen 1999; Neville et al. 2006; Bernardi et al. 2007b).

In America's Cup sailing all manoeuvres occur manually without the assistance of stored energy, hence the physiological demands placed on the crew have been suggested to be high (Bauer 1986), but have not been carefully researched. An individual's exercise intensity during racing is thought to depend largely on the weather conditions, the race tactics, the role of the athlete within the crew (Allen and De Jong 2006; Neville et al. 2006), and perhaps also on how evenly the competing boats are matched (Whiting 2007). There is evidence that some positions, for example *bowmen* are able to sustain a mean heart rate of >70% of their maximum for the duration of a 2.5 h race, and *grinders* achieve a VO_2 as high as 90% of VO_{2peak} during certain manoeuvres (Bernardi et al. 2007b). However, there has been no systematic investigation of exercise intensity during America's Cup sailing.

There are some indications that body composition may be specific to the role of the athlete (Lambert and Lelguen 2001; Pearson et al. 2005), however, little is known of the physical characteristics (anthropometry and fitness) of the athletes, particularly with respect to the different positions. The America's Cup protocol limits the total weight of the crew hence maximising performance for a given body mass is important with clear implications for body composition.

Grinding (standing arm-cranking) is the primary physical activity during America's Cup sailing (Figure 1.2). Grinding drives the winches, which in turn, control the sails and mast of the yacht (Whiting 2007) and is therefore a key activity in all manoeuvres. Grinding involves short bursts of high intensity exercise in order to complete each manoeuvre, interspersed with longer rest intervals, but no quantitative description of the activity pattern of grinding has been completed. America's Cup (IACC version 5) yachts typically have four arm-crank stations (grinding pedestals), each manned by one or two athletes (*grinders*), depending on the prioritisation of grinding and other tasks. As the difference between competing yachts is often most apparent during manoeuvres, grinding is considered an important component to overall race performance. Therefore it appears useful to document the athlete's maximal capability for grinding and consider the optimisation of this activity.

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. 2007b) and peak power (Vandewalle et al. 1989; Hubner-Wozniak et al. 2004; Bouhlel et al. 2007; Pearson et al. 2007) present in the literature. The only reports of standing arm-cranking in America's Cup sailors appear to suggest reasonably high VO_{2peak} (47 $ml \cdot kg^{-1} \cdot min^{-1}$, n=16, (Bernardi et al. 2007b)) and high peak anaerobic power values (929 ± 100 W, n=6, (Pearson et al. 2007)).

Figure 1.2 America's Cup sailors shown grinding at a grinding pedestal (courtesy of Luna Rossa © Luna Rossa Trademark Sarl)

The optimisation of performance during standing arm-cranking has received very little scientific attention. 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 are largely unknown. This may have an important bearing on the selection of gear ratios and the optimisation of power production during America's Cup sailing. In cycling, the manipulation of joint angles, through changes in the structure of bicycle components, has been shown to influence performance (Hamley and Thomas 1967; Too and Landwer 2000; Martin and Spirduso 2001). For example, changes in seat height and cycle crank lengths directly affect hip and knee joint angles, the range of motion and angular velocity of the joints, and thus cycling performance (Too and Landwer 2000). It seems highly likely therefore that changes to the configuration of arm-crank ergometry, specifically crank length and crank-axle height, could also affect performance. Given the angle-torque and torque-velocity relationships of human muscle function, there is a clear rationale for how interventions that effect upper extremity joint range of motion and angular velocities may influence arm-cranking performance. It appears that the crank length and crank-axle height of the grinding pedestals on America's Cup yachts have been largely determined by other aspects of yacht design, such as the height of the boom and aerodynamics, without any understanding or consideration of the effects on grinding performance.

Although grinding is regarded as predominantly upper-body exercise, some athletes grind with distinct flexion and extension of the knee joint, and rotation of the pelvis in the horizontal plane, whilst for others the lower body is more rigid. It has been proposed that the lower limbs and trunk musculature contribute substantially to grinding performance (Bernardi et al. 2007b; Pearson et al. 2007), but this idea is equivocal. One report suggested that the trunk and lower limbs should "remain square", and "rotation of the hips should be avoided" during grinding (Chisnell 2008). During other predominantly upper body sports activities (e.g. cross-country skiing (Holmberg et al. 2006), tennis serving (Girard et al. 2007)) restriction of lower limb mobility impaired performance and elicited greater physiological stress. This evidence might indicate that involvement of the lower limbs is beneficial to grinding performance, although the optimum grinding technique has not been researched.

America's Cup yacht racing predominantly takes place during the summer months when athletes may be exposed to hot and humid environmental conditions for prolonged periods. The high energy expenditures of sailors, combined with prolonged exposure to hot environmental conditions will result in elevated body temperatures and substantial sweat losses during racing. There are reports of heat illness during sailing (Miller 1987; Allen 2003; Allen and De Jong 2006; Neville et al. 2006) and evidence that dehydration is a common problem for elite Dinghy sailors (Mackie and Legg 1999). One report of recreational Dinghy sailors found a modest rate of sweat loss (~ 0.4 $L \cdot h^{-1}$) over a 5 h sailing period (Slater and Tan 2007). In addition to water, important electrolytes are lost in sweat, most notably sodium, chloride, potassium and magnesium (Maughan 1991), that could compromise endogenous electrolyte concentrations during competition. During America's Cup sailing large differences (~ 4-fold) in the apparent wind speed (AWS), and thus expected evaporative cooling, exist between upwind and downwind sailing. Upwind sailing also typically results in sailing against the prevailing waves with increased exposure to sea spray. Thus the environmental conditions can vary widely during a race. Furthermore, athletes typically wear waterproof clothing to prevent saturation, and this may impair thermoregulation in hot conditions. Hyperthermia and dehydration are well known to negatively influence cognitive and physical performance (Howe and Boden 2007), but their occurrence in America's Cup sailing has not been investigated.

Upper respiratory infections (URI) are the most common medical complaint of athletes, including America's Cup sailors (Robinson and Milne 2002; Neville et al. 2006), and can negatively affect training and performance (Pyne and Gleeson 1998). During a two year training period prior to the 31st America's Cup, 40% of all illnesses were URI and accounted for > 60% of days absent from sailing due to illness (Neville et al. 2006). The risk of illness seems to increase during periods of heavy training and competition (Peters and Bateman 1983; Novas et al. 2003; Libicz et al. 2006). This increased susceptibility to URI is thought to be largely due to a depression of immune system function as a result of multifactorial stress including physiological, psychological, environmental and behavioral (Dawes 1972; Tomasi et al. 1982; Cohen et al. 1999; Calder and Jackson 2000).

The majority of all infections (~95%) are initiated at the mucosal surfaces (Bosch et al. 2002), which are protected by complex immune surveillance through the secretion of antimicrobial proteins. The most abundant and responsive salivary antimicrobial protein is salivary immunoglobulin A (s-IgA) (Lamm 1997; Woof and Kerr 2006), which plays a crucial role in immune defence (Mazanec et al. 1993). Elite athletes are frequently exposed to exercise stress, and the effects of both acute and chronic exercise on s-IgA have been well documented (Tomasi et al. 1982; Mackinnon et al. 1993b; Gleeson et al. 2000b; Novas et al. 2003; Libicz et al. 2006). Much of the immunology research in athletes has concentrated on post-exercise salivary immunity when athletes seem to experience a transitory decrease in s-IgA for up to 24 h post strenuous training or competition. It is during this "open window" period of immune depression (Pedersen et al. 1994) when athletes are thought to be at greatest risk of URI. However, there are few longitudinal studies that have examined the relationship between immune depression and the incidence of URI (Mackinnon et al. 1993a; Gleeson et al. 1999b; Novas et al. 2003; Fahlman and Engels 2005) and these typically have had a low number of subjects or low sample collection frequency.

1.2 Aims and Organisation of the Study

The aim of this research was to report the physiological demands of America's Cup yacht racing. The progression of six experimental studies is shown in Figure 1.3. The first experiment (Chapter 3) analysed the nature of America's Cup racing; quantified the activity pattern of grinding and the exercise intensity of the crew during racing; as well as documenting the anthropometric and fitness characteristics of the athletes. The second study (Chapter 4) assessed the physiological characteristics of elite America's Cup sailors during grinding (standing arm-cranking). In particular, key indices of aerobic endurance performance (aerobic power and the onset of blood lactate accumulation) and the torque-crank velocity and power-crank velocity relationships during maximal grinding, and thus the peak power and optimum crank velocity, were determined. The third investigation (Chapter 5), attempted to identify the optimal crank lengths and crank-axle heights for maximum power production during standing arm-cranking. In order to quantify the importance of lower limb movement to grinding the fourth study (Chapter 6) compared the physiological stress of grinding with free and restricted knee joint motion. The fifth experiment (Chapter 7) assessed the acute thermoregulatory responses (core and skin temperatures, fluid and electrolyte losses) to racing. The sixth and final study (Chapter 8) examined the chronic responses to training by documenting the interrelationships between URI, s-IgA and fatigue during a prolonged period of preparation and training.

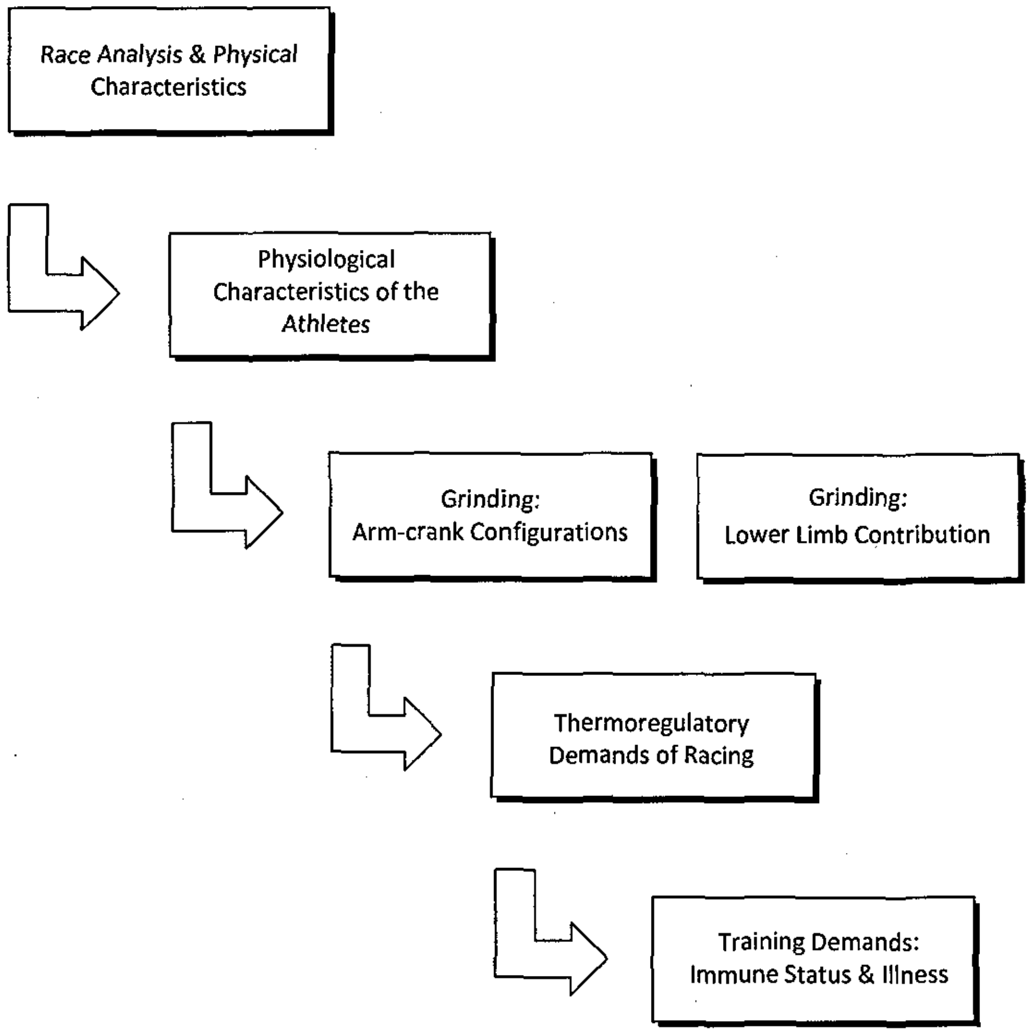


Figure 1.3 Schematic of the research studies, in order to determine the physiological demands of America's Cup yacht racing.

CHAPTER 2

REVIEW OF LITERATURE

The literature review is divided into three major sections. The first section highlights the literature relevant to America's Cup yacht racing, arm-cranking (grinding) and upper body work. The second and third sections review the literature on thermoregulation, fluid and electrolyte balance; and stress, fatigue and salivary immunology, respectively.

2.1 America's Cup Yacht Racing

During the 31st America's Cup, Challenging teams competed in up to 50 races over 22 weeks, with two races per day during the earlier rounds of the competition (Neville et al. 2006). America's Cup racing is a 'match-race' format (i.e. two boats at a time) around a two lap upwind and downwind course of ~11 nautical miles (20 km) (Figure 2.1). Races typically last between 60 and 120 min. A number of technical manoeuvres occur during racing, requiring skill and effort, the most common being upwind tacking and downwind gybing, where a yacht changes direction from one side of the wind to the other (port/starboard) (see magnified insert, Figure 2.1). The timing and magnitude of these manoeuvres are largely dependent on the direction of the wind, the sea current, the position of the other yacht and the tactics employed during the race. Other critical manoeuvres are the mark roundings, where the yacht rounds the upwind or downwind mark during which time the foresail (genoa or spinnaker) is lowered and a new sail hoisted (Figure 1.1). Numerous other manoeuvres occur during racing such as 'peeling' (changing a sail during a leg), 'circling' (positional jousting during the pre-start), and 'dialing-up' (forcing the other yacht to point into the wind), all requiring high technical precision. Racing is strategically challenging, with each team trying to out-manoeuvre the opposition, by locating more favourable wind or drawing a technical penalty (foul) that requires the other yacht to perform a 'penalty turn' (a full-circle taking ~30 s). In fact one crew position, the *tactician*, is devoted almost entirely to these strategic considerations.

One observation of a single team during the 31st America's Cup noted an average of 30 upwind tacks and 15 downwind gybes per race (Bernardi et al. 2007b), each manoeuvre taking on average 13 s and 19 s, respectively (this data was reported from a semi-professional team that was ranked last during the 31st America's Cup and thus these results should be interpreted with caution). However, many aspects of America's Cup racing have not been clearly documented for example: the precise race duration, number of manoeuvres and activity cycles, duration and intensity of manoeuvres as well as the environmental strain.

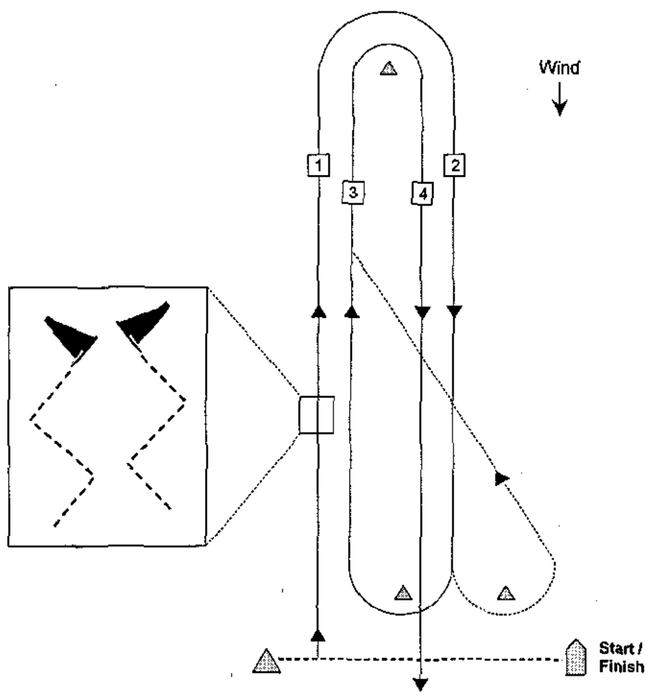
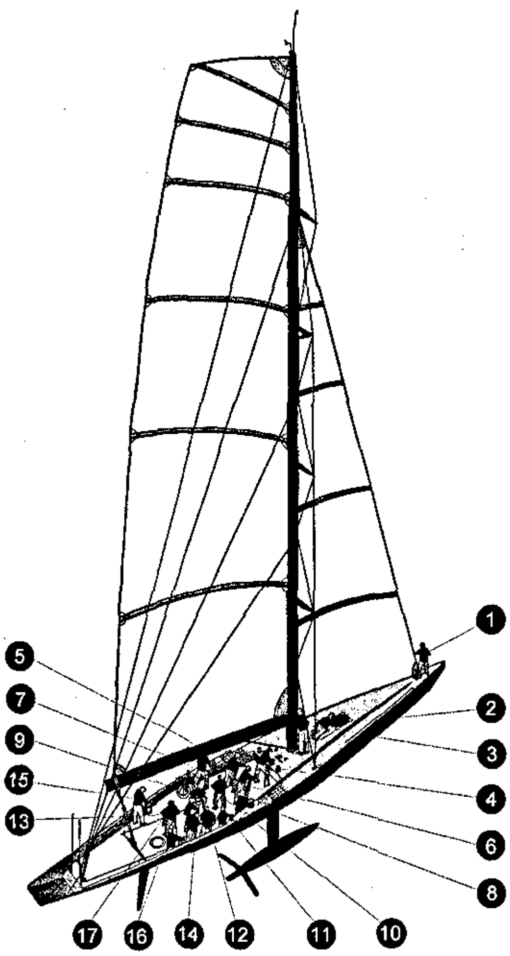


Figure 2.1 An America's Cup match-race course, with each leg being 4.6 to 5.6 km (2.5 to 3.0 nautical miles) in length. 1 & 3 are upwind legs and 2 & 4 are downwind legs. Teams can choose to round either mark at the end of leg 2. Magnified insert shows the boats tacking upwind.

The racing crew on-board an America's Cup yacht comprises 17 skilled athletes. The physical requirements of each position are determined by the primary activities specific to the role (Blondelle and Simonnet 1984; Bertrand and Robinson 1985; Bessinger 2002). A brief description of each role and their position on-board is provided in Figure 2.2. The athletes can be divided into five groups of similar physical and technical requirements, namely; *grinders, bowmen, trimmers, utilities* and *afterguard* (Table 2.1) (Allen 1999;

Neville et al. 2006; Bernardi et al. 2007b). The majority of teams have two full crews of athletes to enable competitive in-team training and practice racing.



1. Bowman (*bowman*): Works on the narrow foredeck; organises the hoisting and dropping of sails; climbs out to the end of the pole if necessary; assists with grinding upwind

2. Mid-bowman (*bowman*): Works on narrow foredeck with bowman and below deck for packing and connecting sails

3. Mastman (*grinder*): Responsible for attaching and gybing the spinnaker pole; assists bowman and mid-bowman; main task is grinding

4. Pitman (*utility*): Controls all the ropes at the base of the mast; the communication link between the crew and the bowmen during manoeuvres; grinds upwind

5. Port Grinder (*grinder*): Primary task is grinding, which provides the power to turn the winches

6. Starboard Grinder (*grinder*): Primary task is grinding, which provides the power to turn the winches; responds to instruction from the trimmer

7. Upwind Trimmer (*trimmer*): Trims the shape of the genoa sail by continually adjusting hydraulics and easing and trimming the sail according to the changes in wind speed; sail shape determines the speed of the boat

8. Downwind Trimmer (*trimmer*): Trims the shape of the spinnaker sail by continually easing and trimming the sail according to the changes in wind speed; sail shape determines the speed of the boat

9. Mainsail Trimmer (*trimmer*): Adjusts the shape of the main sail by continually trimming and easing the sail and by adjusting the shape of the mast through a series of hydraulic pumps. The shape of the main sail largely determines the speed of the boat.

10. Mainsail Grinder (*grinder*): Primary task is grinding and pumping the mast hydraulics; predominantly works with the mainsail trimmer

11. Traveler Strategist (*utility*): Works with the mainsail trimmer and adjusts the position of the mainsail block according to the waves and wind speed; goes up the mast to look for wind during light conditions.

12. Helmsman (*afterguard*): Steers the boat and ultimately responsible for how the boat manoeuvres.

13. Tactician (*afterguard*): Makes the tactical race decisions, such as when to tack or gybe or how to out manoeuvre the opposition.

14. Navigator (*afterguard*): Controls the on-board computer systems and instruments; gives information on the position of the boat as well as on the opposition.

15. Utility (*utility*): Responsible for reporting the wind changes; assists with grinding upwind; assists the bowmen downwind

16. Runner Trimmer (*utility*): Adjusts the tension in the backstays which control the stiffness of the mast and effect the shape of both the mainsail and genoa sail.

17. Runner Grinder (*grinder*): Grinds the runners for the runner trimmer and assists with the mainsail grinding.

Figure 2.2 An International America's Cup Class version 5 racing yacht, showing the position and role of the 17 athletes.

Table 2.1 America's Cup crew divided into groups of similar on-board physical requirements.

Position	Crew [n]	Requirements
Grinders	5	Strength, power and endurance
Bowmen	2	Speed, agility, strength, flexibility, low centre of gravity, and good peripheral vision
Trimmers	3	Speed, fast hand eye coordination, strong upper body pulling power, good visual acuity and depth perception
Utilities	4	High strength to weight ratio, good peripheral vision and general conditioning
Afterguard	3	High level of technical skill, good communication and decision making skills

Preparation for the America's Cup usually entails 3 to 4 years of training and yacht development, during which time professional athletes sail and train together on a full-time basis. Training consists of daily land-based conditioning (1 - 2 h), such as strength and power development, and on-water sailing and training (3 – 6 h). Other daily tasks involve technical meetings, video analysis, debriefings, boat maintenance and packing and carrying sails. The working day usually lasts 8 to 12 hours (Neville et al. 2006).

Based on measurements of energy expenditure during sailing and training activities, combined with estimations of energy expenditure for other daily activities, Bernardi et al. (2007a) estimated the total daily energy expenditure for America's Cup *grinders* to be ~ 5800 kcal (56 $kcal.kg^{-1}.day^{-1}$) (Bernardi et al. 2007a). The energy expenditure for *bowmen* and "all other crew" was estimated to be 5300 and 4000 $kcal{\cdot}day^{-1}$, respectively. These estimations of energy expenditure highlight the high physical demands of this sport. As a result of the high volume of training, overall workload and multifactorial stress of America's Cup preparation, fatigue, illness and 'over-training' can occur in America's Cup sailors (Neville et al. 2003; Neville et al. 2006).

2.1.1 *Anthropometric Characteristics*

The total weight of the 17 athlete racing crew is restricted by the International America's Cup Class (IACC) version 5 rule to 1,570 kg (92.4 kg / athlete), and crews are subjected to pre-regatta weight controls as well as random post-race checks. The body mass and anthropometry of the athletes appear to depend on the position or role of the athlete (Lambert and Lelguen 2001; Pearson et al. 2005; Neville et al. 2006; Bernardi et al. 2007b) (Table 2.2). Pearson et al. (2005) reported *grinders* to be significantly heavier (and have a greater lean body mass) and taller than all other positions.

Table 2.2 Anthropometric characteristics of America's Cup sailors

	Grinders	Bowmen	Trimmers	Utilities & Afterguard
Bernardi et al. 2007				
31st America's Cup –team ranked bottom 2				
N	6	2	5	3
Age	28 ± 5	29 ± 2	29 ± 8	30 ± 7
Body mass	103 ± 4	77 ± 1	80 ± 8	78 ± 6
Fat %	13 ± 2	10 ± 1	10 ± 1	15 ± 1
Neville et al. 2006				
31st America's Cup – team ranked top 4				
N	12	6	7	10
Age	31 ± 5	32 ± 4	35 ± 5	36 ± 7
Body mass	99 ± 5	83 ± 6	84 ± 6	89 ± 9
Fat %	10 ± 4	12 ± 4	12 ± 4	17 ± 7
Pearson et al. 2005				
31st America's Cup – team ranked top 4				
N	12	5	7	11
Age	29 ± 5	32 ± 7	35 ± 6	38 ± 10
Body mass	105 ± 7	78 ± 4	82 ± 10	83 ± 7
Fat %	17 ± 1	13 ± 2	14 ± 3	15 ± 3
Lambert & Lelguen 2001				
30th America's Cup – team ranked bottom 2				
N	7	5	4	5
Age	30 ± 6	31 ± 6	30 ± 4	35 ± 4
Body mass	95 ± 10	75 ± 4	79 ± 8	82 ± 10
Fat %	19 ± 6	17 ± 2	18 ± 6	22 ± 3

All data are mean ± SD

Due to the body mass restrictions, a common strategy of teams is to reduce the body fat of the whole crew in order to maximise lean muscle mass of the positions with the greatest strength and power requirements, such as the *grinders*. As grinding requires high levels of strength and power, *grinders* are selected, in part, for their large muscle mass and power (Bauer 1986; Pearson et al. 2005). The mean body mass of two of the top four teams during the 31st America's Cup was 90 kg and the percentage body fat was 14% (Pearson et al. 2005; Neville et al. 2006). Whereas two teams ranked in the bottom two during the 30th and 31st America's Cups had lower mean body mass (84 and 88 kg, respectively; Table 2.2) (Lambert and Lelguen 2001; Bernardi et al. 2007b). By calculating lean body mass from the data in Table 2.2, there is a suggestion of a greater lean mass in the top ranked teams when compared to lower ranked teams.

2.1.2 *Physical Activities and Demands during America's Cup Racing*

The physiological demands placed on the crew have been suggested to be high (Bauer 1986), but have not been carefully researched. An individual's exercise intensity during racing is thought to depend largely on the weather conditions, the race tactics, the role of the athlete within the crew (Allen and De Jong 2006; Neville et al. 2006), and perhaps also on how evenly the competing boat are matched (Whiting 2007). However, there has been no systematic investigation of exercise activity profiles or intensity during America's Cup sailing.

The activities and the work intensity performed by all the athletes (other than the *helmsman*) are varied, with each role having a primary task as well as being required to perform some activities which are common to all the crew, such as *grinding*, the main physical activity in America's Cup yacht racing. Examples of other activities include, trimming (*trimmers* adjust the angle of the sails), top-handle winching (*utilities* often adjust a winch with a top-handle as opposed to grinding), packing sails (*bowmen* prepare used sails below deck for rehoisting), and bouncing the halyard (*mastman* hoisting a sail by hand). Heart rate data (unpublished data collected by the author) illustrates that *bowman* can sustain an average heart rate of >70% of their maximum for the full duration of a 2.5 h race. In addition, the analysis of on-board video data (unpublished data) has indicated an average work to rest ratio of approximately 1:3 during strenuous racing. Furthermore, blood lactate levels of ~5 $mmol \cdot L^{-1}$ have been found in *grinders* during sailing (Lambert and Lelguen 2001).

The physical preparation of the athletes is largely specific to their role (Figure 2.2), with *grinders* performing predominantly functional power exercises and high intensity interval training on arm-crank ergometers. Other positions such as the *bowmen* train to improve their reaction speed and agility, while *trimmers* require visual depth perception and hand-eye coordination (Valencia-Sailing 2006; Neville 2008).

One of the most physically demanding activities in America's Cup sailing is grinding. As all manoeuvres are performed manually without the assistance of stored energy, the sailors drive arm-cranks (grinding pedestals) that supply the power to turn the winches which pull the ropes for trimming and hoisting the sails (Figure 2.3). Big-boat yacht racing is one of the only able bodied sports where arm-cranking is the primary physical activity. America's Cup yachts (IACC version 5) typically have four grinding pedestals, and although all the crew (other than the *helmsman*) contribute to grinding during racing, there are between five and six athletes (*grinders*) from the crew primarily dedicated to this activity. The grinding cranks are unidirectional, due to the trans-directional gear shift mechanism of the winch system transfer-boxes. In other words, gear selection can be changed by changing the direction of crank rotation. A grinder can select from as many as 9 different gears, with the primary *grinders* mainly grinding in the, more efficient, forward direction (Pearson et al. 2007). Grinding involves short bursts of high intensity exercise in order to complete each manoeuvre, interspersed with longer rest intervals. Bernardi et al. (2007) found the oxygen uptake of *grinders* during gybing and tacking to be 53 and 68% of VO_{2peak}, respectively, and increased to 65 and 91% of VO_{2peak}, respectively, after a series of manoeuvres (>3) (Bernardi et al. 2007b). Although this study was performed by semi-professional America's Cup sailors performing simulated race manoeuvres, the authors suggested that the accumulative effect of frequent grinding required substantial aerobic energy provision in addition to anaerobic metabolism. The heel angle of the yacht can also influence grinding performance. A heel angle of 25° has been found to reduce peak power by as much as ~ 20% (Pearson et al. 2007). However, the majority of grinding usually occurs when the yacht is relatively flat; passing head-to-wind during tacking and all of the downwind leg, hence the heel angle is of little importance. To date there has been no thorough quantitative description of the activity pattern of grinding during sailing.

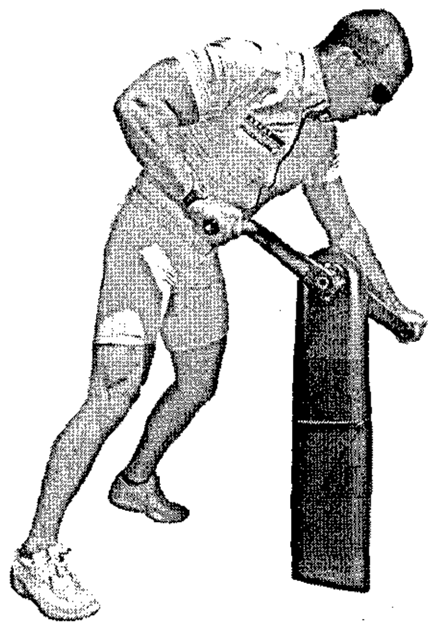


Figure 2.3 An America's Cup grinder, driving a grinding pedestal which supplies the power to turn the winches for trimming and hoisting sails (courtesy of Romolo Ranieri, © Vernon Neville 2008)

2.1.3 *Upper body Exercise*

Arm-cranking exercise has received some scientific attention, due to its role in cardiovascular (Lazarus et al. 1981; Westhoff et al. 2008) and injury rehabilitation (Carson 1989), as well as being an appropriate means of exercise for individuals with spinal cord injury or lower limb disability (Hicks et al. 2003; Valent et al. 2008), particularly with the recent increase in the profile of Paralympic and disability sport (Goosey-Tolfrey and Tolfrey 2004; Goosey-Tolfrey et al. 2006; Smith et al. 2006). Arm-cranking has also been used as an appropriate mode for assessing upper-body trained able bodied athletes (Tesch 1983; Driss et al. 1998; Hubner-Wozniak et al. 2004; Pearson et al. 2007; Zagatto et al. 2008), including America's Cup sailors (Pearson 2003; Pearson et al. 2005; Bernardi et al. 2007b). Upper body exercise (arm-cranking) has been found to elicit ~ 70% of the maximal aerobic power achieved during lower body exercise (cycling) in untrained participants (Bergh et al. 1976; Sawka et al. 1982; Pandolf et al. 1984; Martin et al. 1991). Upper body peak power appears to range from 50% less than the lower body, up to just 15% less, depending on upper body training and competition status (Zagatto et al. 2008; Hubner-Wozniak et al. 2004). These differences in performance are due to a range of anatomical, physiological and biomechanical factors that distinguish upper body from lower body exercise, which will be considered in the first part of this section of the review. Many of the differences between the arms and the legs may be attributed to the relative infrequent use of the arms compared to the legs during daily activities and that the arms are not load bearing limbs. Hence, arm muscle quantity and quality may be 'underdeveloped' in untrained individuals (Turner et al. 1997). Therefore this review tries to draw upon data from upper body trained populations where possible, whilst also recognising that evidence from untrained individuals may highlight underlying differences between the upper body and lower body musculature.

2.1.3.1 *Anatomical and Morphological Considerations*

Leg muscle volume is on average ~ 5 fold greater than arm muscle volume in untrained individuals (6300 *vs.* 1200 cm^3) (Stahn et al. 2007). It is expected that this difference could be considerably less in upper body trained athletes. Both autopsy and biopsy studies have confirmed a greater proportion of type II muscle fibres in the arm than the leg muscles (Johnson et al. 1973b; Turner et al. 1997). Type II fibres in the arms have a lower total mitochondrial volume density than the legs (3.9 *vs.* 5.0%) (Turner et al. 1997), and a smaller capillary cross sectional area (Turner et al. 1997; Calbet et al. 2005), in addition to type II fibres having a lower oxidative, but higher glycolytic, enzyme activity compared to type I fibres (Stallknecht et al. 1998). These differences in the physiology of the fibre types have consequences for the metabolic and cardiovascular responses to upper body exercise.

2.1.3.2 *Cardiovascular Considerations*

In untrained individuals, at a given submaximal exercise power output, upper body work (arm-cranking) elicits a higher heart rate (Bevegard et al. 1966; Toner et al. 1990) and systolic and diastolic blood pressure (Bevegard et al. 1966), lower stroke volume (Toner et al. 1990) and greater peripheral resistance (Stenberg et al. 1967) than lower body exercise (cycling). In addition, at the same VO_2 as leg cycling, upper body exercise has been found to result in greater physiological stress, rate of perceived exertion (RPE; Borg 1982) and heart rate (Pandolf et al. 1984; Leicht et al. 2008).

A lower oxygen extraction capacity has been reported in the arms of both untrained individuals (Volianitis and Secher 2002), and well trained athletes (Calbet et al. 2005) compared with the legs. This is probably due to a shorter blood transit time and smaller diffusion area in the arms than legs (Calbet et al. 2005). Even though oxygen diffusion is considerably greater in upper body trained athletes compared with healthy individuals (Volianitis et al. 2004), arm muscle oxygen extraction remains lower than that of leg muscle in elite cross-country skiers, despite high levels of upper body training (Calbet et al. 2005). In addition, the smaller active muscle mass of upper body exercise has cardiovascular consequences; it provides reduced muscle pump activity, and thus smaller venous return, and greater peripheral resistance that elevates blood pressure (Stenberg et al. 1967).

2.1.3.3 *Metabolic Considerations*

There is evidence to suggest catecholamine and blood lactate thresholds are lower for arm-cranking than cycling (Schneider et al. 2000). During arm-cranking at relatively low intensities the release of epinephrine stimulates the onset of muscle glycogenolysis via the activation of phosphorylase (Chasiotis 1988), which leads to an earlier onset of lactate production (Aminoff et al. 1998; Schneider et al. 2000; Van Hall et al. 2003). Congruently, several studies have reported higher rates of lactate production in the arms (arm-cranking) compared to the legs (cycling) at the same relative workloads (Aminoff et al. 1998; Schneider et al. 2002). The relatively low muscle oxidative capacity of the upper body due to the anatomical differences described above, and the greater proportion of type II muscle fibres and their earlier recruitment during upper body work (Bigland and Lippold 1954; Sawka 1986; Kang et al. 1997), may explain the earlier anaerobic contribution and lactate response of arm-cranking.

Arm muscle has been found to release more lactate per active muscle mass than leg muscle in both untrained participants (Ahlborg and Jensen-Urstad 1991) and elite cross-country skiers (Van Hall et al. 2003). In addition, Van Hall et al. (2003) found arm muscle to have a lower ability to utilise lactate than leg muscle during moderate to high intensity activity (Van Hall et al. 2003). These findings have been attributed to differences in muscle fibre type between the arms and legs; with the rate of lactate production greater in fast-glycolytic (type II) fibres, and the uptake and oxidation greater in slow-oxidative (type I) fibres.

2.1.3.4 *Biomechanical Considerations*

Upper and lower body ergometry differ in freedom of movement available. During cycling, hip, knee and ankle flexion and extension are performed in one plane of movement and the trunk remains relatively fixed, due to being seated. Whereas during arm-cranking the wrist, elbow and shoulders move in different planes, and the trunk is unrestricted, which facilitates greater trunk movement and requires more stabilisation (Toner et al. 1983). This greater freedom of movement results in larger variations in the movement strategy/technique employed by individuals, and thus also the degree and pattern of muscle recruitment (Calbet et al. 2005). During leg cycling the dominant phase of movement and force generation is the push phase (with the major force component vertically downward), where the weight of the limb and to a lesser extent the trunk can be utilised. Whilst there appear to have been no measurements of the unilateral power profile during a revolution of arm-cranking the dominant phase of the movement is also considered to be the push phase (with the major force component horizontally forwards). As the crank handles at this point of the arm-cranking revolution are above (sitting) or at a similar height (standing) to the centre of mass there is little opportunity to apply body mass to the movement. These biomechanical differences may explain the significantly lower mechanical efficiency of arm-cranking compared to cycling (Kang et al. 1997).

2.1.4 *Standing Arm-crank Ergometry*

Standing arm-cranking has been used to train and evaluate upper body athletes, for example wrestlers and javelin throwers (Hubner-Wozniak et al. 2004; Bouhlel et al. 2007), and is also becoming increasingly popular in the health and fitness industry with the recent launch of 'Kranking®' fitness classes, as the upper body equivalent to 'Spinning®' (Finnegan 2008). Whereas seated arm-cranking is an important exercise for disabled and wheel chair athletes, as well as for sports such as kayaking, where the athlete is seated, standing arm-cranking may be a more functional activity for a wider range of sports applications. As opposed to seated arm-cranking, where the involvement of the lower limbs is restricted, during standing arm-cranking there is more potential for the proximal kinetic chain to generate force. America's Cup grinding is essentially standing arm-cranking, hence this mode of ergometry is highly specific to the activity of the athletes in this sport.

To date the majority of research has been performed during seated arm-cranking that restricts 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; Vrijens et al. 1975; Mercier et al. 1993; Bernardi et al. 2007b) and peak power (Vandewalle et al. 1989; Driss et al. 1998; Hubner-Wozniak et al. 2004; Bouhlel et al. 2007; Pearson et al. 2007) present in the literature. Surprisingly, the one study to compare standing and seated arm-cranking, found no difference in the cardiorespiratory response, although a higher work load was evident (13%) during standing arm-cranking (Vokac et al. 1975). The higher peak power output values reported during standing compared to seated arm-cranking appear to indicate a greater ability for power production when standing (Table 2.5).

2.1.5 *Physiological Capacity during Arm-cranking/Grinding*

The first indication of the physical status of America's Cup sailors was by Bauer (1986), who reported that a *bowman* training for the 26th America's Cup had a treadmill VO_{2max} of 61 $ml \cdot kg^{-1} \cdot min^{-1}$ (Bauer 1986). A few subsequent studies have evaluated the maximal oxygen uptake of America's Cup crews during the much more appropriate exercise mode of arm-cranking (Lambert and Lelguen 2001; Bernardi et al. 2007b). However there remains little data available in the literature on the physiological or performance characteristics of America's Cup athletes, hence comparison to other upper body athletes is informative.

2.1.5.1 *Upper body Aerobic Power*

The lower aerobic power (~70%) of the upper body in untrained individuals appears to be due to peripheral factors including a smaller active muscle mass with limited oxidative capacity (Pandolf et al. 1984; Sawka 1986). The marked difference in cardiovascular response and aerobic power between upper and lower body exercise in untrained participants (Sawka et al. 1982; Pandolf et al. 1984) is not as clear in well trained athletes. In athletes, any differences seem to depend largely on the nature of exercise performed (Secher et al. 1974). Well trained upper body athletes have smaller differences between upper and lower body VO_{2peak} (~12%) (Secher et al. 1974; Seals and Mullin 1982). In fact, some upper body trained athletes (swimmers) appear to have greater VO_{2peak} during arm-cranking than cycling (Secher et al. 1974). Hence, it is not uncommon for well trained upper body athletes (such as swimmers, rowers, kayakers and America's Cup sailors) to have high arm-crank VO_{2peak} values, greater than 4.0 $L \cdot min^{-1}$ (Table 2.3) (Secher et al. 1974; Tesch 1983; Mercier et al. 1993; Bernardi et al. 2007b). The high aerobic power of these athletes seems to be due to their increased arm muscle mass, as well as elevated vascular conductance and diffusion capacity for oxygen compared with untrained participants (Secher and Volianitis 2006), supporting an enlarged regional vascular capacity. With the substantial variations in VO_{2peak} depending on the activities performed by the athlete, it is clear that in order to determine maximal oxygen uptake, the mode of testing should be closely related to the actual activities performed by the athlete.

With the relatively smaller muscle mass of the upper limbs, it has been suggested that maximal oxygen uptake testing should be short enough to avoid local fatigue (Sawka et al. 1983a; Goosey-Tolfrey et al. 2006), hence discontinuous protocols have been suggested (Washburn and Seals 1983). However, neither the duration (5 to 7 min *vs.* 14 to 19 min), nor the mode of testing (continuous *vs.* discontinuous) seems to effect VO_{2peak} during maximal arm-cranking (Washburn and Seals 1983). Furthermore, similar results have been found between ramp and step protocols (Smith et al. 2004). On the other hand, crank rate has been shown to affect VO_{2peak} (Sawka et al. 1983a; Smith et al. 2001; Smith et al. 2007), with constant crank rates of between 70 and 80 rpm resulting in significantly greater VO_{2peak} than slower crank rates (Sawka et al. 1983b; Smith et al. 2001).

Table 2.3 Peak oxygen uptake of athletes in different sports during arm-cranking

Study	Sport	Level	n	VO_{2peak} [L·min^{-1}]
Secher et al. 1974	Swimming	Elite	1	4.73
Mercier et al. 1993 *	Swimming	Competitive	8	4.38
Secher et al. 1974	Rowing	Elite	6	4.35
Tesch 1983	Kayak	Elite	5	4.30
Bernardi et al. 2007b *	America's Cup sailing	Competitive	16	4.13
Holmberg et al. 2006	Cross-country skiing	Elite	11	3.98
Vrijens et al. 1975 *	Kayak	Elite	5	3.95
Seals & Mullin 1982	Sailing	Competitive	12	3.36
Secher et al. 1974	Kayak	Elite	2	3.22
Seals & Mullin 1982	Swimming	Competitive	11	3.22
Forbes & Chilibeck 2007	Kayak	Competitive	10	3.14
Seals & Mullin 1982	Wrestling	Competitive	10	3.10
Horswill et al. 1992	Wrestling	Elite	14	3.01
Seals & Mullin 1982	Gymnastics	Competitive	10	2.82
Swaine & Winter 1999	Swimming	Competitive	12	2.40
Jemni et al. 2006	Gymnastics	Elite	12	2.20
Goosey-Tolfrey et al. 2008	Wheelchair athletes	Elite	8	1.48
Goosey-Tolfrey et al. 2006	Quadriplegic games players	Elite	8	0.96

** Standing arm-crank ergometry*

The only study to report aerobic power in America's cup sailors during arm-crank ergometry found a mean VO_{2peak} for the crew of 16 athletes to be 47 ml·kg^{-1}·min^{-1}, with *bowmen* reportin g the highest relative values (52 ml·kg^{-1}·min^{-1}) (Table 2.4). The high relative VO_{2peak} found for *bowmen* is thought to be a result of their activities on-board being largely continuous in nature. Interestingly, the high peak power values reported by Bernardi et al. (2007) for the *grinders*, are similar to those found in competitive cyclists.

Table 2.4 Physiological characteristics of America's Cup sailors during incremental arm-cranking to exhaustion (*Bernardi et al.* 2007b)

	VO_{2peak} [L·min^{-1}]	VO_{2peak} [ml·kg^{-1}·min^{-1}]	Peak Power [W]
Grinders (n=6)	4.6	45	393
Bowmen (n=2)	4.0	52	350
Trimmers (n=5)	3.8	47	334
All Others (n=3)	3.6	46	280

2.1.5.2 *Peak Power*

Similar differences to aerobic power have been found in peak power between the upper body (arm-cranking) and the lower body (cycling). The large variations in the proportion of upper body compared to lower body power are dependent on the exercise activities and the mode of training performed by the athlete. Elite table tennis players have more than 50% difference in upper body to lower body power (Zagatto et al. 2008), whereas elite wrestlers have as little as 15% difference in peak power output (Hubner-Wozniak et al. 2004). Other athletes, such as elite gymnasts and competitive javelin throwers have ~35% greater leg power (Jemni et al. 2006; Bouhlel et al. 2007). Swimmers have been found to have amongst the highest relative upper body power with values of 11.5 W·kg^{-1} (828 W) during standing arm-cranking (Mercier et al. 1993), and during seated arm-cranking, gymnasts achieved upper body power of 10.6 W·kg^{-1} (700 W, Table 2.5) (Jemni et al. 2006).

To date, the highest reported upper body peak power was 929 ± 100 W for a cohort of elite America's Cup *grinders* performing standing arm-cranking (Pearson et al. 2007). Although impressive, this is still considerably less than the highest individual power output reported in elite track sprint cycling (2282 W) (Gardner et al. 2005). In addition, Pearson et al. (2007) found a 17% difference in peak power between grinding forwards and backwards (Pearson et al. 2007), indicating that grinding forwards is considerably more effective. More detailed physiological assessment of America's Cup athletes during relevant activity, primarily grinding, is required to more clearly describe the characteristics of this cohort of elite athletes, and any differences due to crew position.

Table 2.5 Peak power output of athletes in different sports during arm-cranking

Study	n	Arm-cranking	Sport	Level	PPO [W]
Pearson et al. 2007	6	Standing	America's Cup	Elite	929
Mercier et al. 1993	8	Standing	Swimming	Competitive	828
Hubner-Wozniak et al. 2004	10	Standing	Wrestling	Elite	732
Bouhlel et al. 2007	10	Standing	Javelin	Competitive	720
Driss et al. 1998	18	Standing	Volleyball	Competitive	719
Vandewalle et al. 1989	18	Standing	Swimming	Competitive	718
Jemni et al. 2006	12	Seated	Gymnastics	Elite	701
Horswill et al. 1992	14	Seated	Wrestling	Elite	537
Aziz et al. 2002	13	Seated	Waterpolo	Elite	479
Aschenbach et al. 2000	8	Seated	Wrestling	Competitive	370

2.1.5.3 *Torque- and Power-Velocity Relationships*

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). Similar results have been found during arm-cranking (Vandewalle et al. 1989; Vanderthommen et al. 1997). The determination of the optimum pedalling rate for peak power, as determined from the maximum of the power-velocity curve (128 rpm), has been used to determine optimal gearing for elite track sprint cycling (Gardner et al. 2007). Interestingly, the optimum crank velocity, determined from the predicted maximum crank velocity, reported by junior swimmers during arm-cranking (~127 rpm) was similar to that of elite cyclists (Vandewalle et al. 1989), although further investigation is required to confirm these findings.

The peak velocity of grinding during America's Cup racing has been reported to be between 120 and 150 rpm (Bernardi et al. 2007b), but the optimum velocity for power production and the nature of the torque-velocity and power-velocity relationships of elite upper body trained athletes during standing arm-cranking are largely unreported. This may have an important bearing on the selection of gear ratios and the optimisation of power production during America's Cup sailing.

2.1.6 *Influence of Crank Configuration on Performance*

Since power is the product of force and velocity, changes to muscle length, muscle moment-arm length and the torque-velocity relationship will affect power output (Hoy et al. 1990; Too and Landwer 2000). The manipulation of joint angles affects muscle length which can change the muscle force produced, and taken together with a change in muscle moment-arm, will affect torque and angular velocity and therefore power production (Hoy et al. 1990). In cycling, the manipulation of joint angles, through changes in the structure of bicycle components, has been shown to influence performance (Hamley and Thomas 1967; Too and Landwer 2000; Martin and Spirduso 2001). For example, changes in seat height and cycle crank lengths directly affect hip and knee joint angles, lower limb muscle lengths, the range of motion and angular velocity of the joints, and thus cycling performance (Too and Landwer 2000). Changes in hip angle as a result of posture (sitting upright or leaning forward) also significantly influences power output during cycling (Welbergen and Clijsen 1990; Too 1994). The optimal crank length for maximum power production has been reported to be 20% of leg length (Martin and Spirduso 2001) and the optimal seat height appears to be 109% of inseam length (ischium to foot) (Hamley and Thomas 1967). It seems highly likely therefore that changes to the configuration of arm-crank ergometry, specifically crank length and crank-axle height, could also affect performance. Given the angle-torque and torque-velocity relationships of human muscle function, there is a clear rationale for how interventions that effect upper extremity joint range of motion and angular velocities may influence arm-cranking performance. The only study to determine the influence of crank length on arm-crank ergometry, compared the configurations of two different ergometers; a standard arm ergometer (crank length, 140 mm) and a modified leg ergometer (crank length, 170 mm) (Kang et al. 1999). The arm ergometer resulted in greater cardiorespiratory and metabolic responses than the modified leg ergometer, however it is not known if these results were due to the difference in crank length or the difference in diameter and weight of the flywheels. The majority of arm-cranking studies have used modified cycle ergometers and substituted pedals for handles (Vokac et al. 1975; Bohannon 1986; Vandewalle et al. 1989; Mercier et al. 1993; Bouhlel et al. 2007). Hence the crank length adopted by most arm-crank studies is 170 to 175 mm, which may not be ideally suited to the upper limbs.

On IACC version 5 yachts the typical crank length and crank-axle height are 250 and ~850 mm, respectively (Bernardi et al. 2007b; Pearson et al. 2007). Considering the advancement in yachting technology evident in the America's Cup, it is surprising that there seems to be no scientific rationale for the crank length and crank-axle height of the grinding pedestals. The height of the grinding crank-axle appears to have been largely determined by other aspects of yacht design, such as the height of the boom and aerodynamics, without an understanding or consideration of the effects of crank height on grinding performance.

2.1.7 *Lower Limb Contribution to Upper body Exercise*

For most upper body open kinetic chain sporting activities (e.g. tennis and throwing), the majority of kinetic energy and force is derived from the larger proximal body segments, such as the upper leg, back and trunk, and transferred through the body segments to the terminal link, the hand (Figure 2.4) (Kibler 1998).

The contribution of the lower limbs to upper limb force generation has been studied in a number of sports activities, including the tennis serve and cross-country skiing double-poling (Holmberg et al. 2006; Girard et al. 2007). Tennis serve performance (accuracy and speed) was significantly affected by restricted knee joint motion, when the knee joint was splinted to prevent flexion and extension, confirming the importance of the lower limbs in force generation (Girard et al. 2007). In addition, restricting knee joint mobility during submaximal double-poling in a group of elite cross-country skiers elicited a higher blood lactate concentration and heart rate response with no difference in oxygen consumption at the same work load (Holmberg et al. 2006). These findings suggest that the dynamic use of the lower limbs may benefit performance by decreasing the cardiovascular and metabolic stress compared to upper body exercise alone. Moreover, in a study with various different proportions of arm-cranking and cycling, cardiovascular strain (heart rate and stroke volume) were found to reduce when slight involvement of the lower body (cycling) was added to upper body exercise (arm-cranking) (Toner et al. 1990). The authors suggested that the engagement of the lower body during upper body exercise may attenuate the strain placed on the cardiovascular system by the added muscle pump activity of the legs facilitating venous return (Toner et al. 1990). In addition, Van Hall and colleagues found the arm muscles of elite cross-country skiers to have a lower ability to utilise lactate and a higher ability to produce lactate during moderate to high activity (Van Hall et al. 2003). The authors attributed these differences to the contrasting muscle fibre type composition of the arms and legs, with increased rate of lactate production occurring in type II fibres and greater uptake and oxidation in type I fibres. These results may also suggest that activation of the leg muscles during arm exercise may assist in lactate clearance. Taken together, it is evident that the use of the legs during upper limb exercise may increase performance and reduce physiological stress.

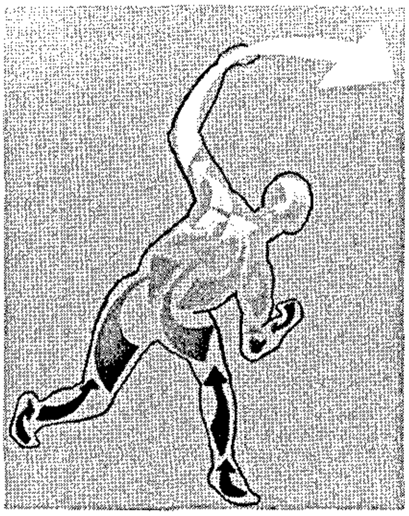


Figure 2.4 Illustration of the transfer of kinetic energy and force from the base of support (the feet), to the terminal link (the hand) during a tennis serve (Kibler 1998)

2.1.8 *Grinding and Injury Risks*

America's Cup sailors are at risk of injury (Allen 1999; Allen 2005; Neville et al. 2006), similar to that of other elite non-contact team sports (Hootman et al. 2007). The anatomical locations most frequently injured are the lumbar spine (range: 12-30%) and shoulder regions (15-18%) (Allen 1999; Allen 2005; Neville et al. 2006), while the positions at greatest risk of injury seem to be the *bowmen* (3.2 / 1,000 h sailing) and *grinders* (3.1 / 1,000 h sailing) (Neville et al. 2006). Chronic injuries (predominantly tendinopathies and neuropathies) were found to be largely attributed to high repetition activities, such as grinding (Neville et al. 2006). Poor grinding technique has also been suggested as a possible risk factor for lower back and shoulder injuries (Neville et al. 2003; Allen 2005; Molloy et al. 2005), particularly if there is an overreliance on the upper extremity as the force generator. In addition, the majority of activities performed during America's Cup sailing, such as grinding, require forward flexion of the spine with repetitive lumbar rotation (see Figure 1.2), and often with high loads (Allen 2005; Neville et al. 2006). This posture places excessive strain on the lumbar spine and thus may increase the risk of lower back injury (Bono 2004). Allen (2005) suggested that appropriate ergonomics of the grinding pedestals may reduce this potential risk of injury and therefore warrants investigation.

2.2 Thermoregulation

The majority of the chemical energy consumed by human metabolism is converted to heat. During exercise, metabolic rate increases substantially causing dramatic increases in heat production and several complex heat loss mechanisms attempt to prevent excessive heat gain. Hot environmental conditions add to the thermal strain imposed by exercise, as the transfer of heat from the body to the environment is reduced, further promoting the rise of core temperature (hyperthermia). During prolonged exercise in the heat, sweating in order to attenuate the rise in core temperature by evaporation, leads to significant fluid losses (hypohydration) that may compromise ongoing thermoregulation. Both hyperthermia and hypohydration can lead to significant performance decrements and in extreme cases, heat illness. As the intensity of exercise during America's Cup yacht racing is relatively high, and it is usually sailed during the summer months in hot and humid environmental conditions, compromised performance is likely. Neville et al. (2006) reported a number of incidents of heat illness and dehydration during the 31st America's Cup, similarly, Miller (1989) reported a risk of dehydration during training for the 26th America's Cup.

The human body is considered to be in a thermo-neutral state at approximately 37 ± 1°C (Benzinger 1969). A rise in body temperature greater than ~1°C above the resting core body temperature, results in hyperthermia characterised by an increased strain on the cardiovascular system in an effort to reduce body heat (Cheung 2007). To maintain a tolerable level of body temperature and prevent the progressive storage of body heat, an efficient means of heat dissipation is required. This occurs via a complex thermal system that transports excess heat from deep body tissues to the skin surface where it is lost to the environment. A temperature gradient between deep tissues and the blood enables heat to be transferred to the blood, which is carried to the skin surface for dissipation of heat.

Heat is lost to the environment by the processes of conduction, thermal radiation, convection and the evaporation of water from the respiratory tract and the skin. The loss of heat via conduction is minimal, unless one is submerged in water (Brotherhood 2008). Radiative heat is emitted by the body as infrared radiation, but can also be gained by exposure to direct sunlight or reflective heat off water or reflective surfaces. Convection occurs between the body and the surrounding air (Nielsen et al. 1988). The overall heat loss through conduction, radiation and convection largely depends on the temperature gradient between the skin surface and the environment, and is therefore relatively small in cooler environments (Webb 1995). As the ambient temperature rises, the gradient declines and at approximately 33°C the gradient is reversed and heat is gained by the body through conduction, radiation and convection (Saunders et al. 2005). Therefore evaporation, primarily from perspired sweat on the skin surface, becomes the main means of heat loss in hot environmental conditions. The main factors contributing to the regulation of body temperature are summarised by the following heat balance equation (Cheuvront and Haymes 2001):

Heat storage = Metabolism ± Radiation ± Convection ± Conduction - Evaporation

2.2.1 *Performance and Thermoregulation during Exercise in the Heat*

Fatigue, as defined by the inability to maintain a required power output during exercise, occurs as a result of several complex factors including; metabolic by-products, finite energy stores, thermoregulatory stress and reduced motor drive (Hargreaves 2008), all of which are influenced by the intensity and duration of exercise. During exercise, metabolic heat production is elevated leading to an increase in core temperature. If the exercise takes place in a hot and humid environment it has been surmised that the rise in body temperature during exercise is the primary cause of fatigue (Adams et al. 1975; Gonzalez-Alonso et al. 1999; Galloway and Maughan 2000).

2.2.1.1 *Hyperthermia and Critical Core Temperature*

The human body has an upper limit core temperature, where biological processes are compromised, performance deteriorates and heat illness becomes a risk. It is widely accepted that the human body reaches this "critical" core temperature at 39 to 41°C (Nielsen et al. 1993; Gonzalez-Alonso et al. 1999; Galloway and Maughan 2000; Morris et al. 2005).

In laboratory studies, fatigue seems to occur at critical core temperature regardless of exercise intensity or initial body temperature. Gonzalez-Alonso et al. (1999) found that fatigue occurred at a core temperature of 40.1°C during cycling to exhaustion in hot conditions and exercise capacity (measured as the time to exhaustion) was dependent upon the initial starting temperature and the rate of heat storage (Gonzalez-Alonso et al. 1999).

In a review of laboratory and field studies, the majority of all subjects reached exhaustion at a core temperature of 38.6 and 39.5°C, respectively (Sawka et al. 2001a), suggesting that subjects are able to tolerate greater heat gain in the field compared with laboratory studies. This implies that laboratory studies may lack ecological validity, and that field studies are required to fully understand the thermoregulatory demands and consequences of outdoor sports.

2.2.1.2 *Exercise Duration and Intensity*

The influence of hot environmental conditions on endurance performance has been extensively studied during steady state exercise such as cycling (Galloway and Maughan 2000; Tucker et al. 2004; Tucker et al. 2006) and running (Gonzalez-Alonso et al. 1999). Pugh et al. (1967) reported a mean T_{rec} of 39.0°C (range: 36.7 to 41.1°C) in 47 runners at the end of a marathon, with the first four runners, and therefore the highest exercise intensities, leading to the highest core temperatures (Pugh et al. 1967). More recently after 15 min of high intensity (93% of VO_{2max}) treadmill running at a constant ambient temperature (29°C), oesophageal temperature (T_{oes}) was elevated by 2.2°C above baseline, compared with a 1.0°C rise after moderate intensity (70% of VO_{2max}) exercise (Kenny and Niedre 2002). Therefore the rise in core temperature is strongly influenced by the rate of metabolic heat production. In prolonged exercise, the rate of body heat production is therefore largely dependent on the intensity of exercise.

The effects of the heat on intermittent exercise, similar to that performed in 'stop-and-go' team sports is less well understood, largely due to the difficulty in measuring performance, the random nature of the exercise, and the different activity patterns in each specific sport. Drust et al. (2000) found little evidence to indicate any difference in the physiological responses between intermittent and steady state exercise at the same mean power output, suggesting that the effect of heat was similar (Drust et al. 2000). During intermittent exercise the majority of studies have found substantially reduced performance, as measured by the distance run in hot compared with moderate conditions (Morris et al. 1998). This was attributed to a greater rate of rise in core temperature during the hot trial. Similar results have been found in repeated high intensity exercise; where an 11% decrease in mean power output occurred in repeated 15 s maximal sprint cycle performance with hyperthermia (39.5°C) (Drust et al. 2005). In contrast, during maximal exercise (< 15 s), the influence of any rise in core temperature seems negligible, due to the short duration of the activity (Cheuvront et al. 2006; Judelson et al. 2007a; Judelson et al. 2007b).

With upper body exercise resulting in greater cardiorespiratory and metabolic strain than lower body exercise (Sawka 1986), it could be expected that it would also elicit greater heat storage. However, at the same absolute intensity (VO_2, 1.6 $L\cdot min^{-1}$), core temperature and sweat responses were similar for arm-cranking and cycling, whereas thermoregulatory responses were lower during the same relative arm-cranking intensity (Sawka et al. 1984). These results suggest that thermoregulatory responses are dependent on the absolute metabolic intensity rather than the nature of activity.

2.2.1.3 *Cardiovascular Consequences*

The need to transfer heat to the skin increases the demand on the cardiovascular system and cardiac output increases to service both metabolic and cutaneous thermal requirements in the heat. The demand for blood in both the exercising muscles and at the skin surface reduces the central blood volume and cardiac filling pressure (Montain and Coyle 1992), which reduces stroke volume. In order to preserve cardiac output heart rate is increased resulting in a "cardiovascular drift" to compensate for the reduced stroke volume (Montain and Coyle 1992). At the point when near maximum heart rate is reached, cardiac output peaks and blood flow to the skin is reduced in order to maintain central blood pressure (Adams et al. 1975; Patterson et al. 1994; Gonzalez-Alonso et al. 1999). This, in turn, compromises heat dissipation and causes core body temperature to rise further. The actual mechanisms regulating cardiac output maintenance during exercise in the heat are complex, multifactorial (Gonzalez-Alonso et al. 1999) and outside of the scope of this report.

2.2.1.4 *Metabolic Changes during Hyperthermia*

The rate of muscle glycogen degradation and concomitant lactate accumulation are faster during exercise in the heat (Febbraio et al. 1994; Morris et al. 2005); but as glycogen stores are not depleted at exhaustion following intermittent high intensity exercise, it is unlikely that these metabolic changes are the cause of fatigue (Maxwell et al. 1999; Morris et al. 2005). Nevertheless, carbohydrate ingestion during exercise in the heat appears to prolong time to fatigue (Below et al. 1995; Galloway and Maughan 2000; Carter et al. 2003) and attenuate decreases in skill performance (Vergauwen et al. 1998); the mechanisms for which are currently unclear. In most circumstances though, high core temperature seems to be the critical factor for fatigue in the heat.

2.2.1.5 *Central Fatigue Mechanisms*

An alternative more recent model suggests that fatigue during prolonged exercise (continuous or intermittent) in the heat, may not be due to critical core temperature *per se*, but rather to the anticipatory regulation of cellular preservation for the avoidance of catastrophe (Marino 2004; Noakes et al. 2004). During self-paced running (Noakes 2007a) or cycling (Tucker et al. 2004), speed (or power output) seems to be regulated by a sensational feedback of the environmental conditions and the known exercise duration in order to anticipate the avoidance of catastrophe. Numerous neural mechanisms occur in the brain and central nervous system (CNS) during exercise in the heat which may provide some evidence to this "central governor model of exercise regulation" (Noakes et al. 2001; Noakes et al. 2005). There is a decrease in the electrical activity of the brain, which is highly correlated with the rise in core temperature (T_{oes}) (Nybo and Nielsen 2001a), and associated with the rating of perceived exertion (RPE) (Nybo and Nielsen 2001b). It has been suggested that exercise intensity is controlled by the perception of the rate of heat storage in order to avoid excessive heat accumulation and catastrophic elevation of core body temperature (Tucker et al. 2006). Furthermore, since RPE is the only variable that always seems to be at or near maximum at the time of exhaustion during all forms of exercise (Noakes 2007b), it may be that a reduction in motivational drive to continue exercise under thermoregulatory strain has the greatest influence on fatigue.

2.2.1.6 *Core Temperature Measurement*

Core body temperature refers to the deep central temperature of the body, however, it is not consistent and variations occur throughout the organs of the body. Core temperature has been measured at different sites and by various methods including; rectal, oesophageal, oral, auxiliary, aural (tympanic) and more recently intestinal. Oesophageal, rectal, and intestinal temperatures provide the most valid and reliable measures of core body temperature (O'Brien et al. 1998; Lee et al. 2000; Gant et al. 2006; Byrne and Lim 2007;

Casa et al. 2007). Oesophageal temperature (T_{oes}) is considered to be the most accurate measure of core temperature due to the proximity to the left atrium. However, this technique causes discomfort during exercise and is temporarily influenced by the ingestion of fluids. Rectal temperature (T_{rec}) has been the most widely used index of core temperature in exercise studies, but this method is limited to steady-state exercise due to its' slow response (Byrne and Lim 2007). Intestinal temperature (T_{int}) has recently gained popularity in field research, as it is simple to use and less invasive than T_{oes} and T_{rec} (Lim et al. 2008). T_{int} has only been measured during a limited number of studies of intermittent team sports training (American football (Godek et al. 2006)) and competition (soccer (Edwards and Clark 2006)), especially at elite level. A number of validity studies have confirmed the accuracy of T_{int} in a range of exercise and environmental conditions (O'Brien et al. 1998; Gant et al. 2006; Casa et al. 2007). The reliability of T_{int} is dependent on the timing of the sensor ingestion prior to measurement, ensuring that it travels beyond the stomach and is not influenced by the ingestion of fluids or solids (Lee et al. 2000), but also avoiding expulsion (O'Brien et al. 1998). Transit durations have been reported as ranging from 8 h to 5 days (Lee et al. 2000). Lee et al. (2000) recommended that the sensors be ingested approximately 6 h prior to measurement to avoid temperature fluctuations and the risk of expulsion (Lee et al. 2000).

2.2.1.7 *Skin Temperature Measurement*

Cutaneous vasomotor control is important in thermoregulation and is influenced largely by skin temperature (Regan et al. 1996; Savage and Brengelmann 1996), and therefore by underlying muscle tissue temperature and the environmental conditions. In order to conserve body heat, vasoconstriction occurs at skin temperatures below thermoneutral (~33°C) (Hardy et al. 1965), whereas in hot conditions or during exercise, when skin temperature increases (> 33°C), cutaneous vasodilation occurs to promote heat loss (Johnson et al. 1973a). Regional differences in skin temperature are largely dependent on the nature of exercise performed (Sawka et al. 1984), exposure to environmental conditions (Regan et al. 1996) and the distribution of clothing worn (Stephenson et al. 2007). Numerous body surface area (BSA) weighted formulae have been suggested for the determination of mean skin temperature (Jirak et al. 1975), with the following 4-site formula proposed by Ramanathan (1964) commonly accepted in field studies (Ramanathan 1964):

Mean skin temperature $= (0.34*T_{chest}) + (0.15*T_{forearm}) + (0.33*T_{thigh}) + (0.18*T_{calf})$

2.2.2 *Hypohydration and Fluid Balance*

Exercise in hot environmental conditions results in body fluid loss through evaporation, as sweat is secreted on the skin surface to assist in the dissipation of heat. If insufficient fluids are consumed to counter the fluid lost via sweating, dehydration occurs. Excessive sweat losses lead to plasma hyperosmolality, as sweat is hypotonic relative to plasma (Sawka et al. 1985), and reduce blood plasma volume which is detrimental to central blood pressure and cardiac output. In order to protect blood volume and maintain cardiac output, and therefore blood flow to the working muscles and skin, fluids are redistributed from the intracellular to extracellular compartments (Nose et al. 1988; Sawka et al. 2001b). As blood becomes hypovolaemic, the ability to maintain central venous pressure and adequate cardiac output to support metabolism and thermoregulation during exercise is compromised and skin blood flow and sweat rate are reduced (Sawka 1992). An early study by Adams et al. (1975) attributed running fatigue in hot environmental conditions to thermoregulatory overload as a result of dehydration induced attenuation of cutaneous blood flow (Adams et al. 1975).

2.2.2.1 *Prolonged Endurance Exercise and Hypohydration*

The effects of hypohydration on the cardiovascular response to prolonged endurance exercise has been well documented (Saltin 1964; Armstrong et al. 1985; Montain and Coyle 1992; Below et al. 1995; Gonzalez-Alonso et al. 1995), with as little as a 1-2% decrease in body mass effecting performance (Armstrong et al. 1985). For example, in well trained cyclists performance at 90% VO_{2peak} in hot conditions (32°C) was reduced by 31% after initially cycling for 60 min at a moderate intensity with restricted fluid intake (dehydration ~ 2% of body mass), compared with regular fluid intake (9.8 ± 3.9 min *vs.* 6.8 ± 3.0 min) (Walsh et al. 1994). Thus even moderate levels of dehydration may have a detrimental effect on prolonged exercise performance in hot conditions. However, in temperate conditions, Sharwood and colleagues (Sharwood et al. 2004) reported fluid losses as high as 10% of body mass during an Ironman triathlon with little detrimental effect on 'health' or performance. Similarly, Pugh et al. (1967) reported a 6.7% loss of body mass by the winner of a marathon, which may indicate that for endurance running, a loss of body mass may compensate for reduced performance when dehydrated (Pugh et al. 1967). Taken together, the effects of hypohydration seem less critical in temperate compared with hot conditions (Sharwood et al. 2004; Oliver et al. 2007a), and it is the combined effect of dehydration and hyperthermia which seems to have the greatest effect on cardiovascular function. Gonzalez-Alonso (1998) showed that dehydration (4% of body mass) and hyperthermia (1°C increase in core temperature) independently reduced stroke volume (7 to 8%) and increased heart rate without compromising mean arterial pressure or cardiac output. However when dehydration was combined with hyperthermia, during prolonged cycling, the decrease in mean arterial pressure and stroke volume (20%) was substantial, resulting in a decline in cardiac output (Gonzalez-Alonso 1998). Hence, the physiological consequences of hypohydration during exercise seem to be exacerbated in the heat.

2.2.2.2 *Intermittent Exercise and Hypohydration*

The effects of hypohydration on intermittent exercise are less well understood than in prolonged endurance exercise. Maxwell et al., (1999) observed a 4% decrement in sprint performance during an intermittent maximal anaerobic running test (MART) after subjects were dehydrated by ~1.5% of body mass (Maxwell et al. 1999). Similar reductions in performance have been reported in other sport specific intermittent tests (e.g. LIST) conducted in hot conditions (30°C) (Morris et al. 1998). Decrements in performance during field studies are often difficult to quantify, particularly in team sports. Few field studies have accurately measured fluid loss during competition, particularly at elite level (see Table 2.6 for a review of fluid balance during various sports (Sawka et al. 2007)). In intermittent team sports, soccer has received the greatest attention, with the majority of research indicating mean sweat losses of approximately 0.7 - 1.3 $L{\cdot}h^{-1}$ during training (Maughan et al. 2004; Maughan et al. 2005; Shirreffs et al. 2005) and 1.2 - 1.6 $L{\cdot}h^{-1}$ during competition (Broad et al. 1996; Maughan et al. 2007b), with individuals varying between 0.4 and 3.2 $L{\cdot}h^{-1}$ (Shirreffs et al. 2006). Sweat loss seems to be independent of environmental conditions, with similar sweat rates reported in warm and cooler conditions, possibly as a result of self-adjustment in exercise intensity and clothing selection (Broad et al. 1996; Shirreffs et al. 2006; Maughan et al. 2007b). Similar losses have been reported during tennis training (~ 1.1 $L \cdot h^{-1}$, (Bergeron et al. 2006)) and indoor netball competitions (~ 1.0 $L \cdot h^{-1}$, (Broad et al. 1996)), with indoor basketball players experiencing slightly greater sweat losses (~ 1.6 $L \cdot h^{-1}$, (Broad et al. 1996)). Godek and colleagues recently reported considerably higher sweat losses (~ 2.1 $L \cdot h^{-1}$ with some athletes as high as 3.6 $L \cdot h^{-1}$) in both college and professional American football players during training (Godek et al. 2005b; Godek et al. 2006). These relatively high sweat losses appear to be related to the large body surface area (BSA) of these athletes; as after adjusting for BSA, their sweat rate was similar to cross-country runners training in the same environment (Godek et al. 2005a). There is currently little data available on fluid loss during sailing, with no reports in the published literature on big-boat sailing. Recently, Slater and Tan (2007) reported mean sweat losses of ~ 0.5 $L \cdot h^{-1}$ in amateur Dinghy sailors during competition (Slater and Tan 2007). However, the duration between pre- and post-sailing measurements was 5 h, despite a competition period being less than 2 h; therefore, the sweat rate during competition was probably considerably higher than that reported.

Table 2.6 Sweat rates, voluntary fluid intake and levels of dehydration in various sports. Adapted from (Sawka et al. 2007)

		Sweat Rate [L·h^{-1}]		Fluid Intake [L·h^{-1}]		Dehydration [% BM]	
Sport	**Condition**	**Mean**	**Range**	**Mean**	**Range**	**Mean**	**Range**
Waterpolo (Cox et al. 2002)	Training	0.29	[0.23-0.35]	0.14	[0.09-0.20]	0.26	[0.19-0.34]
	Competition	0.79	[0.69-0.88]	0.38	[0.30-0.47]	0.35	[0.23-0.46]
Basketball (Broad et al. 1996)	Training	1.37	[0.90-1.84]	0.80	[0.35-1.25]	1.00	[0.0-2.0]
	Competition	1.60	[1.23-1.97]	1.08	[0.46-1.70]	0.90	[0.2-1.6]
Netball (Broad et al. 1996)	Training	0.72	[0.45-0.99]	0.44	[0.25-0.63]	0.70	[+0.3-1.7]
	Competition	0.98	[0.45-1.49]	0.52	[0.33-0.71]	0.90	[0.1-1.9]
Soccer (Shirreffs et al. 2005)	Training	1.46	[0.99-1.93]	0.65	[0.16-1.15]	1.59	[0.4-2.8]
Soccer (Maughan et al. 2005)	Training	1.13	[0.71-1.77]	0.28	[0.03-0.63]	1.62	[0.87-2.55]
Soccer (Maughan et al. 2007b)	Competition	1.12	[0.55-1.51]	0.58	[0.05-1.46]	1.10	[+0.05-2.07]
American Football (Godek et al. 2005a)	Training	2.14	[1.10-3.18]	1.42	[0.57-2.54]	1.50	
Cross-country running (Godek et al. 2005a)	Training	1.77	[0.99-2.55]	0.57	[0.00-1.30]	0.97	
Dinghy Sailing (Slater and Tan 2007)	Competition	0.47	[0.37-0.56]	0.24	[0.15-0.34]	1.00	

Mean voluntary fluid intake during intermittent team sport exercise is usually from 0.5 to 1.0 L·h^{-1} (Broad et al. 1996; Godek et al. 2005b; Shirreffs et al. 2006; Maughan et al. 2007b; Zetou et al. 2008), equivalent to a replacement of ~ 40-60% of the fluid lost. Hence, mean dehydration is seldom > 2% of body mass in team sports. However, large individual variability occurs, with some team sport athletes experiencing dehydration > 3% of body mass during training (Godek et al. 2005a; Shirreffs et al. 2006), hence the American College of Sports Medicine recommendations for rehydration strategies to be individualised (Sawka et al. 2007). During prolonged sailing 88% of New Zealand Olympic class sailors reported symptoms of dehydration during one season (Mackie and Legg 1999), highlighting dehydration as a common problem in this sport. Dehydration has also been reported to occur during America's Cup yacht racing (Miller 1987; Neville et al. 2006).

During competition the replacement of fluid is often limited by the nature and regulations of the sport, with the majority of team sports (e.g. soccer, rugby and hockey) only allowing for fluid replacement during stoppages in play. Fluid replacement in competitive sailing is usually limited by the constraints of added weight and little space for storing fluids on the deck of the yacht (Slater and Tan 2007), hence sailors rarely carry adequate fluids (Mackie and Legg 1999; Slater and Tan 2007). However, in America's Cup yacht racing, sailors are able to carry sufficient fluids on-board without compromising technical weight restrictions.

2.2.2.3 *Maximal Exercise and Hypohydration*

Shorter duration exercise, such as a single repetition of peak power (vertical jump height) or peak force (isometric squat) do not seem to be effected by moderate hypohydration (up to 5% loss of body mass) (Judelson et al. 2007b). In addition, maximal efforts lasting 15 s (sprint cycle performance) do not seem affected by dehydration (3.5%) and moderate hyperthermia (1°C) when compared with euhydrated trials (Cheuvront et al. 2006). Whereas, performance in multiple-repetitions and sets of resistance exercise, decreased when subjects were dehydrated (2.5-5.0% of body mass) and moderately hyperthermic (38.5°C), compared with euhydration (Judelson et al. 2007a; Judelson et al. 2007b). In addition, Hickner et al. (1991) reported that performance during a 6 min arm-cranking protocol, similar to America's Cup grinding, deteriorated by 3.4% following a 3 day, 4.5% reduction in body mass (Hickner et al. 1991). Therefore it is concluded that a single bout of short-duration maximal exercise is not affected by hypohydration, although prolonged or repeated maximal exercise is significantly influenced by fluid loss.

Fluid balance is a measurement of the change in hydration status of an individual. Clearly any pre-exercise fluid deficit exacerbates the dehydration that occurs during exercise. Maughan et al. (2007) recently reported that 35% of the soccer players competing in an English Premier League Reserve game were dehydrated prior to the start of the game (>900 $mmol \cdot L^{-1}$ urine). Therefore, the measured level of dehydration after the game (~1.1%) would have been a considerable underestimate for the pre-game dehydrated athletes (Maughan et al. 2007b).

2.2.2.4 *Fluid Balance Measurement*

Although there is no clear definition or clinical symptoms of dehydration *per se*, it is usually determined as the percentage of body mass lost due to the acute loss of total body water (TBW) as a consequence of exercise, hypohydration, environmental conditions, illness or pharmacological intervention. The most common type of dehydration relating to exercise, is hypertonic dehydration, which is characterised by reductions in plasma volume, serum hyperosmolality (>300 $mmol \cdot kg^{-1}$) and serum hypernatraemia (sodium >145 $mmol \cdot L^{-1}$) (Weinberg and Minaker 1995). Various methods of determining fluid balance status (TBW) have been adopted, including changes in body mass, bioelectrical impedance, urine indices (volume, colour, osmolality, specific gravity) and serum indices (osmolality, sodium and haemoglobin concentration, haematocrit and specific hormone levels) (Shirreffs 2000; Oppliger and Bartok 2002; Armstrong 2005). As yet there is no consensus as to a single indicator of hydration status and the choice is usually dependent on the application or the equipment available. Urine osmolality has been recommended as a valid and relatively simple indicator of hydration status, with urine osmolality >900 $mmol \cdot L^{-1}$ indicating dehydration (Shirreffs and Maughan 1998). Urine specific gravity (as measured by refractometry) has been shown to be equally reliable and highly correlated (r^2=0.96) to urine osmolality, with values greater than 1.030 $g \cdot ml^{-1}$ indicating dehydration (Armstrong et al. 1998). The most commonly used indicator of dehydration is the acute change in body mass, which is a simple and reliable measure, particularly for the field-based practitioner (Maughan et al. 2007a). The National Athletic Trainers Association (NATA) position statement regarding fluid replacement recommends using the change in body mass, urine specific gravity and urine colour as indicators of hydration status (Casa et al. 2000). More recently the American College of Sports Medicine (ACSM) position statement on fluid replacement suggested the following first morning measurement as indices of dehydration (Sawka et al. 2007):

- Body mass loss > 2% of body weight
- Plasma osmolality > 290 $mmol \cdot L^{-1}$
- Urine specific Gravity > 1.020 $g \cdot ml^{-1}$
- Urine Osmolality > 700 $mmol \cdot L^{-1}$

2.2.3 *Electrolyte Balance*

During exercise a number of electrolytes are lost in sweat, most notably; sodium, chloride, potassium and magnesium. The concentration of each in sweat is variable, both between and within individuals and largely dependent on the level of aerobic fitness, rate of secretion, diet, hydration status and the degree of heat acclimation. The sweat electrolyte concentration may also be related to specific activities, such that runners have been shown to have lower sodium and chloride concentrations than equally well trained swimmers (Henkin et al. 2007). Sweat rate (Cotter et al. 1995) and sweat electrolyte composition (Costa et al. 1969) seem to vary by body region, with some regional electrolyte concentrations being greater than whole-body sweat concentrations (Lemon et al. 1986; Shirreffs and Maughan 1997).

Electrolytes are reabsorbed back into the plasma via active transport, as sweat passes through the sweat glands to the skin surface. However, the rate of reabsorption is unable to match high sweating rates and electrolyte loss generally increases with the rate of sweat loss (Morgan et al. 2004). As sodium is the major ion in extracellular fluid and sweat, considerable amounts are lost during heavy sweating, with as much as 10 g lost during a 2 h professional American football training session in warm conditions (Stofan et al. 2002). In team sports, sweat sodium concentrations range between 22 and 101 $mmol \cdot L^{-1}$ (513 to 2330 $mg \cdot L^{-1}$) (Stofan et al. 2002; Maughan et al. 2007b), reflecting large individual variations, and reinforcing the need for individualised assessments and electrolyte replacement strategies (Maughan et al. 2007b). Typical sweat and plasma concentrations for each of the main electrolytes are listed in Table 2.7

Replacing electrolytes, particularly sodium, during and after exercise is important in maintaining euhydration. Apart from aiding in the absorption of water, sodium also plays an important role in stimulating thirst and increasing voluntary fluid consumption. An alternative and effective means of replacing lost electrolytes post-exercise is the consumption of solid foods and water (Maughan et al. 1996). Other electrolytes are also important in maintaining fluid balance and cellular function. Potassium is the major ion in intracellular fluid that is important in enhancing water retention in the intracellular space (Maughan et al. 1994); while there is some evidence that magnesium loss may play a role in muscle cramping (Roffe et al. 2002; Mooren et al. 2005).

Table 2.7 *The individual range of concentrations of the main electrolytes found in sweat and plasma*

Electrolyte	Plasma	Sweat
Sodium ($mmol.L^{-1}$)	130 - 155	20 - 100
Chloride ($mmol.L^{-1}$)	96 - 110	10 - 70
Potassium ($mmol.L^{-1}$)	3.2 - 5.5	2 - 10
Magnesium ($mmol.L^{-1}$)	0.7 - 1.5	0.2 - 1.2

2.2.3.1 *Mean Sweat Concentration*

Although it is generally accepted that some specific regional sweat electrolyte concentrations are greater than whole-body concentrations (Costa et al. 1969), the mean of specific regional sites may provide an accurate indication of whole-body sweat concentrations (Patterson et al. 2000; Maughan and Shirreffs 2004; Maughan et al. 2004). Patterson et al. (2000) determined that mean whole-body sweat concentrations for sodium and chloride can be accurately determined from an area-weighted mean of four skin regions (Patterson et al. 2000):

Mean whole-body concentration = 28.2% chest + 28.2% back + 11.3% forearm + 32.3% thigh.

Other researchers have suggested that a simple mean of four sites (chest, scapular, forearm and thigh) is a valid indicator of whole-body sweat concentration (Maughan et al. 2004).

2.2.4 *Motor Skill and Cognitive Function*

Intermittent sports such as soccer, hockey and competitive sailing, not only require the maintenance of physiological function, but are multi-tasked and require specific complex motor and decision making skills. The preservation of motor skill and cognitive performance function during strenuous exercise in hot humid conditions is therefore important. Hypohydration affects both, sports skill and cognitive function during exercise. Following 90 min of intermittent running (LIST) in moderate conditions, soccer specific skill performance was found to deteriorate by 5% when subjects were moderately dehydrated (2.4% of body mass) compared with *ad libitum* fluid replacement (McGregor et al. 1999). Soccer skill performance has also been found to decrease when subjects were dehydrated by as little as 1.5 to 2% of body mass (Edwards et al. 2007). Furthermore, dehydration of 2% after exercise in the heat impairs cognitive performance, (8% decrease in arithmetic ability, 11% decrease in short-term memory) (Gopinathan et al. 1988). Similarly, in hot conditions (35°C *vs.* 23°C), tennis skill performance (service, groundstroke and volley accuracy and power) was significantly reduced after 60 min of exercise (Dawson et al. 1985). In addition, Sunderland and Nevill (2005) reported a 6% reduction in field hockey skill performance after 30 min of interval exercise in hot (30°C, 38% RH) *vs.* moderate (19°C, 51% RH) conditions, and attributed the decrease to a higher core temperature (T_{rec}) at the end of the exercise (39.6 *vs.* 39.0°C) (Sunderland and Nevill 2005).

2.2.5 *Environmental Conditions*

A recent retrospective survey of heat related injuries in Australian sport requiring hospitalisation over a 2-year period, reported the majority of cases occurring during the summer months (Driscoll et al. 2008). Sports which result in the greatest exposure to the environment, such as: triathlon, cricket and endurance running were at greatest risk of heat illness (Driscoll et al. 2008). Interestingly, there were no reported cases of heat illness in sailing.

Body heat loss is particularly challenged during exercise in hot environments. The effectiveness of evaporation is determined by both the water vapour pressure gradient between the skin surface and the air (i.e. the environmental humidity), and the rate of airflow over the skin surface (Wendt et al. 2007; Brotherhood 2008). The guidelines published by the United States National Weather Service on the risk of heat related illness during exercise, based on the heat exchange capacity of the environment, states that exercise in environmental conditions greater than 41°C with 40% RH or 31°C with 100% RH increases the risk of heat stroke (Figure 2.5).

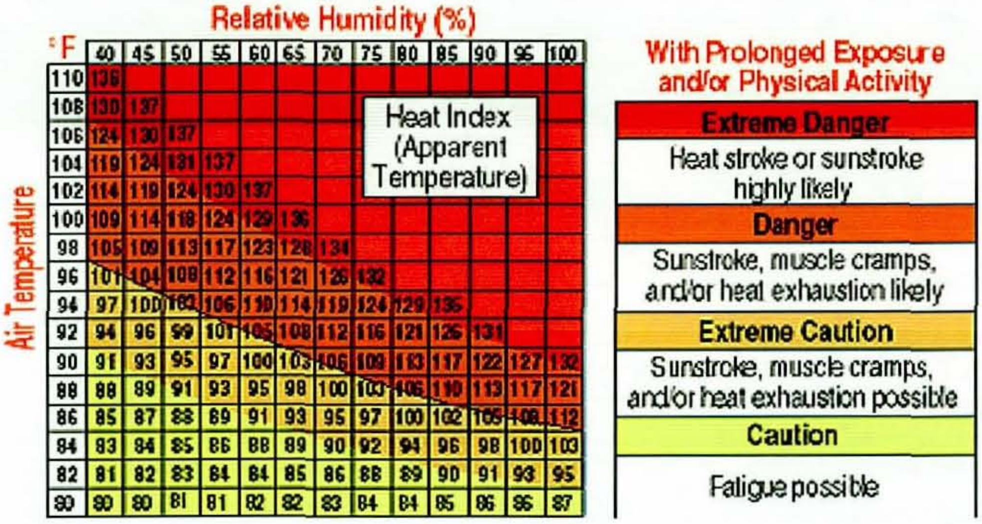


Figure 2.5 Risk of possible heat illness, based on the environmental capacity for heat exchange. (http://weather.noaa.gov/weather/graphics/heatindexchart.jpg [Accessed 2008 February19])

The importance of airflow for evaporation is clear; velocities greater than 3 $m \cdot s^{-1}$ result in lower skin and core temperature (T_{rec}) during exercise, compared with wind speeds of less than 2 $m \cdot s^{-1}$ in hot conditions (35°C) (Adams et al. 1992). Higher wind speeds facilitate increased heat transfer to the environment and thus reduced heat transfer. This evidence also indicates that the limitation for heat transfer is not a result of thermoregulatory capacity of the human body but the inability to dissipate heat to the environment. Similarly, a well controlled study by Saunders et al., (2005) showed that higher wind velocities resulted in increased performance (longer time to exhaustion) and significantly lower T_{rec} than lower wind velocities during moderate intensity cycling at 33°C and 59% RH (Figure 2.6) (Saunders et al. 2005).

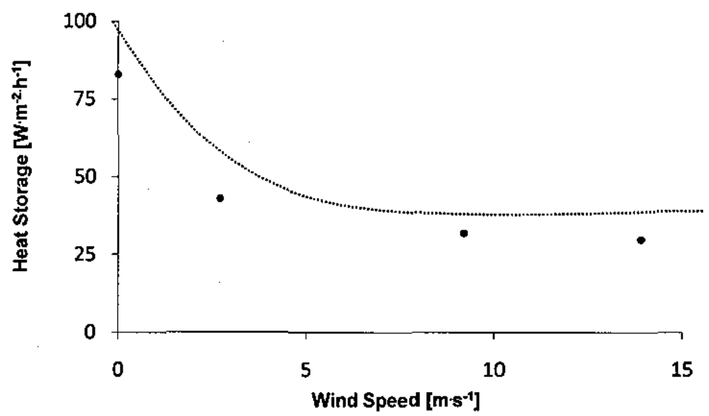


Figure 2.6 Heat storage of the human body during exercise trials with different air velocities (Saunders et al. 2005)

2.2.6 *Clothing*

Clothing provides an important protective barrier from the environment. In hot conditions, clothing prevents direct radiant heat gain from the sun or reflective surfaces such as water (Pascoe et al. 1994a; Pascoe et al. 1994b). The colour of clothing also plays an important role in reducing radiant heat gain; white fabrics gain less radiant heat than black (Nielsen 1990). However, clothing can also increase thermal strain by creating a layer of insulation which restricts air flow and concomitant evaporation from the skin surface during exercise in hot conditions (Kenny et al. 1999). Therefore, in the heat, clothing which provides the least resistance to evaporation may be preferable (Nagata 1978; Brotherhood 2008). Close knit polyester fabrics (with little permeability) generally cause greater sweat production and increased thermal strain than cotton or wool fabrics (Kwon et al. 1998), however cotton and wool have a higher rate of regain (i.e. cotton fibres absorb more sweat than synthetic fibres), which decreases the skin-clothing-air vapour pressure gradient, thereby, reducing evaporative potential and increasing the weight of the garment. Hence in hot and humid conditions, the ideal fabric should be highly permeable (high wicking ability) with little regain.

2.2.7 *Heat Acclimatisation*

Prolonged (acclimatisation) or repeated exposure (acclimation) to heat results in physiological adaptations which can attenuate the impact of hot environmental conditions on exercise performance (Nielsen et al. 1993; Montain et al. 1996; Cheung and McLellan 1998). These adaptations include decreased core temperature at rest and a lowered rate of rise in heart rate and core temperature during exercise (Nielsen et al. 1993), increased sweat rate and earlier onset of sweating response (Armstrong and Maresh 1991) and decreased sweat electrolyte concentrations (Allan and Wilson 1971). Large increases in sweat rate (68%) and decreases of up to 50% in sweat sodium concentration have been reported when individuals were acclimatised to hot conditions over a period of 3 weeks (Allan and Wilson 1971). The improved ability of the acclimatised athlete to reabsorb sodium from sweat, maintains extracellular electrolyte concentration (hypertonic plasma) which assists in the redistribution of fluid from intracellular spaces in order to preserve plasma volume (Patterson et al. 2004). The increase in plasma volume is important in preserving cardiac output during exercise in the heat (Patterson et al. 2004). Adaptations begin after just a few days of exercise in the heat with complete physiological adaptation usually taking 7 to 14 days of moderate to high intensity training (Montain et al. 1996; Pandolf 1998). The rate of adaptation is largely dependent on the degree of thermal strain during exercise, as the rise in core temperature and sweating response seem to be the critical stimuli for acclimation. Hence, intensity rather than volume of exercise appears to be most important in determining an adaptation response (Armstrong and Maresh 1991). Furthermore, as many of the physiological adaptations to heat exposure are similar to those developed in well trained endurance athletes, athletes with high aerobic fitness are able to perform longer in hot environments and tolerate higher levels of body temperature than subjects with lower aerobic fitness levels (Cheung and McLellan 1998).

In summary, strategies to attenuate the rise in core temperature, such as; euhydration, clothing selection and acclimatisation are important in maintaining performance in hot environmental conditions.

2.3 Immune Function and Illness

2.3.1 *Upper Respiratory Infections*

The most common medical complaint of athletes, including America's Cup sailors, are upper respiratory infections (URI), such as viral rhinitis (common cold), pharyngitis, bronchitis and sinusitis (Peters 1997; O'Kane 2002; Neville et al. 2006; Simasek and Blandino 2007). Most URI are caused by respiratory viruses through exposure to infectious pathogens either by direct physical contact or aerosolised droplets (O'Kane 2002). The onset of symptoms usually occurs 1 to 3 days after exposure to an infectious agent. Symptoms usually last for 5 to 10 days (Simasek and Blandino 2007; Spence et al. 2007) and can include nasal congestion, sore throat, rhinorrhea, cough, sneezing, feeling unwell and can be accompanied by muscle aches and fatigue and occasionally headaches (Department of Health 2005). The infectious period of an individual usually begins one day before the start of symptoms and continues for up to five days of illness (Department of Health 2005).

2.3.1.1 *URI and the Athlete*

It is well accepted that moderate levels of physical activity may reduce the incidence and severity of URI (Nieman 2000; Klentrou et al. 2002; Matthews et al. 2002). When sedentary individuals engaged in 45 minutes of moderate physical activity three times per week over a 12 week period, the severity of common cold symptoms and the number of days of influenza were reduced significantly (Klentrou et al. 2002). This is in contrast to that seen in elite athletes where elite female rowers, for example, reported 57% more URI than matched non-athletic controls over a two month training period (Nehlsen-Cannarella et al. 2000). In a recent cross-sectional study, elite triathletes reported three times as many URI incidents than sedentary controls and one-and-a-half times more than recreationally competitive triathletes during a five month training and competition period (Spence et al. 2007). Although much of the research on the incidence of illness in athletes has concentrated on endurance athletes (Peters and Bateman 1983; Nieman et al. 1990; Nieman et al. 2006), there is evidence that elite athletes in most sports involving intense training experience a similar pattern (Novas et al. 2003; Fahlman and Engels 2005; Francis et al. 2005). In general, athletes involved in high training and competition loads seem to be more susceptible to URI than both recreational athletes and the general population (Nieman 2000; Spence et al. 2007), with illness often occurring in periods of heavy training load and during or after competition (Peters and Bateman 1983; Nieman 2000; Novas et al. 2003). This relationship between physical work load and risk of URI has been described previously as a "J-shaped" curve (Nieman 1994) (Figure 2.7). This model suggests that whereas sedentary individuals are at moderate risk of URI, individuals performing regular moderate physical activity have a reduced risk of URI, and athletes performing high training loads have an increased risk of URI (Nieman 1994). URI accounted for 60% of the days absent from sailing due to illness in one team, over a 2 year period prior to and during the 31st America's Cup (Neville et al. 2006). This high incidence of URI was attributed to the high volume of training and sailing performed by America's Cup athletes.

2.3.1.2 *Sailing and URI*

Upper respiratory infections are the most common illness in America's Cup sailing (40% of all illnesses), followed by other stress related disorders such as hypertension and insomnia (13% of all illnesses) (Neville et al. 2006). Illness also affects performance and availability for training. In an illness and injury epidemiology report during a 2 year training period prior to the 31st America's Cup, clinically diagnosed URI accounted for more than 60% of all the illness related days absent from sailing and training and more than 10% of the total number of days absent (injuries and illnesses) from sailing (Neville et al. 2006).

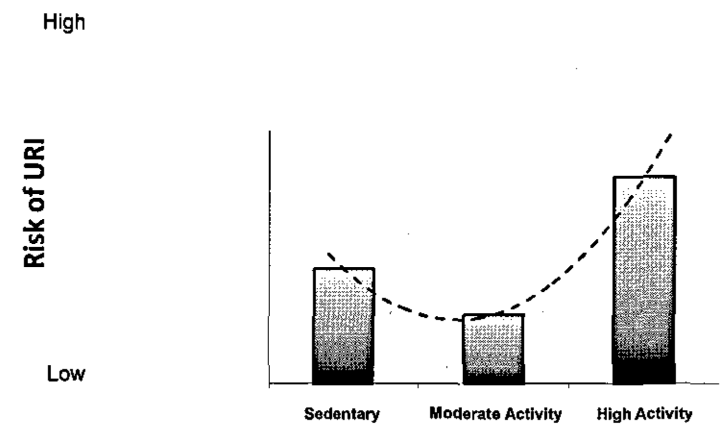


Figure 2.7 The relationship between training load and risk of upper respiratory infections (URI). "J-shaped" model (Nieman 1994)

2.3.2 *Immune Function in Athletes*

2.3.2.1 *Acute effects of Exercise on Immune Function in Athletes*

There is increasing evidence that the susceptibility to URI is largely due to suppression of immune system function as a result of stress, either physiological or other (Gleeson 2006). A number of immune cell functions are temporarily altered following an acute bout of heavy load exercise (Gabriel and Kindermann 1997; Gleeson 2007). The effects are largely dependent on the volume and intensity of the exercise (Nieman 1998), with exhaustive endurance exercise lasting longer than 2 h (McDowell et al. 1992; Nieman 2007) and exhaustive maximal intensity exercise above VO_{2max} (MacKinnon and Jenkins 1993; Fahlman et al. 2001) resulting in immunosupression. This decrease in immune function has been associated with increased incidence of URI in the days and weeks following heavy training load or competition (Heath et al. 1992). During heavy load exercise the plasma concentration of several stress hormones increases, including: epinephrine, growth hormone and cortisol. These changes are thought to have regulatory effects on many immune cell functions (Pedersen et al. 1997), including high levels of circulating pro-inflammatory and anti-inflammatory cytokines (Suzuki et al. 2002), decreases in the number and function of circulating leukocytes (Pedersen and Toft 2000), suppressed natural killer cell count and T cell activity (Mackinnon et al. 1987), as well as decreases in mucosal secretions including immunoglobulins (MacKinnon 2000; Halson et al. 2003; Lakier Smith 2003; Fahlman and Engels 2005).

An "open window" period has been used to describe this post-exercise period of vulnerability (Pedersen and Bruunsgaard 1995), where immune function is compromised for a period of 1 to 72 h depending on the immune parameter (Malm et al. 2004). It is during this "open window" of immune suppression that athletes are at increased risk of infection. See Gleeson (2007) for a comprehensive review.

2.3.2.2 *Chronic effects of Exercise on Immune Function in Athletes*

Regular moderate exercise has important health benefits in stimulating immune function and increasing resistance to URI as well as other illnesses. However, when athletes perform prolonged periods of high intensity training or are experiencing "overreaching" (a temporary reduction in performance), immune function remains suppressed resulting in increased susceptibility to illness, at least until adequate recovery is achieved (Gleeson 2002). These periods are often accompanied by insufficient energy intake, tissue trauma as a result of increased training load, disturbed sleep and psychological stress, all of which have a cumulative effect on the suppression of innate and adaptive immunity (Lakier Smith 2003; Gleeson 2007). The affects on immune cell function are similar to those seen with chronic infection and trauma (Northoff et al. 1998). In extreme circumstances if recovery time is insufficient, the athlete may develop "overtraining syndrome" resulting in persistent underperformance, psychological disturbances, hormonal changes and chronically suppressed immune function with associated sustained illness (Figure 2.8) (Gleeson 2002; Lakier Smith 2003).

In summary, resistance to infection is influenced by the effectiveness of the immune system in protecting the body against pathogenic microorganisms. With temporary immunodepression being relatively unavoidable during heavy load training, it is the degree of depression together with exposure to infectious pathogens during this "open window" period of vulnerability that increases the risk of illness in athletes (Figure 2.9).

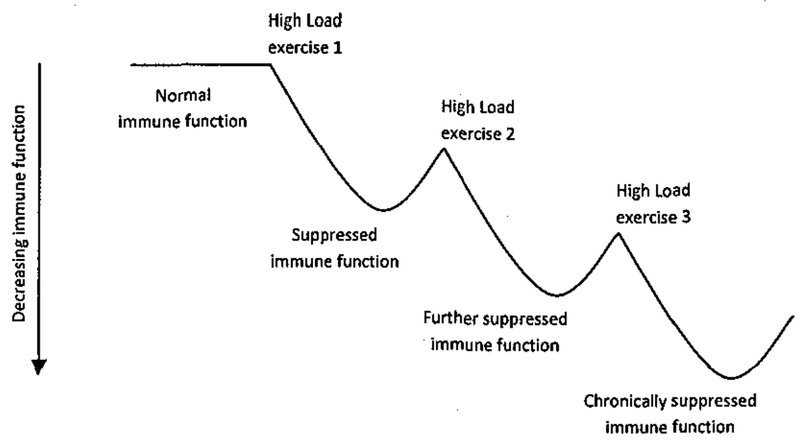


Figure 2.8 Schematic showing the cumulative effects of heavy training load exercise, without sufficient recovery time, on immune function (Mackinnon 1999)

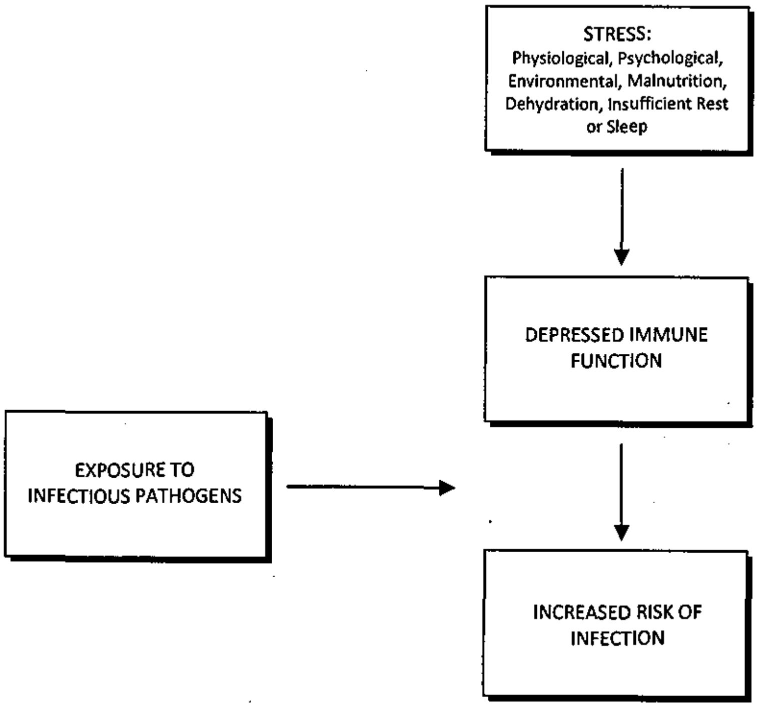


Figure 2.9 Schematic of the basic aetiology of illness in athletes

2.3.3 *Salivary Immunity*

It is estimated that 95% of all infections are initiated at the mucosal surfaces (Bosch et al. 2002). These mucosal surfaces are protected by complex immune surveillance through the secretion of antimicrobial proteins by the mucosal exocrine glands. These antimicrobial proteins act as the first line of defence against infection and disease by neutralizing and preventing microbial entry and replication (Lamm 1997; Bosch et al. 2002; Teeuw et al. 2004). Salivary proteins are synthesized and secreted in the oral cavity by three pairs of major salivary glands (submandibular, sublingual and parotid glands) and many minor glands (Crawford et al. 1975). The main salivary antimicrobial proteins are immunoglobulins, of which secretary immunoglobulin A (s-IgA) is by far the most abundant and responsive to fluctuations in stress (Lamm 1997; Woof and Kerr 2006). Salivary IgA antibodies play a crucial role in immune defence by providing protection at mucosal surfaces via several complex mechanisms (Mazanec et al. 1993).

2.3.3.1 *Salivary Immunoglobulin A*

The primary function of s-IgA is to provide an immunological barrier by preventing microbes, viruses and toxins from penetrating the body through the mucosal surfaces and inhibiting microbial adhesion to epithelial surfaces (Lamm 1997; Woof and Kerr 2006). Salivary IgA antibodies are also able to neutralize specific viruses intracellularly within the mucosal epithelium and prevent microbial internalization and viral replication (Mazanec et al. 1993). There is also evidence that s-IgA antibodies play an important role in phagocytosis by binding to antigens in the mucosal lamina propria and aiding in their excretion into the lumen (Mazanec et al. 1993). Salivary gland function is largely controlled by neurohormonal regulation, and the synthesis and secretion of the antimicrobial proteins respond almost instantaneously to stress (Bosch et al. 2002), resulting in transitory fluctuations in the concentration and flow rate of salivary proteins (Stone et al. 1987b). It is this sensitivity to stress, together with the relatively simple and non-invasive procedure of collection which has resulted in saliva being a focus of immunological research over the past two decades. Furthermore with salivary glands similar in morphology and function to many other exocrine glands they are thought to provide a representative picture of the secretary immune system (Bosch et al. 2002).

Saliva composition and secretion are affected by a number of endogenous and exogenous factors including: the health of the individual, fitness level, age, presence of infection, circadian rhythms and hormonal variations, nutritional deficiencies, fasted state, fluid intake and dehydration, sleep deprivation, psychological stress and the volume and intensity of exercise. There is evidence to suggest that basal s-IgA concentration and the secretion rate may be related to the physical training status of the individual (Francis et al. 2005; Malm 2006). Francis et al. (2005) found elite swimmers to have significantly higher basal s-IgA concentrations than active or sedentary individuals and similar results have been reported in elite female rowers (Nehlsen-Cannarella et al. 2000; Francis et al. 2005). In contrast, an earlier study on elite Nordic skiers reported significantly lower s-IgA concentrations compared with controls, although the authors acknowledged that the athletes may possibly have been in a state of chronic fatigue and stress following a period of intense competition (Tomasi et al. 1982). These findings may also be influenced by the effects of genetic selection or adaptation to training.

The age of the individual can also influence salivary secretion, as flow rate decreases significantly with increasing age (Ben-Aryeh et al. 1984; Navazesh et al. 1992). The presence of infection, particularly during the incubation period, may reduce salivary flow rate and IgA concentration (Mackinnon et al. 1993a; Francis et al. 2005). Circadian rhythms in saliva flow rate and concentration have been reported, with peak values occurring in the afternoon (Dawes 1972). Nutritional deficiencies are known to impair immune function and have been shown to increase the risk of illness (Calder and Jackson 2000; Gleeson and Bishop 2000). Energy restricted diets and low carbohydrate intake not only affect exercise performance but also increase stress hormone secretion that can lead to exercise induced immunodepression (Gleeson et al. 1998). In addition, sufficient intake of specific micronutrients are known to be essential for optimal immune function, including vitamins A, B6, B12, folic acid, C, E, and minerals iron, zinc, selenium and copper (Calder and Jackson 2000; Gleeson et al. 2004a), although excessive intakes of several micronutrients can be potentially harmful to immune function (Gleeson and Bishop 2000). Saliva secretion is also sensitive to the proximity of meals (Dawes 1972), with greater concentrations of IgA reported when fasted (Calder and Jackson 2000). Fluid restriction over a period of 48 h causes a decrease in salivary flow rate (Oliver et al. 2007b), furthermore, fluid intake during exercise prevents dehydration induced increases in stress hormones which may attenuate the decrease in saliva secretion when compared with restricted fluid intake (Bishop et al. 2000). Chronically disturbed sleep patterns and sleep deprivation negatively influence immune function (Shephard and Shek 1997; Cohen et al. 1998). Radomski et al. (1992) reported that after just two days of sleep deprivation, plasma levels of stress hormones increased resulting in immunodepression (Radomski et al. 1992). It has been suggested that subjects should have at least 8 h sleep for several days prior to testing for basal values (Shephard and Shek 1997).

It is widely recognized that psychological stress and negative mood state are associated with depressed immune function (Bosch et al. 2002; Phillips et al. 2006). In a recent community study, the West of Scotland Twenty-07 Study, experience of stressful life events were found to be negatively related to s-IgA secretion rate (Phillips et al. 2006). Salivary IgA was also associated with daily mood fluctuations in male students, with a negative mood being related to decreased s-IgA secretion (Stone et al. 1987a).

2.3.3.2 *Acute effects of Exercise on S-IgA*

The acute effects of exercise on s-IgA are equivocal, and appear to depend on the fitness level of the subjects as well as the training load and type of sporting activity. The general consensus in the literature is that elite athletes experience a transitory decrease in s-IgA after performing heavy load exercise or competition. The effects are usually temporary and normally return to pre-exercise values within 1 to 24 h post-exercise. This was first reported by Tomasi et al. (1982) who showed a significant decrease in pre- to post-exercise parotid s-IgA in elite Nordic skiers after a National Nordic race (Tomasi et al. 1982). Similar results have been reported with elite athletes in kayaking (Mackinnon et al. 1993b), swimming (Gleeson et al. 2000b), tennis (Novas et al. 2003) and triathlon (Libicz et al. 2006). The response of s-IgA to exercise in recreational athletes is less convincing and appears to depend even more on the fitness condition of the individual and the intensity and duration of the exercise performed (Gleeson 2000). Studies involving recreational athletes, have reported post-exercise decreases in s-IgA only after employing maximal or exhaustive intensity exercise protocols or high volume exercise, for example: marathon and ultramarathon running (Nieman et al. 2002; Nieman et al. 2006) or a series of Wingate tests (Fahlman et al. 2001).

2.3.3.3 *Chronic effects of Exercise on S-IgA*

The cumulative effect of intense training has a more pronounced effect on mucosal immune depression (Mackinnon and Hooper 1994; Gleeson et al. 1999b; Gleeson et al. 2000a; Fahlman and Engels 2005; Tiollier et al. 2005; Libicz et al. 2006). In a recent study of elite triathletes competing in the French Iron Tour, which included six triathlons performed on six consecutive days, basal s-IgA concentrations decreased significantly over the course of the competition (Libicz et al. 2006). A case study of an elite Australian kayaker performing multiple daily training sessions reported a significant decrease in pre-training s-IgA concentration over a 2-week training period (~170 $mg \cdot L^{-1}$ to ~50 $mg \cdot L^{-1}$) (Gleeson et al. 2000a). Similar results were reported in army cadets taking part in a 5-day high intensity combat course where the combined stress of high activity load, sleep deprivation, psychological pressure and food restriction resulted in a significant drop in s-IgA concentration (120 ± 14 $mg \cdot L^{-1}$ to 71 ± 9 $mg \cdot L^{-1}$) (Tiollier et al. 2005).

2.3.4 *Salivary IgA and URI*

The effects of exercise on s-IgA and the potential risk of URI associated with heavy training load has been extensively debated over the past two decades and although there is little evidence of a direct link between s-IgA and URI, the general consensus within sports immunology is that elite athletes engaged in high training load and or competition may be at an increased risk of URI. It is undoubted that increased incidence of URI are associated with high load training periods and stress in elite athletes; however, the mechanisms are still largely unknown and few studies have shown a direct association between immune depression and the incidence of URI (Gleeson 2007). In a much cited study of elite Australian swimmers, where 7 saliva samples were collected over a 7 month training period in preparation for the National swimming championships (Gleeson et al. 1999b), the pre-season, pre-training absolute concentration of s-IgA was associated with the incidence of URI during the season. The authors suggested that monitoring the rate of decrease in IgA at regular intervals during the season may assist in predicting illness and concluded that s-IgA concentrations below 40 $mg \cdot L^{-1}$ were associated with an increased risk of URI (Gleeson et al. 1999a; Gleeson et al. 1999b). In a more recent study of college American Football players, 8 saliva samples were collected over the duration of a season and showed that the secretion rate of s-IgA decreased during competition and intense training periods and was inversely related to the incidence of URI (Fahlman and Engels 2005). Moreover, an absolute s-IgA secretion rate of less than 40 $\mu g \cdot min^{-1}$ indicated an increased risk of URI. Other studies have shown less convincing associations, in elite level tennis for example, no significant association was found between s-IgA and URI over a 12 week training period, even though s-IgA was significantly related to the training load (Novas et al. 2003). This is perhaps not surprising given the rather large individual variation in resting s-IgA levels (Francis et al. 2005).

2.3.4.1 *Expressing S-IgA*

Various methods of expressing s-IgA have been adopted which may account for some of the discrepancies in the literature. Salivary IgA has been reported as absolute concentration (Tharp 1991; Gleeson et al. 1999b), secretion rate (Mackinnon et al. 1993a; Fahlman and Engels 2005), ratio to total protein (Tomasi et al. 1982; Steerenberg et al. 1997; Fahlman et al. 2001) or ratio to saliva osmolality (Blannin et al. 1998; Walsh et al. 1999). It has been suggested that during exercise the concentration of IgA should be corrected for saliva flow rate (Stone et al. 1987b; Blannin et al. 1998), as any changes in saliva flow rate during exercise could alter the concentration of IgA. During heavy load exercise salivary flow rate may decrease as a result of dehydration (Walsh et al. 2004), evaporative process during hyperventilation (Reid et al. 2001) and vasoconstriction of salivary gland blood vessels due to sympathetic nervous system activation (Chicharro et al. 1998). Blannin et al. (1998) also reported that the IgA to saliva osmolality ratio was an appropriate measure of s-IgA, as exercise induced changes in concentration would then be accounted for (Blannin et al. 1998). Other studies have suggested that s-IgA should be expressed relative to total saliva protein (Tomasi et al. 1982; Steerenberg et al. 1997; Nieman et al. 2002) in order to account for the effects of exercise induced changes in saliva volume. However, IgA accounts for a relatively small proportion of the total protein found in saliva (~15%) and changes in other saliva proteins also occur with exercise and therefore may be inappropriate to use in relation to exercise (Blannin et al. 1998; Walsh et al. 1999; Libicz et al. 2006) or other interventions (Reid et al. 2001). The absolute concentration of s-IgA seems appropriate for determining resting values, as there is no need to adjust for any exercise or intervention related influences on saliva flow rate (Libicz et al. 2006).

2.3.4.2 *Methodological Limitations*

Immunological research has generally been either cross sectional, intervention or longitudinal in design (Mackinnon 1997). There are few longitudinal studies in the literature, with most having as little as 2 to 8 resting samples over a period of 3 to 12 months, and as long as 2 to 24 weeks between sample collections. The most comprehensive longitudinal mucosal immunity study performed to date, collected saliva samples from elite swimmers, active and sedentary individuals every 2 to 3 days for a 4 week period and reported large within and between subject variations, particularly in the elite athlete group (Francis et al. 2005). Similar large variations in s-IgA have been reported earlier by (Nehlsen-Cannarella et al. 2000) in elite woman rowers. These variations have important implications for the interpretation of studies which have few sample measures. For example, a study on 41 elite Australian swimmers collected only two saliva samples before and after a 4-month training period and concluded that training had no effect on s-IgA concentration and that there was no association between s-IgA and URI (Pyne et al. 2001). Whereas an earlier study on a similar group of 26 elite Australian swimmers where saliva samples were collected at monthly intervals over a period of 7 months reported that s-IgA concentration decreased over the course of the season and pre-training s-IgA was negatively associated with the incidence of URI (Gleeson et al. 1999b).

In general, the interpretation of results in most of the mucosal immunity literature is often difficult, due to substantial differences in study design, variations in exercise protocols and saliva collection procedures and other methodological limitations (Chicharro et al. 1998). The methods used in the collection of basal resting saliva samples for example, are varied, particularly with respect to the time of day, the proximity to meals and the time after previous training sessions. Much of the variation found in the literature may be due in part to this lack of standardization and failure to control for factors affecting the temporal fluctuations in saliva composition. Some studies have collected saliva in the morning after overnight fast (Nehlsen-Cannarella et al. 2000; Tiollier et al. 2005; Libicz et al. 2006), others have collected at midday (Fahlman and Engels 2005; Sari-Sarraf et al. 2007b) or in the afternoon (Mackinnon et al. 1993b; Francis et al. 2005), with some studies having as long as a 4 hour collection window (Francis et al. 2005; Sari-Sarraf et al. 2007b). The proximity to previous training sessions has also varied with samples collected as little as 4 h (Francis et al. 2005) to 6 h (Mackinnon et al. 1993b) post-exercise. The concentration of s-IgA can also be influenced by the collection procedure. For example, saliva extracted from the parotid gland has lower s-IgA concentration to that found in whole mixed saliva (Crawford et al. 1975). Stimulated saliva secretion, either by chewing paraffin wax (Libicz et al. 2006), using absorbant cotton swabs (Nakamura et al. 2006) or forced spitting can also reduce s-IgA concentration (Navazesh and Christensen 1982). Furthermore, analytical methods, storage temperature and calibration protocols can all influence the concentration of s-IgA.

Depending on the diagnosis and severity of illness, the incidence of URI can vary considerably (Neville et al. 2006). The majority of studies have used self-reported illness questionnaires, which are open to inconsistencies in interpretation as the reporting of symptoms is subjective and may not necessarily be infection related (Pyne and Gleeson 1998; Spence et al. 2007). The incidence, symptomatology and pathogenic aetiology of URI was recently determined in a 5-month surveillance study in elite athletes, active and sedentary subjects (Spence et al. 2007). Of the 37 URI episodes reported, infectious pathogens were identified in only 11 (30%), suggesting that not all URI symptoms result from infections and respiratory tract inflammation may be an alternative aetiology for many sore throat symptoms. Consistent diagnosis procedures and reporting of infectious URI, preferably qualified clinical diagnoses are important for accurate URI studies.

CHAPTER 3

RACE ANALYSIS AND PHYSICAL CHARACTERISTICS OF AMERICA'S CUP SAILORS

3.1 Introduction

The America's Cup is the oldest competing trophy in sport, having first been raced in 1851. It is widely regarded as the pinnacle of sailing and held approximately every three to four years between challenging yacht clubs (representing their respective countries) and the winner of the previous America's Cup (the Defender) who also hosts the event (Whiting 2007). The America's Cup is unique in that the format is still largely based on the original Deed of Gift, where the Defender is automatically in the final Match. The International America's Cup Class (IACC) version 5 yachts are 25 m long, weigh 24 tons, have a mast height of 32 m, a downwind sail area of ~700 m^2 and are constructed from specialised composite materials. These high performance yachts are sailed by 17 skilled athletes in a match-race format (i.e. two boats at a time) around a two lap upwind and downwind course of ~11 nautical miles (20 km) (Figure 2.1). For a Challenging team to win the 32^{nd} America's Cup, could have involved between 35 and 47 races, however the nature of racing has not been systematically documented. One observation noted an average of 30 upwind tacks and 15 downwind gybes per race for a single team during the 31^{st} America's Cup (Bernardi et al. 2007b), but many aspects of racing remain poorly understood. A thorough analysis of racing (race duration, number of manoeuvres and winning margin), environmental conditions (wind speed, temperature and humidity) and crew selection strategy (number of rotations) would help to increase our understanding of this sport.

In America's Cup sailing all manoeuvres, including: hoisting and dropping sails before to the start, pre-start circling, sail trimming, tacking and gybing, and upwind and downwind mark roundings, are performed manually without the assistance of stored energy. The physiological demands placed on the crew are high (Bauer 1986), but have not been carefully researched. An individual's exercise intensity during racing is thought to depend largely on the weather conditions, the race tactics, the role of the athlete within the crew (Allen and De Jong 2006; Neville et al. 2006), and perhaps also on how evenly the competing boats are matched (Whiting 2007). However, there has been no systematic investigation of exercise intensity during America's Cup sailing. Each of the 17 positions on board are role specific, with the athletes typically divided into five groups of similar roles. A brief description of each position is provided in Figure 2.2. Grinding (standing arm cranking) is a key activity in driving the winches for all the boat's manoeuvres, with between five and six athletes (*'grinders'*) from the crew primarily dedicated to this activity. Grinding involves short bursts of high intensity exercise in order to complete each manoeuvre, interspersed with longer rest intervals, but no quantitative description of the activity pattern of grinding has been completed. The manoeuvres that require maximal effort grinding in order to change the direction of the boat, and where teams strive to gain an advantage, are tacks (upwind turns), gybes (downwind turns) as well as the mark roundings (Figure 1.1 and Figure 2.1). Grinding is also used to trim (adjust) the sails in order to optimise speed and position of the yacht.

Although America's Cup sailors are heterogeneous with respect to body composition (Lambert and Lelguen 2001; Pearson et al. 2005), little is known of the physical characteristics (anthropometry and fitness) of the athletes, particularly with respect to the different positions. The America's Cup protocol limits the total weight of the crew to 1,570 kg (92.4 kg per athlete) hence maximising performance for a given body mass is important with clear consequences for body composition. The teams that compete in the America's Cup are of heterogenous standard, with some teams having substantially larger budgets, and a greater number of sailors and support staff. It is unknown if the difference in performance between teams is in part attributed to the physical fitness of the crew, as opposed to technical, tactical and technological factors.

The aims of this study were threefold. Firstly, to analyse the nature of America's Cup racing. Secondly, to quantify the activity pattern of grinding and the exercise intensity of the different crew positions during racing. Thirdly, to document the anthropometric and fitness characteristics of athletes in different positions, and compare the physical fitness of two teams of different standard and experience.

3.2 Methodology

3.2.1 *Race Analysis*

The 32nd America's Cup (including the Louis Vuitton Cup Challenger series) took place from April to July 2007 in Valencia, Spain, between 12 participating teams (11 Challengers and 1 Defender). The race format comprised of a double round-robin qualifying series, where all the challenging teams raced each other twice over 20 days. The top four teams then contested for the Challenger series semi-finals and final, both being best-of-9 races, with the winner competing against the Defender in the 32nd America's Cup final Match. This resulted in 135 races over the 10 weeks of competition. Race statistics including: race duration, winning margins, number of manoeuvres (tacks and gybes), true wind speed and crew rotations were taken from the official America's Cup website (www.americascup.com) and from data presented by Virtual Spectator®. Environmental temperature and relative humidity were taken from a Meteorological Data Service buoy close to the race course at 6 m above sea level.

The apparent wind speed (AWS) was calculated using the formula (Larsson & Eliasson 2007):

$$AWS = \sqrt{(TWS^2 + VS^2 - 2*TWS*VS*\cos(TWA))}$$

Where TWS is true wind speed, VS is boat speed, and TWA is true wind angle in degrees.

3.2.2 *Participants*

The participants were all male professional America's Cup sailors who consented to participation in the study which was approved by the University's Ethical Advisory Committee. The body composition measurements were made on 92 athletes representing 4 teams during the 32nd America's Cup and one team from the 31st America's Cup. Their collective experience included 212 America's Cup campaigns. Fitness data was collected on a subset of 66 athletes from two teams that competed in the 32nd America's Cup. Team A (n=37) was ranked in the top 4 (budget: ~€120 million; support staff: ~110; sports science and medical staff: 6), and Team B (n=29) ranked in the lower 7 (budget ~€30 million; support staff: ~25; sports science and medical staff: 2). The mean age of Team A and Team B was 36 ± 6 and 32 ± 8 y respectively and their collective experience included

106 and 34 America's Cup campaigns respectively. The exercise intensity data were collected from two America's Cup teams (n=34) during 9 Challenger series races.

3.2.3 *Exercise Intensity and the Activity Pattern of Grinding*

Heart rate data (Polar Team System, Finland) was collected during 7 round-robin and 2 semi-final races, and used as an index of exercise intensity. The duration of grinding bouts and rest intervals were determined from on-board video footage of 11 races from 3 qualifying and 4 non-qualifying teams during the Challenger series. Specifically, video of the three mid-deck grinding pedestals (Port, Starboard and Mainsheet *grinders*) was analysed and the manoeuvre associated with each grinding bout noted.

3.2.4 *Anthropometry*

Anthropometic 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 digital scales to the nearest 0.1 kg (Tanita BWB-800, Tokyo, Japan and Seca 769, Hamburg, Germany) and stature 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):

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

3.2.5 *Fitness Testing*

Fitness tests were performed on the same day with a ~45 min recovery period between strength or strength endurance tests and ~2 h rest prior to rowing. The test protocol included: bench press, followed by pull-ups, push-ups, sit-ups and 2,000 m indoor rowing.

Upper-body Strength (Bench Press). One repetition maximum (1RM) was used to assess upper body strength (Logan et al. 2000). The weight was lowered unassisted until the bar was in contact with the chest and pushed up vertically until the arms were locked straight.

After completing a warm up of submaximal lifts, an initial weight of ~10 kg below the athlete's expected maximum weight was selected, whereafter five attempts were given to progressively increase the weight by 2.5 to 5 kg with a 5 min rest interval between each attempt.

Strength Endurance. Three standardised field tests were used to assess muscular endurance (pull-ups, push-ups and sit-ups) (Pate et al. 1993; Legg et al. 1997). Pull-ups were recorded as the maximum number of repetitions performed with an underhand grip, beginning with the arms fully extended and raising the chin above the level of the hands. Movement of the lower body was restricted with the hips maintained in extension and the knees bent at 90°. Push-ups were recorded as the maximum number performed in 60 s. With hands shoulder width apart, the chest was lowered to touch the investigator's hand which was 50 mm from the ground, and returned to the straight arm position. Sit-ups were performed for 120 s with knees bent at 90° and the feet restrained on the floor. Hands gripped the ear at all times and the athletes were required to flex the trunk and touch their knees with both elbows and return to touch the investigator's hand which was placed on the mat in line with the athlete's scapular.

Rowing Performance. Indoor rowing is commonly used by sailors to train aerobic and anaerobic endurance (Legg et al. 1997; Legg et al. 1999). The time taken to row 2,000 m on an indoor rower (Concept 2, Vermont, USA), with the drag factor set at 125, was recorded.

3.2.6 *Statistical Analysis*

Anthropometric and heart rate data for the different crew positions were compared with one-way ANOVA. An independent *t* test was used to determine the difference in the duration of tacks and gybes between qualifying and non-qualifying teams. Differences in physical fitness between positions and teams were compared using a two-way ANOVA. Bonferroni post hoc tests were used to determine differences between positions, and make pairwise comparisons of the same position from each team. Bivariate relationships were assessed with Pearson's product moment correlation. Statistical analysis was performed with SPSS version 14 for Windows. The level of significance was set at $P<0.05$, and data are presented as mean ± SD.

3.3 Results

3.3.1 *Race Analysis*

Over the 135 races, mean race duration was 82 ± 9 min (range: 64 to 105 min) with upwind and downwind stages being on average 22 ± 3 min (range: 14 to 31 min) and 19 ± 3 min (range: 13 to 28 min) respectively. Challenging teams completed between 20 and 39 races, with teams having two races on 40% of the race days during the qualifying series. The mean winning margin was 74 ± 77 s for all races and 24 ± 11 s during the America's Cup final Match. The mean number of upwind tacks and downwind gybes was 20 ± 10 (range: 5 to 53) and 8 ± 3 (range: 2 to 18) respectively, with a combined total of 30 ± 11 manoeuvres per race (range: 12 to 65). The true wind speed (TWS) was 5.1 ± 1.1 $m{\cdot}s^{-1}$ (range: 2.6 to 8.7 $m{\cdot}s^{-1}$), resulting in upwind and downwind AWS of 9.7 and 2.7 $m{\cdot}s^{-1}$, respectively. The environmental temperature was 27 ± 4 °C (range: 22 to 38 °C) and relative humidity 60 ± 13% (range: 34 to 82%). Race duration was inversely related to wind speed ($r=-0.41$, $P<0.001$) and the number of manoeuvres (tacks and gybes) was inversely related to the winning margin between the two boats ($r=-0.43$, $P<0.001$). During the qualifying series (first two round-robins) an average of 1.8 athletes were rotated for each race, while an average of only 0.2 athletes were rotated during the knock-out rounds.

3.3.2 *Exercise Intensity and the Activity Pattern of Grinding*

The mean work period of grinding during tacking and gybing was 5.5 ± 0.5 s and 11.2 ± 1.4 s respectively, with the qualifying teams grinding for less time than the non-qualifying teams during both tacks (5.1 ± 0.4 s *vs*. 6.2 ± 0.7 s, $P<0.001$) and gybes (10.2 ± 1.4 s *vs*. 12.5 ± 2.6 s, $P<0.001$). The longest grinding bouts occurred when rounding the upwind (10.5 ± 4.8 s) and downwind (35.8 ± 12.5 s) marks. In contrast the most frequent grinding task, sail trimming, lasted 3.7 ± 2.1 s. *Grinders* performed on average 143 work bouts lasting 5.5 ± 5.4 s (range: 2.2 to 66.3 s) during a race, which equated to a work:rest ratio of ~1:6, and as high as 1:3 during the most strenuous races as a result of an increase in the number of tacks and gybes. Mean heart rate (HR) during racing was ~64% of laboratory determined HRmax for all positions, with *bowmen* significantly higher than *trimmers* and *afterguard* (71 ± 4% vs 61 ± 6% and 56 ± 7%, $P<0.05$; Table 3.1). Peak HR achieved during racing was 92% of HRmax for all positions with *bowmen* and *grinders* attaining 96% and 93%, respectively. Figure 3.1 shows the HR (mean HR, 79% of HRmax) of a *grinder* during a strenuous race.

Table 3.1 Mean and Peak heart rate (HR) during America's Cup yacht racing according to position. Laboratory HRmax values are shown for reference. Data are mean ± SD of 9 America's Cup races.

Position [n]	Laboratory HR max [beats·min⁻¹]	During Racing HR mean [beats·min⁻¹]	HR mean [%]	HR peak [beats·min⁻¹]	HR peak [%]
Grinders [13]	189 ± 4	124 ± 15	66	175 ± 13	93
Bowmen [4]	195 ± 5	138 ± 9[a]	71	187 ± 8	96
Utilities [6]	189 ± 7	121 ± 13	64	174 ± 15	92
Trimmers [5]	187 ± 3	115 ± 11	61	170 ± 9	91
Afterguard [6]	190 ± 6	106 ± 13	56	164 ± 20	87
ALL [34]	**189 ± 5**	**121 ± 12**	**64**	**174 ± 13**	**92**

[a] *Significantly higher than Trimmers and Afterguard (P<0.05)*

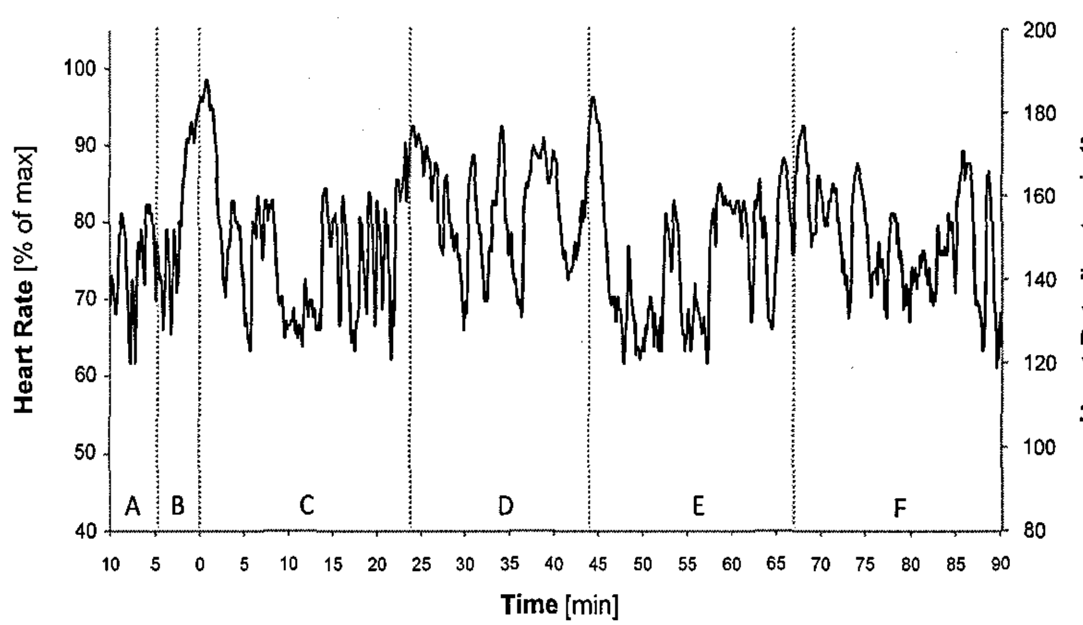


Figure 3.1 Heart rate of a *grinder* during a typical America's Cup yacht race (A: warm-up; B: pre-start; C: upwind leg1; D; downwind leg1; E: upwind leg2; F: downwind leg2). Race duration: 1h 29; Mean HR: 150 beats·min^{-1} (79% of HRmax)

3.3.3 *Anthropometry and Fitness*

The anthropometric characteristics of all 92 athletes are shown in Table 3.2. *Grinders* were significantly taller and heavier than all other positions (P<0.01) and had a greater body surface area (BSA, P<0.01). Percent body fat was similar between positions with a mean for all athletes of 13 ± 4%. When comparing the physical fitness between two teams of different standard and experience (mean number of America's Cup campaigns per athlete; Team A, 2.9 ± 1.4 *vs.* Team B, 1.2 ± 0.5; Table 3.3), Team A had significantly greater bench press 1RM, number of push-ups and sit-ups than Team B (P<0.01). Pairwise comparisons between comparable positions from each of the teams revealed differences between *grinders* (bench press, push-ups, pull-ups and sit-ups, all P<0.01) and *utilities* (push-ups and sit-ups, P<0.05). When comparing fitness between positions, *grinders* had a greater bench press 1RM than all other positions (P<0.01), and completed the 2,000 m row quicker than the *afterguard* and *utilities* (P<0.05). The *afterguard* were lower than all positions for bench press (P<0.05), and lower than *grinders* and *bowmen* (P<0.01) for push-ups and performed less pull-ups than *bowmen* (P<0.01). There was little difference in sit-ups between positions.

Table 3.2 Anthropometric characteristics of America's Cup athletes from four teams according to position

	N	America's Cups	Age [y]	Stature [m]	Body Mass [kg]	Σ 7 Skinfolds [mm]	Body Fat [%]	Body Surface Area [m²]
Grinders	34	73	32 ± 6	1.88 ± 0.05[b]	103 ± 7[b]	75 ± 22	13 ± 4	0.23 ± 0.01[b]
Bowmen	11	26	32 ± 6	1.77 ± 0.04	82 ± 10	67 ± 19	11 ± 4	0.20 ± 0.01
Utilities	15	35	34 ± 7	1.80 ± 0.06	88 ± 9	80 ± 23	14 ± 4	0.21 ± 0.01
Trimmers	16	35	36 ± 5	1.80 ± 0.06	82 ± 5	70 ± 16	12 ± 3	0.20 ± 0.01
Afterguard	16	44	41 ± 7[a]	1.83 ± 0.06	87 ± 9	80 ± 31	15 ± 6	0.21 ± 0.01
All	92	212	35 ± 7	1.83 ± 0.07	92 ± 12	75 ± 23	13 ± 4	0.22 ± 0.02
[range]			[21 to 54]	[1.66 to 2.00]	[60 to 121]	[35 to 155]	[4 to 30]	[0.17 to 0.25]

[a] greater than grinders, bowmen and utilities (P<0.01); [b] greater than all other positions (P<0.001)

Table 3.3 Physical fitness of two teams of different standard and experience competing in the 32nd America's Cup (Team A: ranked in top 4/12 and Team B: ranked in bottom 7).

	N	America's Cups	Age [y]	Body Mass [kg]	Bench Press [kg]	Pushups [N in 60 s]	Pullups [N]	Situps [N in 120 s]	2000 m Row [min:s]
TEAM A									
Grinders	12	33	36 ± 6	106 ± 6	142 ± 14[b]	77 ± 10[b]	17 ± 5[b]	108 ± 9[b]	6:50.7 ± 17.5
Bowmen	5	17	36 ± 5	83 ± 6	100 ± 7	67 ± 5	16 ± 4	89 ± 10	7:05.0 ± 12.0
Utilities	7	18	33 ± 6	93 ± 9	104 ± 17	62 ± 10[c]	13 ± 4	88 ± 16[c]	7:12.1 ± 15.0
Trimmers	6	16	36 ± 7	81 ± 5	106 ± 18	64 ± 11	15 ± 4	95 ± 10	7:14.6 ± 17.2
Afterguard	7	22	41 ± 7	87 ± 4	78 ± 12	54 ± 13	12 ± 8	78 ± 16	7:15.8 ± 31.2
All	37	106	36 ± 6	93 ± 12	113 ± 28[a]	66 ± 13[a]	15 ± 5	93 ± 16[a]	7:05.6 ± 20.7
TEAM B									
Grinders	10	10	27 ± 4	102 ± 8	119 ± 25	56 ± 10	11 ± 3	67 ± 14	6:54.2 ± 18.1
Bowmen	4	4	28 ± 5	81 ± 16	100 ± 20	60 ± 8	19 ± 6	72 ± 10	7:17.4 ± 28.6
Utilities	6	8	33 ± 10	83 ± 8	80 ± 22	50 ± 7	15 ± 4	59 ± 5	7:13.3 ± 16.4
Trimmers	4	5	34 ± 6	84 ± 5	90 ± 20	60 ± 28	12 ± 4	84 ± 16	7:06.9 ± 20.4
Afterguard	5	7	43 ± 7	84 ± 12	58 ± 16	38 ± 4	7 ± 4	68 ± 25	7:37.9 ± 30.4
All	29	34	32 ± 8	90 ± 13	94 ± 30	52 ± 12	12 ± 5	69 ± 16	7:10.6 ± 25.6
Total	66	140	34 ± 7	91 ± 12	104 ± 30	60 ± 14	14 ± 5	83 ± 20	7:07.9 23.0
[range]			[21 to 54]	[60 to 121]	[40 to 175]	[35 to 90]	[3 to 27]	[45 to 125]	[8:09.0 to 6:20.3]

[a] Team A significantly greater than Team B (P<0.001); [b] grinders in Team A significantly greater than grinders inTeam B (P<0.01); [c] utilities in Team A significantly greater than utilities in Team B (P<0.05)

3.4 Discussion

This is the first detailed report on the nature of America's Cup yacht racing. The mean race duration (82 min) was less than the 2 to 3 h reported for the 31st America's Cup (Neville et al. 2006; Bernardi et al. 2007b), and can be explained by the reduced race distance (2 laps instead of 3 laps) for the 32nd America's Cup. Race duration (64 to 105 min) and the number of tacks and gybes (9 to 62) were highly variable, with race duration partially dependent on the wind speed; as the wind speed increased, race duration decreased (r=-0.41). The number of manoeuvres (tacks and gybes) increased with how closely matched the boats were (determined by the winning margin, r=-0.43). The greater number of manoeuvres in a close race, in addition to the psychological effect of direct competition would be expected to elevate exercise intensity. The mean winning margin of only 1.5% (~300 m) of race duration for all races (and only 0.4% during the America's Cup final Match) suggests that the difference in speed between the yachts was relatively small. Given these narrow margins of success/defeat, all aspects of performance appear important, including the skill, experience, and fitness of the athletes.

The activity pattern of *grinders* was very intermittent, with grinding bouts lasting on average 5.5 s, and a work:rest ratio of 1:6, which was as high as 1:3 in strenuous races, due to an increase in the frequency of manoeuvres. Hence it can be surmised that the energy demands are predominantly anaerobic, with a substantial aerobic contribution possible, depending on the frequency of the activity cycles. The shortest duration grinding activity was sail trimming (~3.7 s), and this was also the most frequent activity, as the sails are continuously adjusted according to the ever changing wind and sea conditions. Grinding bouts were twice as long for gybing compared with tacking (11.2 *vs*. 5.5 s), mainly due to the larger sail area of the downwind sails. Arguably the most important and technically challenging manoeuvres are the mark roundings, where large gains or losses can be made. The downwind mark rounding required the longest duration of continuous maximal effort grinding (36 s), and was in excess of 60 s in some races. Interestingly, the mean grinding duration for tacks and gybes by the top ranked teams were ~20% quicker than the lower ranked teams. This indicates that the best teams complete the manoeuvres more quickly, presumably due in part to more effective grinding. This clearly highlights the importance of effective grinding to America's Cup performance. However there has been very little research of the physical capability of elite sailors during grinding, and no scientific attention to the optimisation of power production during grinding. The influence of factors such as crank velocity, grinding configuration (crank length and crank-axle height) and technique have not been considered. Future research should also strive to measure the actual power produced during on-board grinding, and more carefully examine how this relates to the speed of manoeuvres.

The typical environmental conditions of the 32nd America's Cup are regarded as moderate (temperature, 27°C; relative humidity, 60%; mean TWS, 5.1 $m \cdot s^{-1}$), although temperatures of up to 38°C were not uncommon. The environmental conditions combined with the prolonged exercise of sailing, including 105 min of racing as well as pre- and post-race sailing sometimes twice per day, may challenge the crew's capacity for thermoregulation. The thermal strain may be particularly severe during downwind sailing due to the low

AWS (28% of upwind AWS), with a consequent reduction in evaporative cooling, and the greater physical work required to gybe the larger downwind sails. The thermoregulatory stress of America's Cup sailing has not been documented, although heat illness and dehydration have been reported during this event (Neville et al. 2006).

Mean HR for all positions during racing was 64% of HRmax, indicating a significant level of cardiovascular stress throughout competition. This was most marked for *bowmen* (mean, 71%; peak, 96%) and *grinders* (mean, 66%; peak, 93%). Although *bowmen* assist with grinding upwind, their tasks are varied and more dynamic than that of *grinders* who are predominantly stationed at one position. The pre-start and mark roundings appear to elicit the greatest rise in HR during grinding, followed by gybing and tacking (Figure 3.1). The *afterguard* had the lowest mean HR (although non-significant) as a result of their predominantly cognitive tasks while racing.

The crew rotation was higher during the qualifying rounds than the knockout stages (1.8 *vs.* 0.2 rotations per race), likely due to the double race days during the earlier rounds. The positions that were typically rotated were *bowmen*, *grinders* and *utilities,* considered to be the more physically demanding positions. The relatively low number of rotations may be indicative of the highly technical and specialised nature of the sport and of each crew position, as well as the close nature of all the racing.

The body fat of the athletes in this study (13%) was lower than previous reports during the 30th (19% (Lambert and Lelguen 2001)) and 31st (15% (Pearson et al. 2005)) America's Cups. However, body mass was greater (92 *vs.* 84 and 89 kg respectively), indicating a substantial increase in lean body mass over the last three America's Cups. In fact a common strategy of the teams has been to reduce the body fat of the whole crew in order to maximise lean muscle mass of the positions with the greatest strength and power requirements. When comparing positional differences, as expected *grinders* were taller and heavier than all other positions. As power production during short bouts of grinding is fundamental to this position, *grinders* are selected, in part, for their large muscle mass. Interestingly, the body mass of *bowmen* has increased considerably since the 30th America's Cup, from 73 kg (Lambert and Lelguen 2001) to 82 kg in the current study. This could be due to the increased physical requirements of working with the larger IACC version 5 sails. When comparing physical fitness between positions (Table 3.3), it is not surprising that *grinders* had greater upper-body strength (bench press) than all other positions, and the *afterguard*, who have the least physically demanding roles, were lower than the other positions. Surprisingly, there was little difference in sit-ups between positions, which may indicate an equal importance of torso stability between roles. The fitness tests used in the current study were relatively crude generic measures of muscular strength, strength endurance and rowing performance. More detailed physiological assessment of America's Cup athletes during relevant activity, primarily grinding, is required to more clearly describe the characteristics of this cohort of elite athletes, and any differences due to crew position.

When comparing the physical fitness of athletes from two teams of different standard and experience, Team A had greater strength and strength endurance (bench press, push-ups and sit-ups) as a whole, than Team B. These differences were most marked between *grinders* and *utilities* (the two positions primarily responsible for grinding). This contrast in physical fitness may in part explain the difference in the speed of manoeuvres between the higher and lower ranked teams, and may highlight the importance of physical fitness of these athletes to performance of the whole team. The discrepancy in physical fitness may be the result of differences in athlete recruitment and/or athlete preparation and management. For example, fatigue is common to America's Cup athletes, even in well resourced teams (Neville et al. 2008), as a result of the high volume of work and sailing involved. This may be further exacerbated in less well resourced teams, where athletes are typically required to take on multiple roles within the team due to the limited number of support staff. Consequently, their ability to prioritise on athletic performance could be compromised. Greater support and care of athletes may help to optimise their physical fitness and response to training (Neville 2008; Neville et al. 2008).

3.4.1 *Conclusions*

The exercise intensity of America's Cup yacht racing is high, but intermittent, and influenced by how evenly matched the boats are and the role of the athlete. Grinding bouts were on average quite short (~5.5 s) but frequent (work:rest ratio 1:6), indicating predominantly anaerobic energy provision, with implications for training prescription. The anthropometric and physical characteristics of the athletes varied according to their role, with *grinders* being bigger and stronger than all other positions. In addition, there appears to have been a substantial increase in lean body mass and a reduction in body fat over the past three America's Cups. The differences in strength and strength endurance between high and low ranked teams likely contributes to the discrepancy in their speed of manoeuvres, and highlights the importance of athlete fitness and preparation in America's Cup yacht racing.

CHAPTER 4

PHYSIOLOGICAL CHARACTERISTICS: AEROBIC POWER AND PEAK POWER

4.1 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. 2007b), 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. 2007b) 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. 2007b).

Grinding has always been considered an important factor in overall America's Cup performance, supported by the finding in Chapter 3 that top level teams complete manoeuvres more quickly, which is attributed in part to more effective grinding. Therefore it appears useful to document the athlete's maximal capability for grinding and consider the optimisation of this activity. 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 the onset of blood lactate) 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*.

4.2 Methodology

4.2.1 *Participants*

Thirty-three elite professional male America's Cup sailors participated in the study. Their physical characteristics are shown in Table 4.1. All athletes sailed for a team ranked in the top three during the 32nd America's 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.

4.2.2 *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 upper body peak oxygen uptake (VO_{2peak}) and anaerobic 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.

4.2.3 *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):

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

4.2.4 *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 (Figure 4.1). 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).

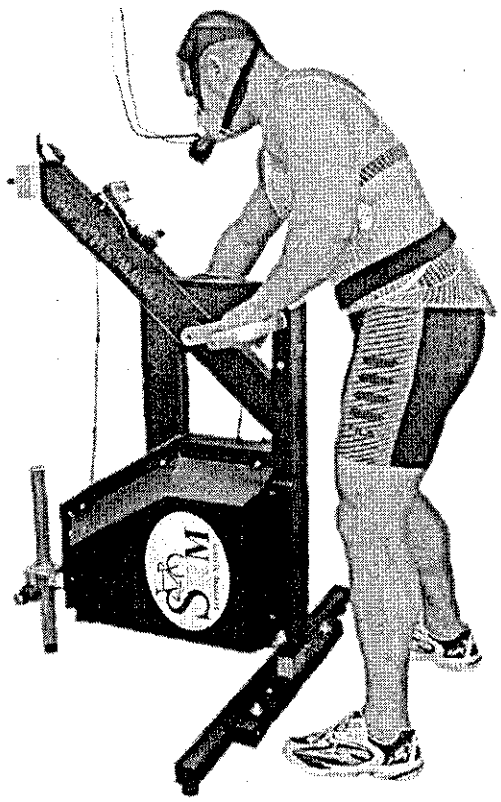


Figure 4.1 Image of the modified SRM arm ergometer used for America's Cup grinding performance analysis. Crank length was 0.25 m and the distance between the handles was 0.44 m. (courtesy of Federico Giovanelli, © Vernon Neville 2008)

4.2.5 *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 athlete's 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 cranking rate of 80 rpm (Smith et al. 2001), and the test was terminated when the athlete was no longer able to maintain a rate 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 1982) 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 as an indication of the anaerobic threshold (Heck et al. 1985). Heart rate, VO_2 and work load at OBLA were calculated using linear interpolation between the relevant data points.

4.2.6 *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 (crank velocity) were recorded throughout each sprint and analysed off-line. Once the prescribed crank 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.

4.2.7 *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.

4.3 Results

The anthropometric characteristics of the sailors are shown in Table 4.1. *Grinders* were heavier than all other positions ($P<0.01$), while *bowmen* had a lower body fat percentage than *utilities* ($P=0.05$).

Table 4.1 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 [m²]
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 ($P<0.03$)

The mean VO_{2peak} for all athletes was 4.69 ± 0.50 L·min^{-1} (range: 3.58 to 5.48 L·min^{-1}), which occurred after 26 min 29 s ± 2 min 27 s of the step test at a mean power output of 332 ± 44 W (range: 235 to 425 W). *Grinders* 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·kg^{-1}·min^{-1}, P=0.04; Table 4.2). Figure 4.2 shows the BLa response to increasing VO_2 as a percentage of VO_{2peak}.

Table 4.2 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}]	Peak Power [W]	BLa [mmol·L^{-1}]
Grinders	9	186 ± 8	5.04 ± 0.41	48 ± 4	369 ± 35^{b}	11.3 ± 1.3
Utilities	6	191 ± 8	4.74 ± 0.35	51 ± 4	332 ± 19	11.7 ± 1.2
Bowmen	6	187 ± 7	4.63 ± 0.39	56 ± 6^{a}	328 ± 35	12.0 ± 2.4
Trimmers	5	190 ± 9	4.50 ± 0.50	55 ± 5	311 ± 45	13.2 ± 2.0
Afterguard	6	181 ± 10	4.18 ± 0.66	49 ± 6	297 ± 50	10.6 ± 2.4
All	32	187 ± 9	4.69 ± 0.50	51 ± 6	332 ± 44	11.7 ± 1.9
range		[167 to 201]	[3.58 to 5.48]	[41 to 62]	[235 to 425]	[8.2 to 15.9]

^{a} Bowmen greater than Grinders (P=0.04); ^{b} Grinders greater than Afterguard (P=0.01)

For the whole crew the OBLA occurred at a power output of 202 ± 31 W (61 ± 6% of W_{max}) and VO_2 of 3.34 ± 0.04 L·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 4.3).

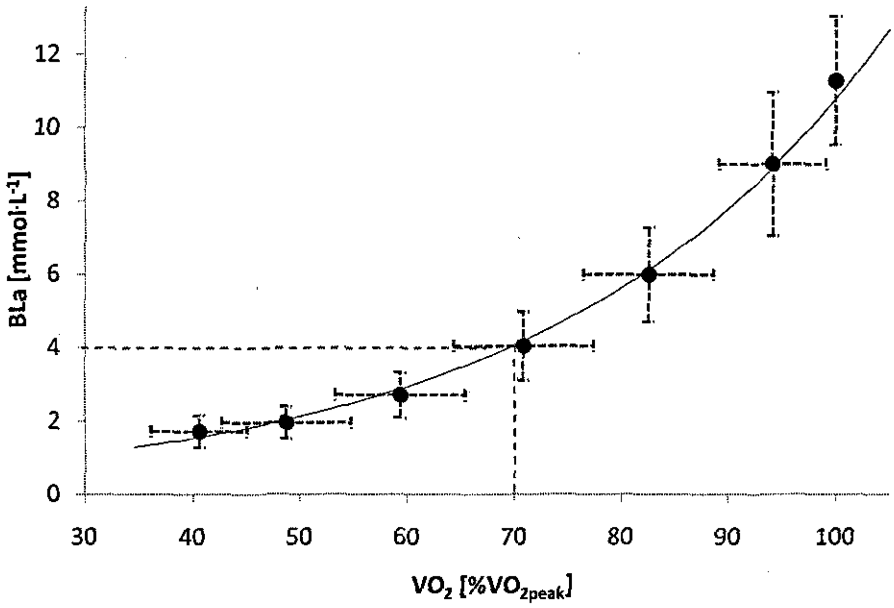


Figure 4.2 *Blood lactate concentration [BLa] with increasing* VO_2 *as a percentage* of VO_{2peak} during each stage of an incremental step testing to exhaustion on a standing arm-crank ergometer (n=33). Data are mean ± SD.

Table 4.3 Physiological responses at OBLA 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)*

For each of the *grinders* the relationship between torque and crank velocity during the isokinetic sprints was linear (r=0.94 ± 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 T_{max}, 212 N·m and ω_{max}, 251 rpm (Figure 4.3).

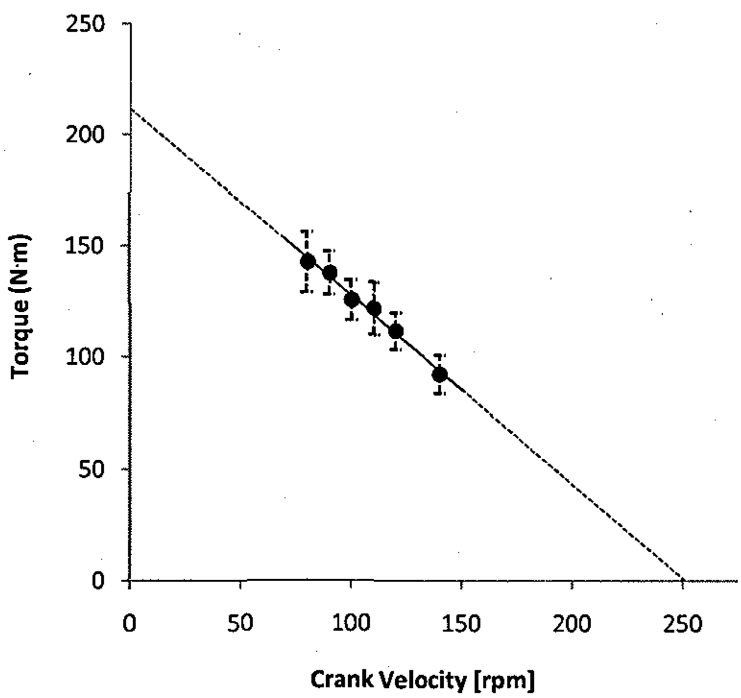


Figure 4.3 Torque and crank angular velocity relationship during standing arm-cranking (grinding) (r=-0.99, P<0.01, n=10).

Peak power during the 7 s sprints is displayed in Figure 4.4. Peak power at 120 rpm was significantly greater (17%) than at 80 rpm (P=0.03, Figure 4A), as was relative peak power (P=0.01, Figure 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·kg^{-1} (range: 12.0 to 15.4 W·kg^{-1}). ω_{opt} occurred at 125 ± 6 rpm (range: 114 to 133 rpm).

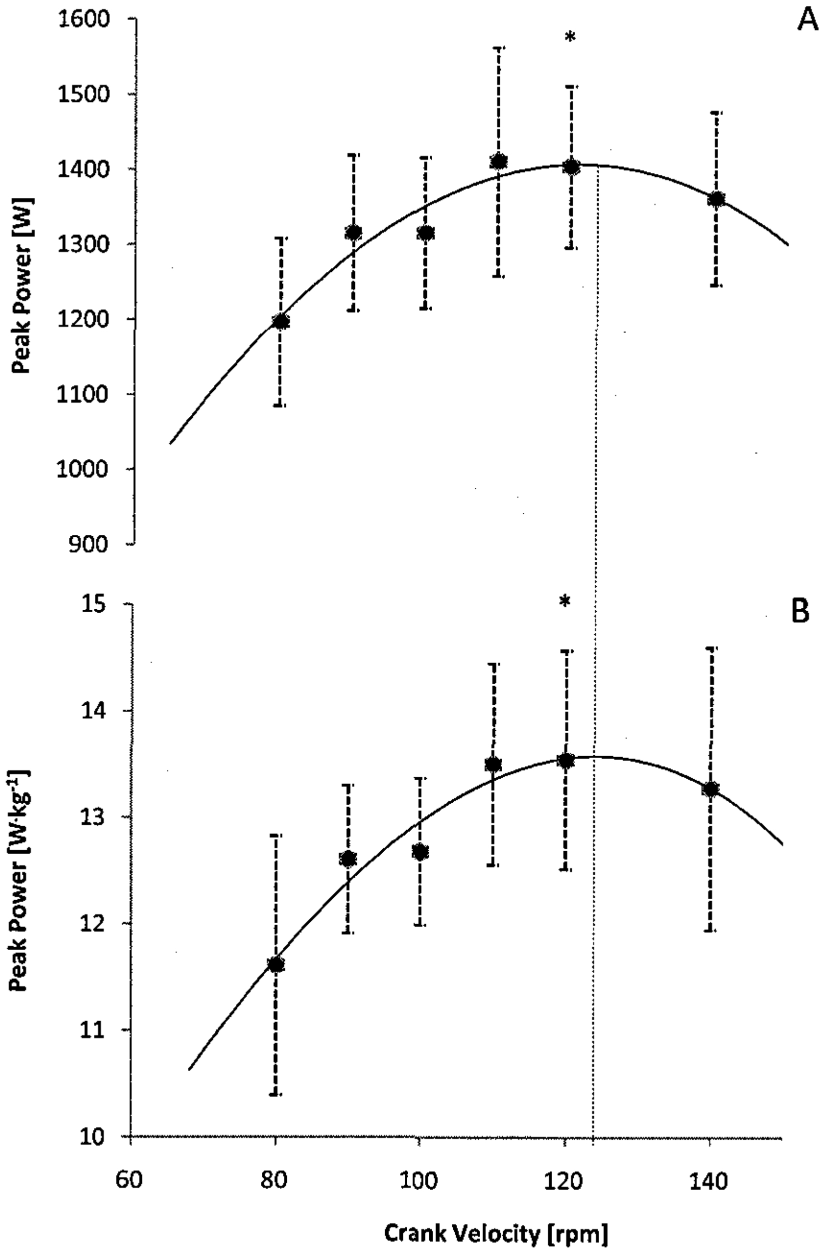


Figure 4.4 Relationship between **[A]** Peak Power (W) and Crank Velocity (angular velocity) during standing arm-cranking (grinding) (r=0.73, n=10). * 120 significantly greater than 80 rpm (P=0.03); **[B]** Relative Peak Power (W/kg) and Crank Velocity (r=0.81, n=10). * 120 significantly greater than 80 rpm (P=0.01).

4.4 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 $L{\cdot}min^{-1}$ (51 $ml{\cdot}kg^{-1}{\cdot}min^{-1}$) that we have found for a whole crew of America's Cup sailors, or the P_{max} of 1420 W (13.7 $W{\cdot}kg^{-1}$) for a sub-group of *grinders*. America's Cup grinding is unique in that it is the only able bodied sporting activity 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 $W{\cdot}kg^{-1}$) in javelin throwers and elite wrestlers (Hubner-Wozniak et al. 2004; Bouhlel et al. 2007) and 700 W (10.6 $W{\cdot}kg^{-1}$) 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 $L{\cdot}min^{-1}$ (Secher et al. 1974)) and elite sprint kayakers (4.3 $L{\cdot}min^{-1}$ (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 $L{\cdot}min^{-1}$) 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 $ml{\cdot}kg^{-1}{\cdot}min^{-1}$). Similar results have been reported previously with *bowmen*, 52 $ml{\cdot}kg^{-1}{\cdot}min^{-1}$ (Bernardi et al. 2007b). 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 activities performed by *bowmen* are typically more prolonged with short recovery periods, and thus more continuous and aerobic in nature than the activities of *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. However, 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 OBLA. 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. 2007b; 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 OBLA 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 make 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. 1973b), 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 large 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 angular 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 to be 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. 1973b).

The only documented evidence of crank velocity during America's Cup racing reported peak velocity of between 120 and 150 rpm (Bernardi et al. 2007b). 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.

4.4.1 *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 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.

CHAPTER 5

INFLUENCE OF ARM-CRANK CONFIGURATION ON GRINDING PERFORMANCE

5.1 Introduction

Arm-cranking, in particular standing arm-cranking has become increasingly popular as a means of assessing upper-limb performance (Hubner-Wozniak et al. 2004; Bouhlel et al. 2007; Pearson et al. 2007). However, the optimal configurations for power production during arm-cranking have not been determined. In cycling, the manipulation of joint angles, through changes in the structure of bicycle components, has been shown to influence performance (Hamley and Thomas 1967; Too and Landwer 2000; Martin and Spirduso 2001). For example, changes in seat height and cycle crank lengths directly affect hip and knee joint angles, the range of motion and angular velocity of the joints, and thus cycling performance (Too and Landwer 2000). The optimal crank length for maximum power production has been reported to be 20% of leg length (Martin and Spirduso 2001) and the optimal seat height appears to be 109% of inseam length (ischium to foot) (Hamley and Thomas 1967). It seems highly likely therefore that changes to the configuration of arm-crank ergometry, specifically crank length and crank-axle height, could also affect performance. Given the angle-torque and torque-velocity relationships of human muscle function, there is a clear rationale for how interventions that effect upper extremity joint range of motion and angular velocities may influence arm cranking performance.

Big-boat yacht racing is one of the only able bodied sports where arm-cranking is the primary physical activity. In the majority of professional big-boat yacht racing classes, manoeuvres are performed manually, without the assistance of stored energy, and arm-cranking ('grinding') is used to drive the winches, which in turn, controls the sails and mast (Whiting 2007). As the difference between competing yachts is often most apparent during manoeuvres, grinding is considered an important component to overall race performance. In support of this idea data presented in Chapter 3 found that a top level team completed manoeuvres more quickly than a lower ranked team, which was attributed in part to more effective grinding. International America's Cup Class version 5 yachts typically have four arm-crank stations ('grinding pedestals'), each manned by two athletes ('*grinders*'). The typical crank length and crank-axle height are 250 and 830-870 mm, respectively, but there seems to be no scientific rationale for these settings (Bernardi et al. 2007b; Pearson et al. 2007). The height of the grinding crank-axle appears to have been largely determined by other aspects of yacht design, such as the height of the boom and aerodynamics, without an understanding or consideration of the effects of crank height on 'grinding' performance.

No studies have examined the effect of changes in crank length and crank-axle height on power production during standing arm-crank ergometry. The identification of optimal crank lengths and crank-axle heights would further our understanding of standing arm-crank ergometry and may enhance the performance of America's Cup *grinders*. Therefore, the aim of this study was to assess the effects of different crank lengths and crank-axle heights on standing arm-cranking power and determine the optimal crank length and crank-axle height for maximum power production.

5.2 Methodology

5.2.1 *Participants*

Nine elite professional male America's Cup yacht racing *grinders* (mean ± SD; age: 36 ± 7 yrs) volunteered to participate in this study. Their physical characteristics are shown in Table 5.1. The athletes had all represented teams that competed in the 32^{nd} America's Cup, with their collective experience including 28 America's Cup campaigns and 13 World Championship titles. Informed consent was provided by all the athletes and the study was approved by the Loughborough University Ethical Advisory Committee.

5.2.2 *Anthropometric Measurements*

All anthropometric 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 to the nearest 0.1 kg using a calibrated digital scale (Metler Toledo KcC 150, Leicester, United Kingdom) and height was measured to the nearest 0.001 m using a stadiometer (Seca 222, Hamburg, Germany). Skinfold thickness was measured in duplicate at seven sites (triceps, biceps, subscapular, abdominal, supraspinale, thigh and medial calf) using calibrated skinfold callipers (Harpenden, Baty

International, West Sussex, United Kingdom). Percentage body fat was calculated from the sum of seven skinfolds (Siri 1961; Jackson and Pollock 1978). Arm span was measured with the athlete standing back against a wall, heels together and arms stretched out horizontally, and the distance between the tips of the furthest fingers on each hand was recorded (Marfell-Jones et al. 2006).

5.2.3 *Experimental Design*

All tests were conducted between 09h00 and 12h00. Anthropometric measurements were taken on arrival at the laboratory. After an initial 10 min self-paced warm-up, athletes performed eight maximum effort sprints at pre-determined combinations of crank length and crank-axle height in a randomised order. The protocol included variable crank lengths (162, 199, 236 and 273 mm) at a constant crank-axle height of 1050 mm, and variable crank-axle heights (850, 950, 1050 and 1150 mm) with a constant crank length of 250 mm. Each sprint was 6 s in duration with a 10 min rest interval between trials to ensure complete recovery. A 5 s countdown was given prior to the start of each sprint during which time a crank velocity of ~50 rpm was maintained. Verbal encouragement was given throughout the test. Torque and crank velocity were recorded throughout each sprint and analysed off-line. Power was determined as the product of torque (T) in Newton metres and crank velocity (ω) expressed in radians$\cdot s^{-1}$.

5.2.4 *Arm-crank Ergometer*

All tests were conducted on an adjustable standing arm-crank ergometer (Technogym Top Excite, Gambettolla, Italy), which was secured to the ground whilst remaining clear of the force plates (Figure 5.1). The resistance of the ergometer was set at level 30 (maximum), after the software was upgraded (Technogym Excite version SW50.22.7) to provide increased resistance. The crank handles were 0.52 m apart (medio-lateral displacement). An SRM power crank (SRM Science Powermeter V, Jülich, Germany) was fitted to the centre axle of the ergometer. 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 prior to each test protocol, according to the manufacturer's guidelines.

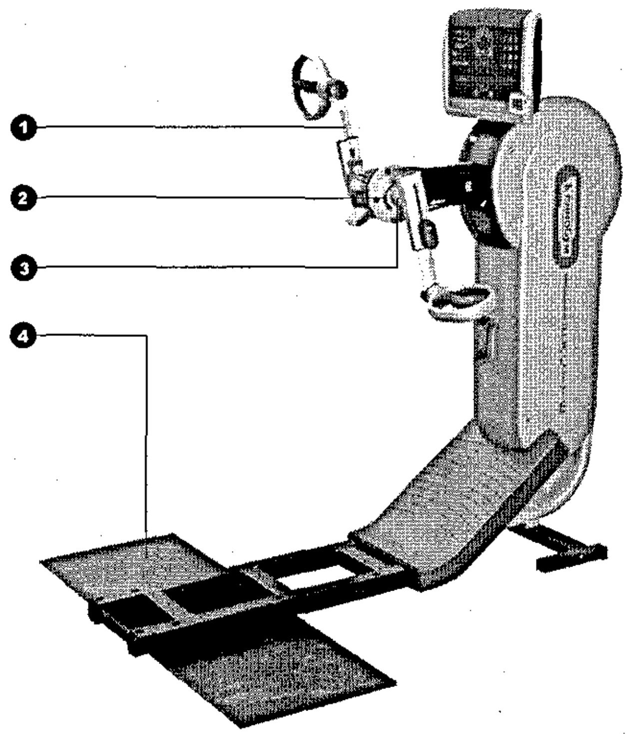


Figure 5.1 Adjustable standing arm-crank ergometer (Technogym Top Excite). (1) Adjustable crank length, (2) SRM scientific powercrank, (3) Adjustable crank-axle height, (4) Ground reaction force platforms (Kistler). Lateral distance between handles, 0.52 m.

5.2.5 *Vertical Ground Reaction Force Measurement*

Vertical ground reaction forces (VGRF) were measured using two calibrated force platforms (Kistler Instrument AG, 9253A2 [right] and 9281CA [left], Winterthur, Switzerland) with a sampling rate of 200 Hz. The arm-crank ergometer was positioned centrally over the two force platforms to allow the athletes to stand with one foot on each platform. The force platforms were calibrated according to the manufacturer's guidelines and zeroed prior to each sprint. The vertical ground reaction forces were analysed for each sprint over 5 s, beginning 1 s after the start of the sprint. The data was analysed to find the total VGRF (VGRFtotal, i.e. the sum of both plates) averaged over 5 s, and average unilateral amplitude of the VGRF (VGRFamplitude, i.e. average of each plate). During each crank rotation there is a shift in weight from one foot to the other producing a sinusoidal force trace. The amplitude of the sinusoidal force trace of each platform was measured as the average difference between the peaks and troughs.

5.2.6 *Video Analysis*

Reflective markers were attached to the right side of each athlete at the following anatomical positions: iliac crest, greater trochanter and lateral epicondyle of the femur, and lateral malleolus of the fibula. All sprints were recorded by a video camera (Panasonic NV-DS99EG mini DV, Japan) at 25 Hz, which was positioned perpendicular to the sagital plane of the ergometer, 7 m from the athletes and at a fixed height of 1 m. Four 500 W lamps were projected onto the athlete to provide additional lighting. Hip joint angle, between the iliac crest, greater trochanter and the knee, knee joint angle and foot-to-floor angle were measured after 3 s of maximal grinding, on the right side of the body, when the right knee was at maximum extension. The determination of joint angles was performed using a digital software program (SiliconCOACH PRO, Dunedin, New Zealand).

5.2.7 *Statistical Analysis*

Peak power, VGRFtotal and VGRFamplitude for the different crank lengths and crank-axle heights were compared with one-way repeated-measures ANOVA. Bonferroni post-hoc tests were used to determine where any differences lay. Pearson product-moment correlation coefficients were calculated to assess bivariate relationships. Analyses were performed using SPSS for Windows version 15.0. Significance was defined as $P \leq 0.05$, and all data are presented as mean ± SEM.

5.3 Results

The anthropometric characteristics of the *grinders* are shown in Table 5.1. The athletes were characterised as having a high fat-free mass. There was a significant difference in peak power between crank lengths (P=0.006), with a lower peak power for 162 mm than all other crank lengths (P<0.03, Table 5.2). When crank length was normalised for arm-span, the relationship between maximum power and crank length (CL) was parabolic and fitted by the equation: Power = $-11.127(CL)^2 + 274.7(CL) - 361.2$; r=1.0 (computed to five decimal places; Figure 5.2). From this relationship, the highest theoretical peak power occurred at a crank length of 12.3% of arm span which in these *grinders* equated to 241 ± 9 mm.

Table 5.1 Anthropometric characteristics of America's Cup grinders

	Body Mass [kg]	Σ 7 Skinfolds [mm]	Body Fat [%]	Fat-free Mass [kg]	Height [m]	Arm span [m]
Mean	103.6 ± 1.3	71 ± 8	13 ± 2	89.8 ± 1.8	1.90 ± 0.01	1.96 ± 0.02
Range	100.3 to 109.9	35 to 106	6 to 24	76.7 to 94.7	1.83 to 1.95	1.86 to 2.05

Data are mean ± SEM (n=9)

Table 5.2 Peak Power during maximal arm-cranking with varying crank lengths and crank-axle heights

	Crank Length [mm]				Crank-axle Height [mm]			
	162	*199*	*236*	*273*	*850*	*950*	*1050*	*1150*
Peak Power [W]	1153 ± 56[a]	1276 ± 47	1335 ± 66	1303 ± 46	1252 ± 43[b]	1340 ± 51	1303 ± 53	1347 ± 46
Range	929 to 1379	1078 to 1455	1104 to 1691	1127 to 1523	1062 to 1442	1187 to 1609	1138 to 1649	1151 to 1523

[a] less than all crank lengths (P<0.03); [b] less than crank-axle height of 1150 mm (P=0.01); Data mean ± SEM (n=9)

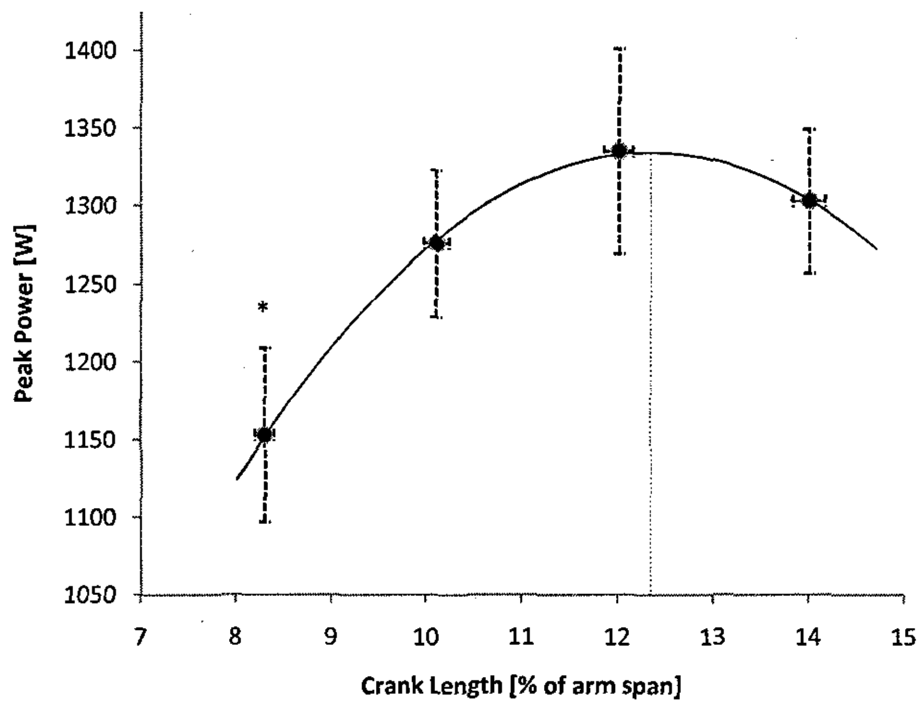


Figure 5.2 Relationship between Peak Power and Crank Length (CL), as a percentage of arm span, during standing arm cranking ('grinding'). The equation was: $Power = -11.127(CL)^2 + 274.7(CL) - 361.2$ (r=1.0, n=9). Data are mean ± SEM. * Significantly less than all other crank lengths (P<0.03)

Peak power was significantly less for the crank-axle height of 850 mm compared to 1150 mm (P=0.01) (Table 5.2). Prior to normalising crank-axle height to stature, two athletes were excluded from the data analysis as they exhibited significant differences in technique from all other athletes. This included substantial ankle plantar flexion, measured by foot-floor angle (53 ± 4° and 42 ± 5° for the excluded athletes *vs.* 4 ± 2° for the remaining athletes, ANOVA P<0.001), thereby confounding their true stature. The theoretical optimum for crank-axle height for the group (n=7) was 57.3% of stature (Figure 5.3), which was 1087 mm in this cohort of *grinders*.

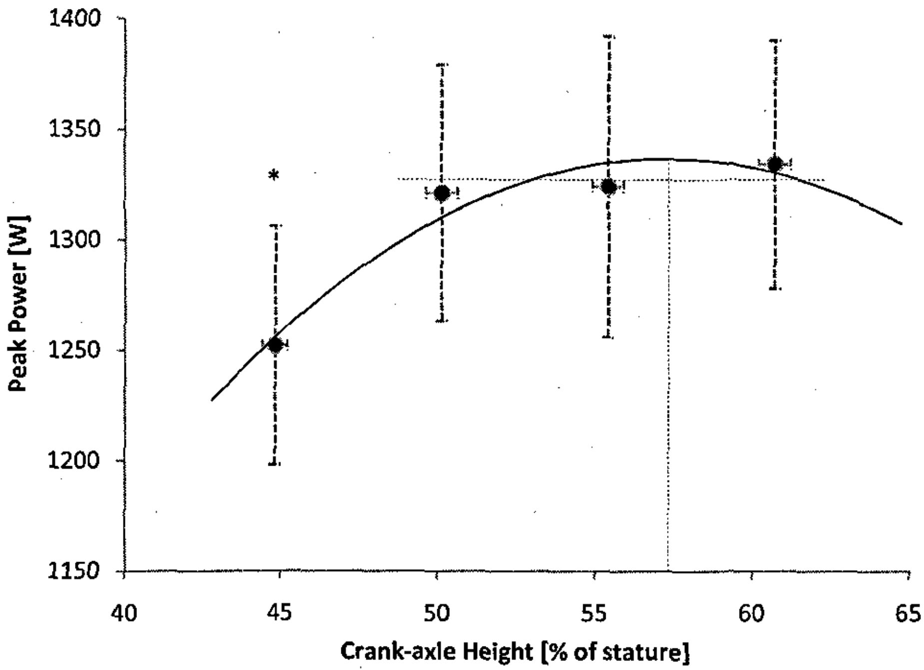


Figure 5.3 Relationship between Peak Power and Crank-axle Height, as a percentage of stature, during standing arm-cranking (grinding). Data are mean ± SEM (r=0.97, n=7). * Significantly less than Crank-axle Height of 60.7% of stature (P=0.01)

Hip joint angle during arm-cranking was influenced by crank-axle height (P=0.001, Figure 5.4), with the hip joint angle at 850 mm significantly less than at 1050 and 1150 mm (127 ± 3° *vs*. 142 ± 3° and 146 ± 3° respectively, P<0.01, n=7), but similar to 950 mm (136 ± 3°). Knee joint angle was unaffected by crank-axle height.

VGRFtotal was significantly different between crank-axle heights (P<0.001, Table 5.3), with 850 mm less than all other heights (P<0.02) and 950 mm greater than 850 mm and less than 1050 and 1150 mm (P<0.02). VGRFtotal was not influenced by crank length. VGRFamplitude was unaffected by crank length, although it did show a correlation to crank length (r=0.97, P=0.02, n=4); these differences were non-significant.

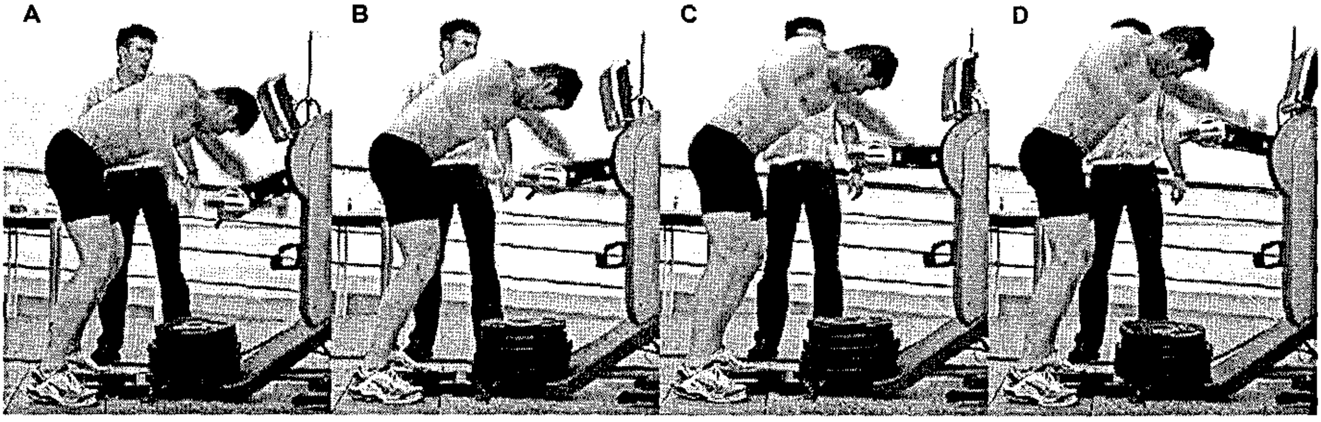


Figure 5.4 Images showing grinding at different crank-axle heights (**A** = 850 mm, **B** = 950 mm, **C** = 1050 mm, **D** = 1150 mm). For the group the hip angle in **A** was significantly less than **C** and **D** (*n*=7, P<0.01). (courtesy of Neville & Folland, © Vernon Neville 2008)

Table 5.3 Vertical ground reaction forces, mean total vertical ground reaction force (VGRFtotal) and unilateral peak-to-trough amplitude (VGRFamplitude) *averaged for left and right legs, during maximal arm-cranking sprints with varying crank lengths and crank-axle heights*

	Crank Length [mm]				Crank-axle Height [mm]			
	162	**199**	**236**	**273**	**850**	**950**	**1050**	**1150**
VGRFtotal [N]	956 ± 21	970 ± 23	968 ± 24	966 ± 20	883 ± 19[a]	925 ± 17[b]	957 ± 20	984 ± 16
VGRFamplitude [N]	959 ± 87	964 ± 100	977 ± 98	996 ± 96	1011 ± 79	979 ± 89	997 ± 85	993 ± 106

[a] less than all other crank-axle heights (P<0.02); [b] greater than 850 and less than 1050 and 1150 (P<0.02); All data are mean ± SEM (n=9)

5.4 Discussion

The main findings of this study were that changes in crank length and crank-axle height influenced performance during maximal standing arm-crank ergometry. The parabolic curves observed for peak power with increasing crank lengths and crank-axle heights can be attributed to interactions between torque, crank velocity, and posture. The design and configuration of arm-crank ergometers and grinding pedestals should recognise the importance of these variables to performance, and we suggest an optimum crank length of 12 – 12.5% of arm span and an optimum crank-axle height of 50 - 60% of stature (~241 and ~1087 mm, respectively, in this cohort of *grinders*).

The peak power values reported in this study (range: 929 to 1691 W, Table 5.2) are among the highest reported during arm-cranking. This is likely due to the unique nature of this cohort of athletes, who are selected and trained for the specific activity of standing arm-cranking (Neville 2008), and the use of more favourable arm-crank configurations than have often been employed. The selection of optimal arm-crank length for maximal power may be of interest to big-boat *grinders* and to studies using standing arm-crank ergometry as a measure of performance. Our data demonstrate that the optimal crank length for maximal power production was 12.3% of arm span, which equated to an optimal crank length of 241 mm (range, 228 to 252 mm) in this cohort of athletes (Figure 5.2). This optimum crank length for the cohort was within 4% (9 mm) of the standard crank length used on America's Cup racing yachts (250 mm or 12.8% of arm span in this cohort). From the crank length-power relationship (Figure 5.2), this equates to a reduction in power of <0.2% for the standard crank length compared to the optimum we have found. Essentially, the standard crank length used in big-boat sailing facilitates very close to optimal power production for these elite *grinders* who have a wide arm span. Overall, the 68% variation in crank lengths used in this study elicited a 16% variation in maximum arm-cranking power, which is considerably greater than the variation reported in cycling (Martin and Spirduso 2001). The optimal crank length in cycling has been determined to be 20% of leg length which equates to ~170 mm for the average population (Martin and Spirduso 2001). Standard cycling cranks (170 to 180 mm) have also been used extensively for arm-crank ergometry studies, with the pedals replaced by handles (Vandewalle et al. 1989; Bouhlel et al. 2007). This length of crank appears to be substantially less than the optimum we have found, and based on our data would have resulted in a 13% reduction in power production, although individual differences in physique might attenuate the magnitude of this decrement.

The influence of crank length on performance is due to the complex interaction of force, torque and angular velocity (Gardner et al. 2007). Shorter crank lengths tend to decrease torque and elevate crank velocity (Martin and Spirduso 2001). Therefore grinding at different crank lengths involves changing the contractile conditions across the range of the power-velocity relationship. As the power-crank velocity relationship is parabolic (Martin and Spirduso 2001; Dorel et al. 2005), it is not surprising therefore that the power-crank length relationship is also parabolic. Hence peak performance (power) occurs at an optimum combination of torque and angular velocity.

In order to remove differences in physique and provide a normalised measurement, crank-axle height was calculated relative to stature. However, two athletes had an obviously different technique to the rest of the cohort, which included substantial plantar flexion of the ankle that changed their effective stature, and they were therefore excluded from the relative height data. There was little difference in performance between crank-axle heights of 50 to 60 % of stature, however, peak power was significantly reduced when the crank-axle height was less than 50% of stature. These results indicate that the typical height of the grinding pedestals used on America's Cup yachts (~850 mm) would reduce peak power by as much as 7% for the athletes tested in this study. Unfortunately, the highest crank-axle height investigated in this study was 60.7% of stature, as it would have been interesting to determine the effect of greater heights.

In cycling, seat-to-pedal height distance influences performance due to changes in joint angle at the hip and knee (Hamley and Thomas 1967). Although it could be assumed that crank-axle height may have a similar effect on standing arm-crank performance, the joints with the greatest range of motion during arm-cranking, the elbow and shoulder, are not directly affected by the crank-axle height. Rather, it is the hip angle which had the greatest change according to the crank-axle height. The decreased hip angle at lower crank-axle heights resulted an increased portion of the athlete's body mass being supported by the ergometer, as shown by the decreased VGRFtotal through the feet, presumably due to the athletes centre of gravity shifting forwards. The additional weight bearing of the upper limbs in this off-balance position results in an increase in energy required to move the limbs and to stabilise the upper body. This internal work is likely to be greater when the athlete is in an unbalanced posture, reducing the energy available at the crank, and may explain the attenuated peak power at the lowest crank-axle height. Another consideration is that with the increased hip flexion at lower crank-axle heights (Figure 5.4), the load on the lower back would be expected to be greater. The incidence of lumbar spine injuries in America's Cup yacht racing is high (Allen 1999; Allen 2005; Neville et al. 2006), and this has been previously attributed to the forward flexed and rotated position of the spine during grinding at standard crank-axle heights (Allen 2005; Neville et al. 2006). Future research should investigate optimal body posture and joint angles on the technique of grinding performance.

5.4.1 *Conclusions*

Crank length and crank-axle height influence performance in standing arm-crank ergometry. The optimal crank length for maximal power was 12.3% of arm-span or 241 mm for the cohort in this study. These results, suggest that standard cycle crank lengths are inappropriate for maximal arm-cranking performance. Optimal crank-axle height was between 50 and 60% of stature (950 to 1150 mm in this study), and a crank-axle height of <50% of stature, which is typically used in America's Cup sailing, may result in reduced performance. The design and configuration of arm-crank ergometers and grinding pedestals should use these findings in optimising performance.

CHAPTER 6

LOWER LIMB CONTRIBUTION TO GRINDING TECHNIQUE

6.1 Introduction

Standing arm-cranking ('grinding') is the primary physical activity in professional big-boat yacht racing such as the America's Cup. Racing yachts are powered by the wind flowing over the sails, which act as aerofoils to create lift, which propels the yacht. The sails are manipulated ('trimmed') by grinding performed on standing arm-crank assemblies ('grinding pedestals') which drive the winch system that in turn controls the sails (Pearson et al. 2007). There are typically four grinding pedestals on an International America's Cup Class version 5 racing yacht, each manned by two athletes ('grinders'). Grinders are characterised by having a large muscle mass and body size (Bernardi et al. 2007b; Neville 2008) in order to generate a high power output during manoeuvres such as tacking and gybing, and while trimming the sails, which have loads of up to several tons. Grinding is largely an intermittent activity, with work bouts ranging from a few seconds to more than 60 s during strenuous manoeuvres, such as the mark roundings. A typical America's Cup race involves ~31 manoeuvres (3 mark roundings, 20 tacks and 8 gybes), and in close racing all manoeuvres require maximal effort grinding. The difference between competing yachts is often most apparent during manoeuvres, hence grinding is considered an important component of overall race performance.

Although grinding is regarded as predominantly upper-body exercise, some athletes grind with distinct flexion and extension of the knee joint, and rotation of the pelvis in the horizontal plane, whilst for others the lower body is more rigid. It has been proposed that the lower limbs and trunk musculature contribute substantially to grinding performance (Bernardi et al. 2007b; Pearson et al. 2007), but this idea is controversial. One report suggested that the trunk and lower limbs should "remain square", and "rotation of the hips should be avoided" during grinding (Chisnell 2008). Hence the optimum grinding technique with respect to the role of the legs is largely unknown. During tennis serving and cross-country skiing double-poling, the influence of the lower limbs on performance has recently been investigated (Holmberg et al. 2006; Girard et al. 2007). As with grinding these activities involve the upper-body performing the majority of the physical work, with a smaller, but perhaps important contribution of the lower-body. A study of the effects of restricted knee and ankle joint mobility on submaximal double-poling in a group of elite cross-country skiers found that lower limb restriction elicited a higher blood lactate concentration and heart rate response with no difference in oxygen consumption (Holmberg et al. 2006). These findings suggest that the dynamic use of the lower limbs may benefit double-poling performance by decreasing the cardiovascular and metabolic stress of exercise.

It has been found that as the proportion of physical work performed by the upper body increases, as a fraction of whole body work, there is a concomitant increase in cardiovascular strain (Toner et al. 1983; Sawka 1986; Secher et al. 1974). In other words, as the contribution of the upper body increases a greater cardiovascular effort is needed to overcome the same workload, resulting in more severe physiological and metabolic strain. This evidence suggests that an increased involvement of the lower body may be advantageous in grinding.

Therefore, the aim of this study was to examine the influence of restricted knee joint motion on the cardiovascular stress of standing arm-cranking (grinding) in elite professional America's Cup grinders. We hypothesized that there would be greater physiological stress during grinding with restricted lower limb activity compared with free/dynamic knee joint movement.

6.2 Methodology

6.2.1 *Participants*

Eight elite professional male America's Cup *grinders* (mean ± SD: age, 37 ± 7; height, 189.5 ± 4.0 cm; body mass, 102.9 ± 3.4 kg; and % body fat, 12.7 ± 5.7%) were recruited for the study. Their collective sailing experience included 19 previous America's Cup campaigns. All the athletes had at least eight years experience as an America's Cup *grinder*. At the time of the study, all the athletes were out of competition and each were following a low to moderate off-season strength and conditioning programme. The athletes were fully acquainted with the nature of the study before they gave written informed consent to participate. The experimental protocol was approved by the Loughborough University Ethical Advisory Committee.

6.2.2 *Experimental Protocol*

The athletes visited the laboratory on two consecutive days. On the initial visit the athletes completed a health questionnaire, which was followed by anthropometric assessments. Nude body mass was measured to the nearest 0.1 kg using a calibrated digital scale (Metler Toledo KcC 150, Leicester, UK) and height was measured to the nearest 0.001 m using a stadiometer (Seca 222, Hamburg, Germany). Skinfold thicknesses were measured in duplicate at seven sites (triceps, biceps, subscapular, abdominal, supraspinale, thigh and medial calf) using calibrated skinfold callipers (Harpenden, Baty International, West Sussex, UK). Percentage body fat was calculated from the sum of seven skinfolds (Siri 1961; Jackson and Pollock 1978). The athletes then returned to the laboratory the following afternoon to complete the exercise testing.

After a 3 min warm-up at 160 W, the athletes performed two exercise trials in a cross-over design, each comprising two 5 min stages separated by a 3 min recovery interval, with a 45 min rest period between trials. The 5 min stages were either normal grinding, where the legs were able to move freely, or splinted grinding, where the legs where restricted from movement (Figure 6.1). For each athlete the same work rate was used for all four bouts of grinding and ranged from 213 to 257 W. The work rate was selected to be at an intensity of ~4 $mmol \cdot L^{-1}$, or ~75% of peak oxygen uptake based on our previous work with this cohort and knowledge of each athlete's current fitness status. The athletes were required to maintain a crank velocity of ~85 rpm during all stages. The legs were restricted from movement by locking the knee joint at full extension with a 20 mm thick wood brace positioned along the posterior of the leg (spanning from the heel to the gluteal fold) and held in place using a neoprene knee brace and taped to the leg at the mid-thigh, knee and ankle joints (Figure 6.1).

6.2.3 *Arm-crank Ergometer*

Exercise testing was performed using a standing arm-crank ergometer (Technogym Top Excite, Gambettolla, Italy), which was secured to the ground (Figure 6.1). The crank length was set to 250 mm, which is similar to that commonly used on International America's Cup Class version 5 yachts (Pearson et al., 2007). Each athlete selected their preferred crank-axle height, which ranged from 1040 to 1150 mm. The crank handles were 520 mm apart (medio-lateral displacement). An SRM power crank (Science Powermeter V, Schoberer RadMesstechnik, Jülich, Germany) was fitted to the centre axle of the cranks. Power was calculated by the system software, based on the equation: power (W) = torque (Nm) x angular velocity ($radians \cdot s^{-1}$) and recorded every 0.5 s. The SRM system was zeroed prior to each test stage and calibrated according to the manufacturer's guidelines prior to the start of each athlete's protocol.

6.2.4 *Physiological Measurements*

An online breath-by-breath gas analysis system (BreezeSuite CPX Ultima, Medical Graphics Corp., Minnesota, USA) was used to monitor oxygen uptake (VO_2), carbon dioxide production (VCO_2), respiratory exchange ratio (RER), and minute ventilation (V_E) during each exercise stage. The athletes wore a telemetric heart rate (HR) monitor (Polar Electro, Finland). Before each test, the gas analyzers were calibrated with known gases (12% O_2 and 5% CO_2) and the flowmeter was calibrated with a 3.0-L air syringe at low, medium, and high flow rates. The athletes breathed through a mouthpiece held in place by a tightly fitted neoprene mask to ensure that all expired air was sampled. Baseline resting data was obtained for one minute prior to the start of each trial. Average values of all the respiratory variables were calculated for the final two minutes of each stage. Earlobe blood samples (5 μM) were analyzed in duplicate for blood lactate concentration using an automated lactate analyser (Analox P GM7, Analox Instruments Ltd., Hammersmith, UK) at rest, one minute post-warm up, and one minute after each exercise stage. The blood lactate analyzer was calibrated before each trial using a lactate standard of 8 $mmol \cdot L^{-1}$.

6.2.5 *Vertical Ground Reaction Force*

The arm-crank ergometer was positioned centrally over two adjacent force plates (Kistler Instrument AG, 9253A2 [right] and 9281CA [left], Winterthur, Switzerland) which were used to measure vertical ground reaction force (VGRF) for each foot independently (Figure 6.1). The force platforms were calibrated according to the manufacturer's guidelines and zeroed prior to each stage. Data was collected for 5 s during the final minute of each stage at a sampling rate of 200 Hz. The data was analysed to determine the total VGRF (VGRFtotal, i.e. the sum of both plates) averaged over the 5 s period, and average unilateral amplitude of the VGRF (VGRFamplitude, i.e. average of each plate) for both conditions. During each crank rotation there is a shift in weight from one foot to the other producing a sinusoidal force trace. The amplitude of the sinusoidal force trace of each platform was measured as the average difference between the peaks and troughs.

6.2.6 *Video Analysis*

Reflective markers were attached to the right side of each athlete on the; greater trochanter and lateral epicondyle of the femur and the lateral malleolus of the fibula. A video camera (Panasonic NV-DS99EG mini DV, Japan) was positioned perpendicular to the sagittal plane of the athlete, 7 m away at a height of 1.0 m. Video data was collected for 30 s during the final minute of each stage at a sampling rate of 25 Hz. The determination of joint angles was performed using a digital software program (SiliconCOACH PRO, Dunedin, New Zealand). The range of motion of the knee joint was determined as the difference between maximal extension and flexion of the right knee joint during one full crank rotation.

6.2.7 *Statistical Analysis*

Physiological data was calculated over the last two minutes of each five minute stage and averaged for each condition. Power output, cardiorespiratory variables, blood lactate, the change in knee angle, and VGRFtotal and VGRFamplitude data were compared between the two conditions using a standard *t*-test for paired samples. Data was analysed using SPSS version 15.0 for Windows (SPSS Inc., Chicago, USA) and all data were checked for normality and presented as mean ± SD. Statistical significance was set at $P \leq 0.05$.

6.3 Results

The splinting intervention had a clear effect on the range of motion of the knee joint (normal, 17.8 ± 5.3° *vs.* splinted, 3.5 ± 3.2°, $P<0.001$). There was no difference in VGRFtotal between the two grinding conditions ($P=0.07$) (Table 6.1), however, normal grinding elicited a greater VGRFamplitude compared with splinted grinding (P=0.01) (Figure 6.2).

Table 6.1 Total vertical ground reaction force (VGRF total) and unilateral amplitude (VGRF amplitude) during normal grinding and grinding with legs splinted

	VGRFtotal (N)	VGRFamplitude (N)
Normal	957 ± 46	776 ± 186*
Splinted	967 ± 47	565 ± 180

** Significantly greater than Splinted (P=0.01)*
Mean ± SD, n=8

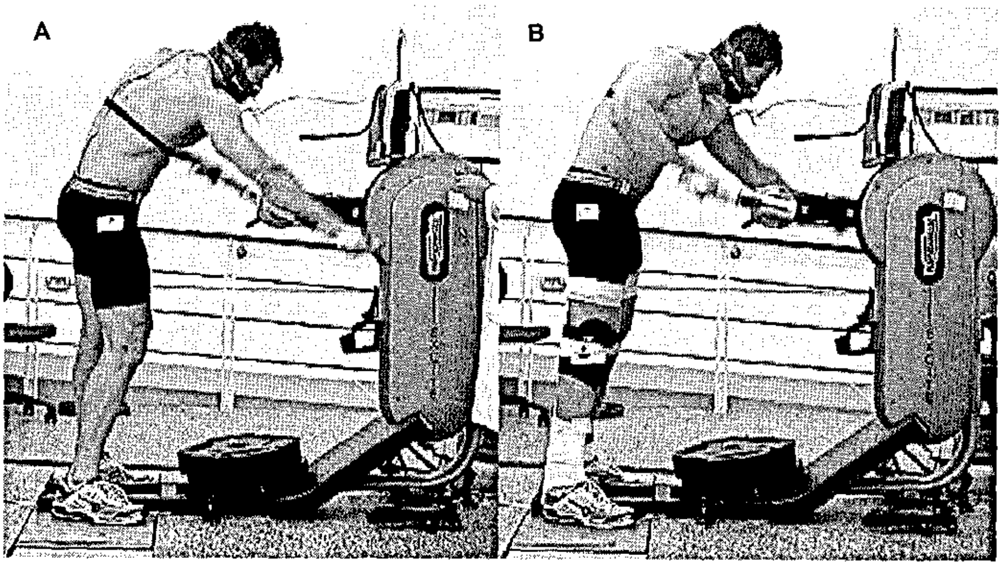


Figure 6.1 Normal grinding (**A**) and Splinted grinding (**B**) showing the change in knee joint angle when splinted. (© Vernon Neville 2008)

The work rate was identical for the two grinding conditions (246 ± 14 *vs.* 246 ± 13 W; P=0.7). The cardiorespiratory and metabolic responses to grinding are presented in Table 6.2. There was no significant difference in VO_2 between the two conditions (P=0.2, Figure 6.3), however, there were increases in VCO_2 (8%, P=0.001, Figure 6.4), RER (11%, P<0.001), V_E (17%, P<0.001) and HR (7 ± 3 beats·min^{-1} higher, P<0.001) during splinted compared with normal grinding. Due to an experimental error blood lactate values were only available on four athletes, however, the rise in the blood lactate concentration above post-warm up values was greater after splinted than normal grinding (4.8 ± 0.8 *vs.* 3.7 ± 1.0 mmol·L^{-1}, P=0.04).

Table 6.2 Cardiorespiratory and metabolic responses of America's Cup grinders during normal grinding and grinding with legs splinted.

	Work Rate (W)	VO_2 (L·min^{-1})	VCO_2 (L·min^{-1})	RER	V_E (L·min^{-1})	HR (beats·min^{-1})
Normal	246 ± 14	4.1 ± 0.2	4.1 ± 0.3	1.01 ± 0.06	129 ± 18	165 ± 13
Splinted	246 ± 13	4.0 ± 0.2	4.5 ± 0.3*	1.12 ± 0.10*	151 ± 18*	172 ± 12*

** Significantly greater than Normal (P<0.001), Mean ± SD, n=8*

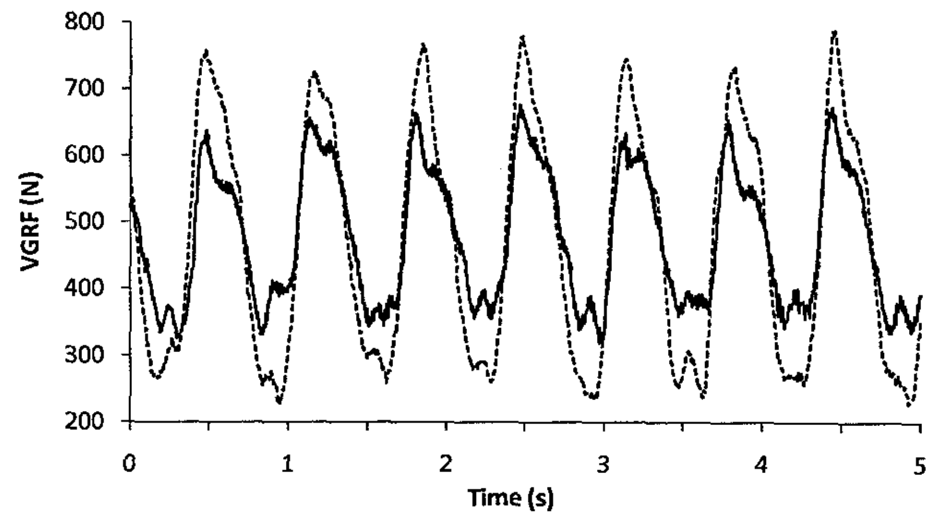


Figure 6.2 Vertical ground reaction force (VGRF) from the right leg of *an athlete (102 kg) during* Normal grinding (broken line) and Splinted grinding (solid line)

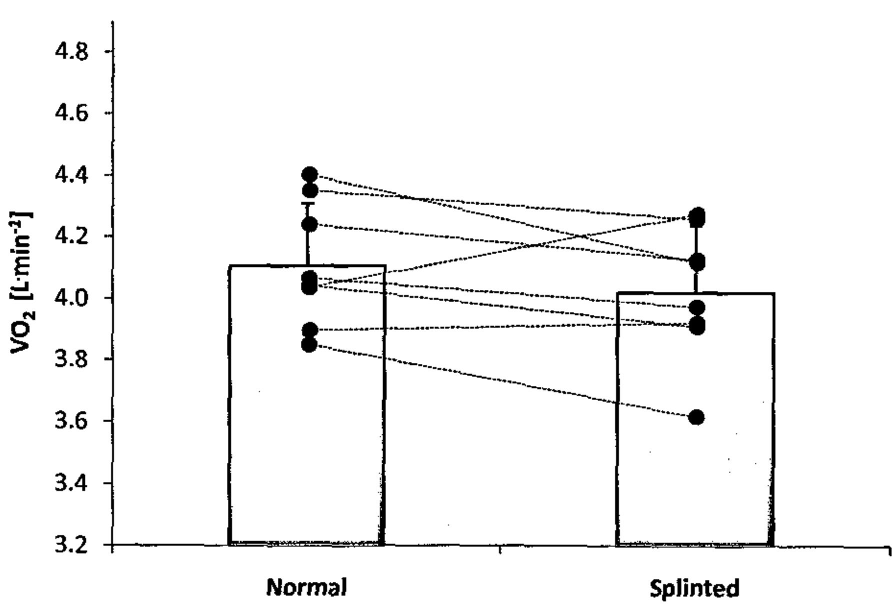


Figure 6.3 Mean VO_2 for the group (bar graph) and individual changes *during normal and splinted grinding* (n=8)

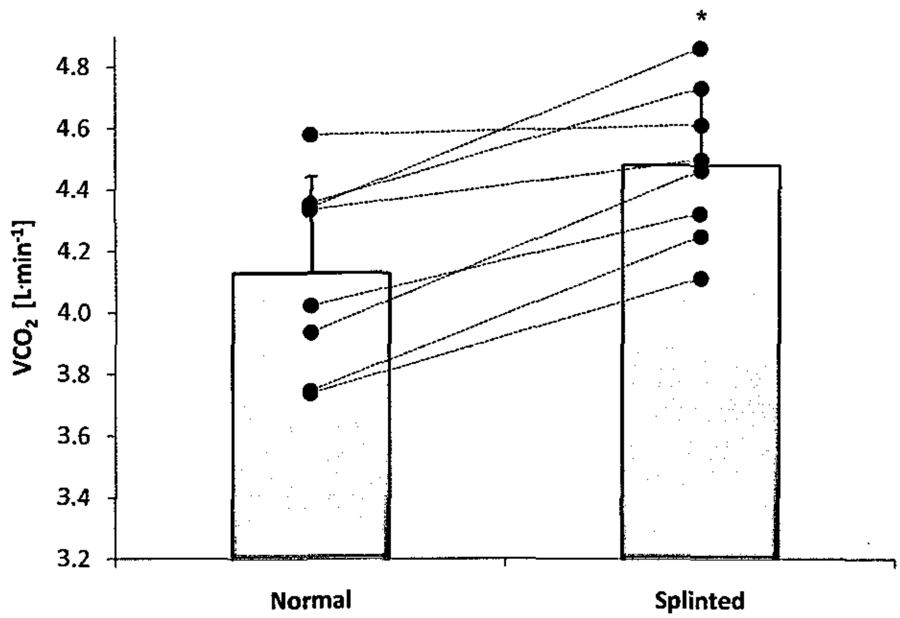


Figure 6.4 Mean VCO_2 for the group (bar graph) and individual changes during normal and splinted grinding (n=8). * Significantly *greater than normal* (P=0.001)

6.4 Discussion

This study examined the influence of restricted knee joint motion on the physiological responses to grinding in elite professional America's Cup sailors. The main findings were that splinted grinding elicited a higher CO_2 production, minute ventilation, heart rate and blood lactate concentration than normal grinding. These data suggest that the lower limbs play an integral role in grinding, and that restricting knee joint movement markedly affects the cardiovascular and metabolic responses to this activity. To our knowledge, this is the first study to characterize the involvement of the lower extremities during standing arm-cranking (grinding). Given these findings, use of the lower limbs seems certain to enhance grinding performance.

The difference in knee joint range of motion between the two conditions clearly demonstrates that the splinting intervention was effective at reducing lower limb movement. Similar splinting techniques have been employed previously in an effort to assess the contribution of joint mobilisation to sports performance (Holmberg et al. 2006; Girard et al. 2007). In the present study vertical ground reaction force was measured from both the left and right legs during normal and splinted grinding. The VGRFamplitude was greater during normal grinding, which highlights a distinct shift in body mass from the left to right leg during grinding (Figure 6.2). This emphasizes the active involvement of the lower extremities during grinding and indicates that, consistent with the study design, the influence of the lower limbs was effectively reduced by the use of splinting. The similar VGRFtotal values during the two conditions, confirmed that the athlete's weight distribution between their feet and the ergometer was unaffected by the splinting intervention.

The work rate was selected to be at the approximate intensity of the 4 $mmol \cdot L^{-1}$ lactate threshold (OBLA), in order that any differences in physiological stress would reveal clear changes in cardiovascular and metabolic responses. The two conditions involved the same power output (246 W, P=0.7), yet carbon dioxide production, minute ventilation, heart rate and blood lactate concentration were all significantly higher during splinted grinding, with no change in oxygen uptake. Therefore restricted lower limb movement resulted in a marked increase in physiological stress, and a shift towards anaerobic metabolism. Similar results have been reported during cross-country skiing, where significant increases in HR, V_E and BLa occurred as a result of double poling with restricted knee and ankle joints (Holmberg et al. 2006).

There are several interconnected explanations for the changes that occurred during lower limb splinting. Firstly, during splinted grinding there is an increase in the proportion of work done by the upper limbs, increasing the demand of these muscles for energy. As the exercise intensity is already at ~ anaerobic threshold during normal grinding, the additional demand for energy will be met by largely anaerobic metabolism and earlier recruitment of the more glycolytic type II muscle fibres (Schneider et al. 2002; Holmberg et al. 2006). The shift in the proportion of work done by the upper body musculature, that appears to be less efficient at oxygen extraction and to have a lower muscle capillary oxygen conductance than leg muscles (Calbet et al. 2005), may contribute to the increase in anaerobic metabolism. Secondly, during dynamic exercise, a decrease in active muscle mass, for the same work load, leads to a reduction in venous return and lower central blood volume (Toner et al. 1983). This has been shown to attenuate central venous pressure, resulting in a greater heart rate response (Ray 1999). The reduced ability for oxygen extraction by the upper body musculature may also require a greater cardiovascular effort in order to complete the same work. Thirdly, the blood lactate concentration is well known to be a balance of production and removal (Hermansen and Stensvold 1972). The upper limbs have a higher tendency to produce lactate and a lower ability to utilize lactate, than the lower limbs during moderate to high activity (Van Hall et al. 2003). The use of lactate by skeletal muscle appears to be higher when light exercise is performed compared with at rest (Hermansen and Stensvold 1972). Therefore, lower limb activity during grinding may also be important for lactate clearance. This indicates that even a small activation of the lower limb muscles (i.e. an active contribution by the legs during grinding) may also be important for lactate clearance (Toner et al. 1990).

A further consideration is the involvement of the kinetic chain in generating force. It is clear from the change in knee joint angle as well as the VGRFamplitude that during normal grinding there is substantial knee extension and flexion. On more detailed kinematic investigation it is clear that knee extension and hip elevation and posterior rotation (in the horizontal plane) of one leg precedes the main power generating push phase of the contralateral arm. In other words the right leg straightens first, in order to shift the centre of mass to the left side and provide momentum for the left arm push. Indicating that during normal grinding the force is initiated proximally and transferred through a coordinated movement of muscle activation along the kinetic chain. Therefore, by restricting the knee motion, VGRFamplitude and the medio-lateral body mass shift, it is likely that the normal pattern of force generation is disrupted, increasing the reliance on the distal upper limbs for force generation. It is possible that greater lower limb activity than was typical in the normal grinding we have observed could be beneficial to grinding performance, however further investigation is needed to better understand the relationship between lower extremity function and grinding performance.

Given the results of this study, it is reasonable to suggest that incorporating appropriate lower limb conditioning and technique exercises into the athletes training programmes may benefit grinding performance by enhancing leg muscle activation and developing lower limb motor control. For example, exercises that invoke specific patters of neuromuscular recruitment and activation along the kinetic chain, such as explosive whole body exercises, and dynamic exercises that activate the trunk muscles in transferring power from proximal to distal are recommended.

An interesting observation of this study was that the self-selected height of the grinding crank-axle (range, 1040 to 1150 mm) was substantially higher (>25%) than that typically used on America's Cup class yachts (~ 830 mm) (Bernardi et al. 2007b; Pearson et al. 2007). This suggests that the standard grinding pedestal height may not be the most comfortable for grinding performance, as well as being a potential risk factor for lower back injury (Allen 2005; Neville et al. 2006).

The results of this study may also have important clinical implications for cardiovascular rehabilitation where patients often use arm-cranking as an alternative form of rehabilitative exercise (Sawka et al. 1983a; Leon 2000; Westhoff et al. 2008). The incorporation of lower limb activity during arm-cranking, would facilitate completion of an equivalent work rate and therefore energy expenditure, oxygen uptake and presumably training response for a lower physiological strain (Vokac et al. 1975).

6.4.1 *Conclusions*

The present study demonstrates that restricted leg movement during standing arm-cranking increases the physiological strain of this activity. Therefore, a purely stabilising role of the lower limbs is discouraged and it is recommended that grinders make dynamic use of the legs to maximise lower limb involvement and decrease cardiovascular and metabolic responses to exercise. Furthermore, the involvement of the lower limbs in grinding reinforces the importance of lower limb conditioning for grinders. Future research on grinding performance should consider evaluating the sequential pattern of muscle activation, and how body segments in the upper and lower-body interact during the different phases of arm-cranking.

CHAPTER 7

THERMOREGULATORY DEMANDS OF RACING

7.1 Introduction

Competitive in-shore yacht racing predominantly takes place during the summer months when athletes may be exposed to hot and humid environmental conditions for prolonged periods. The America's Cup is the most prestigious professional yacht racing event and is regarded as the "Formula 1" of sailing. The 25 m long, 24,000 kg, version 5 International America's Cup Class high performance racing yachts are sailed by a crew of 17 skilled athletes in a "match race" format between two boats around a specific race course (Figure 2.1). In Chapter 3 race duration was found to be 82 ± 9 min (range, 64 to 105 min), which occurs between significant periods of pre- and post-race sailing, in addition there can be two races per day during the early competition rounds (Neville 2008). The physiological and technical demands are specific to the role of the athlete and largely dependent on the wind strength and race tactics (Neville et al. 2006). The crew can be divided into five groups, each involving similar activities, with *bowmen* (including the *mid-bowman*), *grinders* (including the *mastman*) and *utilities* (including the *pitman*, *strategist* and *runner-trimmer*) all in high physically demanding roles and the *afterguard* (including *helmsman*, *navigator* and *tactician*) and *trimmers* in moderately demanding roles (Whiting 2007). The activities on board are intermittent and varied, with work bouts during racing ranging from 5 to 90 s. *Bowmen* and *grinders* are regarded as the most physically intense roles (Bauer 1986), with *bowmen* having high arm crank VO_{2max} values (range: 52 to 61 $ml \cdot kg^{-1} \cdot min^{-1}$) (Bauer 1986; Bernardi et al. 2007b) and *grinders* reported to be working at ~90% of VO_{2peak} (Bernardi et al. 2007b) during strenuous racing.

The environmental conditions of the 32nd America's Cup were documented in Chapter 3 and found, on average, to be moderate (temperature, 27 °C; relative humidity, 60%; mean TWS, 5.1 $m \cdot s^{-1}$). However, the range of conditions achieved highs of 38°C in ambient temperature and 82% relative humidity, which is recognised as 'extremely high risk' of heat illness. The high energy expenditures of these sailors, combined with prolonged exposure to hot environmental conditions will result in elevated body temperatures and substantial sweat losses during racing. In fact, clinically diagnosed heat illness and dehydration have been previously documented in America's Cup sailing (Neville et al. 2006).

Various phases of racing also involve differing environmental stresses. For example, large differences in the apparent wind speed (AWS), and thus expected evaporative cooling, exist between upwind and downwind sailing. Upwind sailing also typically results in sailing against the prevailing waves with increased exposure to sea spray, hence athletes typically wear waterproof clothing to prevent saturation. Athletes are unable to change garments in response to these differing conditions, which may result in high rates of heat storage and restricted evaporative heat loss during downwind sailing. Over prolonged periods this could result in hyperthermia and dehydration to an extent that may negatively influence cognitive and physical performance (Howe and Boden 2007). Despite these issues there is currently a dearth of knowledge regarding thermoregulatory responses during sailing, including the crew roles and phases of racing that involve the greatest heat stress.

The thermoregulatory responses to exercise in controlled laboratory conditions have been well documented (Nielsen et al. 1993; Gonzalez-Alonso et al. 1999; Morris et al. 2005). However the impracticalities associated with accurately measuring core and skin temperatures of athletes during competition and in field settings has until recently limited our understanding of the thermoregulatory responses to these conditions. The recent validation of telemetric intestinal temperature sensors (Gant et al. 2006; Byrne and Lim 2007; Casa et al. 2007) has provided an accurate means of determining core temperature in field studies. Intestinal temperatures have recently been reported during training and competition of athletes (Godek et al. 2005b; Edwards and Clark 2006; Godek et al. 2006). To date body temperature changes during sailing have not been reported, despite reports of heat illness (Allen 2003; Allen and De Jong 2006; Neville et al. 2006), and evidence that dehydration may be a common problem for competitive sailors (Mackie and Legg 1999). For example, 88% of elite New Zealand Olympic class sailors reporting symptoms of dehydration during one season (although the details and severity were not specified). Recreational Dinghy sailors have been reported to lose sweat at a modest rate of ~ 0.4 $L \cdot h^{-1}$ (Slater and Tan 2007), which is much less than in intermittent team sports (e.g. soccer ~ 1.7 $L \cdot h^{-1}$) (Maughan et al. 2007b) and therefore also big-boat sailing. In addition to water, important electrolytes are lost in sweat, most notably sodium, chloride, potassium and magnesium (Maughan 1991), that could compromise endogenous electrolyte concentrations during competition.

The aim of this study was to assess the thermoregulatory responses to big-boat yacht racing and how these were influenced by crew position and the phase of racing (upwind or downwind). Moreover, given the prolonged environmental exposure and physical and mental stress of competitive America's Cup sailing, we aimed to document the thermoregulatory strain of sailors in order to appreciate its' affect on their performance and health. To our knowledge this is the first study to accurately measure core and skin temperatures, fluid and electrolyte losses in elite professional intermittent team sport athletes during competition. Quantifying the thermoregulatory demands of this sport may enhance our understanding of performance limitations as well as the risks of heat injury.

7.2 Methodology

Body temperature, fluid balance and sweat composition data were collected from a professional America's Cup yacht racing crew, 12 months prior to the 32^{nd} America's Cup in Valencia, Spain. The study took place in the mid-afternoon during the month of July (European summer) with environmental temperature, humidity, wind speed and sea state taken from a Meteorological Data Service buoy close to the race course at 6 m above sea level. Data was captured at 30 min intervals and averaged for the duration of the study. The apparent wind speed (AWS), which is the actual wind speed on the boat, was calculated using the formula:

$$AWS = \sqrt{(TWS^2 + VS^2 - 2 \times TWS \times VS \times \cos(TWA))}$$

Where TWS is *true wind speed*, VS is *boat speed, and* TWA is *true wind angle in radians.*

All data were collected before, during and after two short-course races between two similar America's Cup racing yachts. Pre- and post-sailing data were collected at the team's dockside training facility and on-board investigators logged all the data during sailing, including race information (duration and the number of tacks and gybes). The total duration between pre- and post-sailing data collection was 150 min which included 100 min of racing.

7.2.1 *Participants*

Thirty two elite, professional, male America's Cup yacht racing athletes participated in the study (Table 7.1). The participants all sailed for a team regarded as a favourite to win the 32nd America's Cup, with their collective experience including more than 100 America's Cup campaigns. The athletes were all well acclimatised to the environmental conditions, with all athletes having lived and trained at the location for ~ 2 yrs prior to the study. The study was conducted within the team's normal training schedule and overseen by the team's sports science and medical support staff. The data collection procedure was described in detail to all athletes before informed consent was obtained. The study was approved by the local Ethical Advisory Committee.

7.2.2 *Experimental Design*

All athletes reported to the team's training facility at their normal training time (0800 h) and the 23 who volunteered to have core temperature measured were encouraged to empty their bowels prior to ingesting 500 ml of water with a telemetric core temperature (T_{core}) capsule (VitalSense®, Mini Mitter Co., Inc., Oregon, USA). The temperature sensor capsules were ingested 6 h prior to sailing to ensure capsules had progressed sufficiently along the gastrointestinal tract (Lee et al. 2000). Fluid and food intake was standardised and monitored for all participants in the 6 h period prior to sailing. Athletes refrained from caffeine ingestion and avoided any nutrient intake in the 2 h prior to the study. The athletes returned to the team's medical laboratory 1 h prior to sailing for instrumentation and pre sailing blood and urine sample collection. Participants were instructed to empty their bladders prior to measurement of nude body mass (Tanita digital scale WB-110 P MA, Tokyo, Japan; calibrated to 0.1 kg), after which heart rate monitors (Polar® Heart Rate Team System, Finland) were fitted and checked.

Absorbent sweat collection patches (Tegaderm absorbent dressing 5 x 7 cm, 3M, Loughborough, UK) were attached to all athletes on four skin sites (chest, scapular, forearm and thigh) (Patterson et al. 2000) on the left side of the body. The skin surface was initially prepared by cleaning the area with an alcohol swab, shaving with a disposable razor, rinsing with deionised water then drying with a sterilised absorbent gauze swab.

Skin temperatures were measured on 12 athletes by adhesive wireless surface temperature sensors (VitalSense®, Mini Mitter Co., Inc., Oregon, USA), fitted to four standardised sites

(Ramanathan 1964); chest (T_{chest}), thigh (T_{thigh}), anterior calf (T_{tibia}) and forearm (T_{arm}) on the right side of the body and secured with a porous adhesive dressing. Mean skin temperature (T_{skin}) was calculated as an area weighted average (Ramanathan 1964). Intestinal and skin temperature sensors were individually verified to be accurate with a mercury thermometer in a water bath prior to instrumentation. Intestinal temperature was monitored 30 min prior to sailing whilst cold fluid was ingested, to ensure that sensors had advanced far enough along the gastrointestinal tract. The on-board investigators, familiar with using the portable data logger, collected temperature data at regular intervals (~10 min).

All athletes wore the team's standard racing clothing, which was logged, and consisted of either shorts or tights and shorts, and one to three layers of racing tops which typically were a T-shirt, a long sleeve top and a Gore-Tex® jacket. Fluid (water and/or sports drink) and food (sandwiches) intake during sailing was *ad libitum* and measured by having each athlete only drink and/or eat from their individually labelled, pre-weighed containers. The volume of urine excreted by each athlete during the sailing was recorded with a graduated measuring cylinder and logged by an investigator on-board each yacht.

Immediately post-sailing the athletes returned to the dock-side laboratory where the outer surface of sweat patches was irrigated with deionised water and dried. Patches were removed and stored in sealed containers for later analysis. Skin temperature sensors were removed and athletes were towel dried before nude body mass was recorded. Post-sailing blood and urine samples were then collected. Each athlete retrospectively rated subjective race intensity on a simple 1-to-5 scale (1 = very light; 5 = extremely tough).

Venous blood samples (7.5 ml) and urine samples were collected pre- and post-sailing and stored for later analysis. Serum was analysed in duplicate for sodium, potassium and chloride concentrations by indirect potentiometry (Modular Analytics SWA analyzer, Roche Diagnostics, Switzerland) and reported as mean values. Serum and urine osmolality were determined using freezing point depression osmometry (Osmostat OM-6020, Menarini Diagnostics, Italy), and urine specific gravity was quantified (Urisys 2400 analyzer, Roche Diagnostics, Switzerland).

Sweat patches were analysed in duplicate for sodium, potassium and chloride concentrations by indirect potentiometry (Modular Analytics SWA analyzer, Roche Diagnostics, Switzerland) and reported as mean values. Magnesium concentration was determined by the colorimetric endpoint method (Modular Analytics SWA analyzer, Roche Diagnostics, Switzerland). Sweat electrolyte concentration was expressed as the arithmetic mean concentration of the four sites.

Sweat loss was calculated as the change in body mass after correcting for fluid/solid intake and urine volume. Respiratory and substrate losses were not accounted for as these were considered minimal and difficult to accurately determine. Dehydration was expressed as total fluid loss, as a percentage of pre-exercise body mass. Hyperthermia was defined as a state of high body temperature causing potentially negative performance or health outcomes, which are usually observed after ~ 2°C rise above base core temperature.

7.2.3 *Statistical Analysis*

The physiological responses (heart rate, T_{core}, sweat loss, fluid intake, sweat electrolyte concentration and total sweat electrolyte loss) of the different crew positions were compared by ANOVA, and significant interactions were explored using the Holm-Bonferroni step-wise method. Regional skin temperatures were analysed with ANOVA to examine any difference in temperature between the measurement sites. Mean thermoregulatory responses to upwind and downwind legs from both races were calculated for each athlete, and the responses to these two wind conditions compared with a paired *t*-test. Paired samples *t*-tests were also used to assess for any differences in serum and urine composition between pre- and post-sailing. Pearson's product moment correlations were used to determine the strength of bivariate relationships. The level of significance was set at $P \leq 0.05$ and data are reported as mean ± SD.

7.3 Results

The environmental conditions were: air temperature, 32 ± 1°C; relative humidity, 52 ± 5%; humidex 41 ± 4°C; average true wind speed, 5.0 ± 0.2 $m \cdot s^{-1}$ (AWS upwind, 9.2 $m \cdot s^{-1}$; AWS downwind, 2.4 $m \cdot s^{-1}$); sea state, 0.5 m swell. Racing consisted of a 65 min short-course

(2.8 km per leg) two-lap race, followed by a 35 min short-course (2.8 km per leg) one-lap race, with a 23 min active recovery interval between races. The period before and after racing was 27 min, during which time the yachts are towed out and back to the harbour. The subjective race intensity of both boats was similar and described as "moderate", with an overall mean subjective rating of 2.7 ± 0.2 out of 5 (race 1: 65 min, 11 tacks & 9 gybes; race 2: 35 min, 12 tacks & 3 gybes). The mean heart rate for the whole crew was 116 ± 18 beats.min^{-1} (Table 7.2), which was ~ 10% lower than that observed for a higher intensity race (unpublished observations, Table 7.1). Mean and peak heart rate were both influenced by crew position (ANOVA, P<0.01), with the *bowmen* having higher heart rates than the *afterguard.*

Table 7.1 Physical characteristics of America's Cup sailors, including laboratory tested maximum heart rate (HR) and unpublished HR data recorded during strenuous racing

	ALL [n=32]	[Range]	Bowmen [n=6]	Grinders [n=8]	Utilities [n=6]	Trimmers [n=6]	Afterguard [n=6]
Age [y]	36 ± 7	[25 - 47]	36 ± 5	36 ± 7	36 ± 6	35 ± 8	41 ± 8
Body mass [kg]	92.3 ± 11.9	[73.5 - 119.5]	83.2 ± 5.5	107.3 ± 7.9	91.0 ± 10.7	87.6 ± 11.2	87.4 ± 2.8
Height [m]	1.84 ± 0.06	[1.66 - 1.95]	1.80 ± 0.02	1.88 ± 0.05	1.79 ± 0.08	1.84 ± 0.05	1.85 ± 0.06
Body fat [%]	13.2 ± 3.6	[7.6 - 20.2]	11.1 ± 3.5	14.4 ± 4.3	13.7 ± 2.9	12.6 ± 4.2	13.9 ± 2.5
Body surface area [m^2]	2.17 ± 0.17	[1.84 - 2.54]	2.04 ± 0.07	2.37 ± 0.11	2.13 ± 0.16	2.11 ± 0.16	2.12 ± 0.06
Body surface area [cm^2·kg^{-1}]	2.36 ± 0.12	[2.13 - 2.58]	2.46 ± 0.08	2.21 ± 0.07	2.35 ± 0.10	2.42 ± 0.11	2.43 ± 0.04
Maximum HR [beats·min^{-1}]	187 ± 6	[177 - 197]	191 ± 6	186 ± 6	185 ± 7	187 ± 7	185 ± 3
Mean HR during strenuous race (4/5 intensity scale) [beats·min^{-1}]	130 ± 19	[97 - 170]	148 ± 12	135 ± 16	128 ± 24	130 ± 12	108 ± 10

The *bowmen* recorded greater peak T_{core} (39.2 ± 0.2°C; range, 39.0 to 39.5°C) than all other crew positions (Bonferroni, P<0.01), but mean T_{core} was not influenced by position (whole crew: 38.1 ± 0.3°C; ANOVA for position P=0.16; Table 7.2). Several athletes lost skin temperature sensors, particularly from the leg (T_{tibia}) as a result of contact with boat-hardware or sails. From the seven athletes with complete data, regional skin temperatures were lower for the tibia (33.3 ± 1.2°C) than the forearm (35.0 ± 0.5°C; P=0.01 *vs.* tibia) and the scapula (35.0 ± 0.5°C; P=0.05 *vs.* tibia), but similar to the chest (34.4 ± 0.5°C). Overall mean T_{skin} was 34.4 ± 0.5°C.

Table 7.2 Heart rate and intestinal temperatures during America's Cup yacht racing.

	ALL [n=23]	Bowmen [n=4]	Grinders [n=6]	Utilities [n=6]	Trimmers [n=4]	Afterguard [n=3]
Heart Rate						
Mean [beats·min^{-1}]	116 ± 18	140 ± 8[a]	117 ± 20	121 ± 12	108 ± 11	97 ± 12
Peak [beats·min^{-1}]	160 ± 18	184 ± 10[b]	161 ± 19	163 ± 11	155 ± 17	142 ± 12
Intestinal Temperature						
Mean [°C]	38.1 ± 0.3	38.4 ± 0.2	38.0 ± 0.2	38.1 ± 0.4	38.0 ± 0.3	37.9 ± 0.2
Peak [°C]	38.4 ± 0.4	39.1 ± 0.2[c]	38.3 ± 0.3	38.3 ± 0.3	38.2 ± 0.3	38.2 ± 0.1

Significant differences between positions: [a] Bowmen greater than trimmers and afterguard (P<0.05); [b] Bowmen higher than afterguard (P<0.01); [c] Bowmen higher than all other positions (P<0.01)

When comparing the mean response to both upwind and downwind legs of the race, the whole crew had higher heart rates and T_{core} during downwind sailing (Paired *t*-test, both P<0.001, Table 7.3). This effect was most marked for the *bowmen* with heart rate 22 beats·min^{-1} and T_{core} 0.4°C higher downwind (Paired *t*-test, both P<0.05; Figure 7.1). In addition, the majority of athletes, with the exception of *bowmen*, reported being "hot and uncomfortable" when sailing downwind and "wet and cold" upwind.

Table 7.3 Mean intestinal temperature and heart rate during upwind and downwind legs of America's Cup yacht racing

	Intestinal Temperature [°C]		Heart Rate [beats·min^{-1}]	
	Upwind	**Downwind**	**Upwind**	**Downwind**
Bowmen [n=5]	38.3 ± 0.2	38.6 ± 0.2 *	128 ± 11	150 ± 17 *
Grinders [n=7]	38.0 ± 0.2	38.1 ± 0.3 **	116 ± 20	122 ± 21 *
Utilities [n=6]	38.1 ± 0.2	38.2 ± 0.3	121 ± 14	124 ± 14
Trimmers [n=6]	38.0 ± 0.3	38.0 ± 0.3 *	105 ± 9	113 ± 16
Afterguard [n=5]	37.8 ± 0.2	38.0 ± 0.1	96 ± 11	96 ± 16
All [n=29]	38.0± 0.3	38.2 ± 0.3 **	113 ± 17	121 ± 23 *

Significantly greater than upwind (P<0.05; ** P<0.001)*

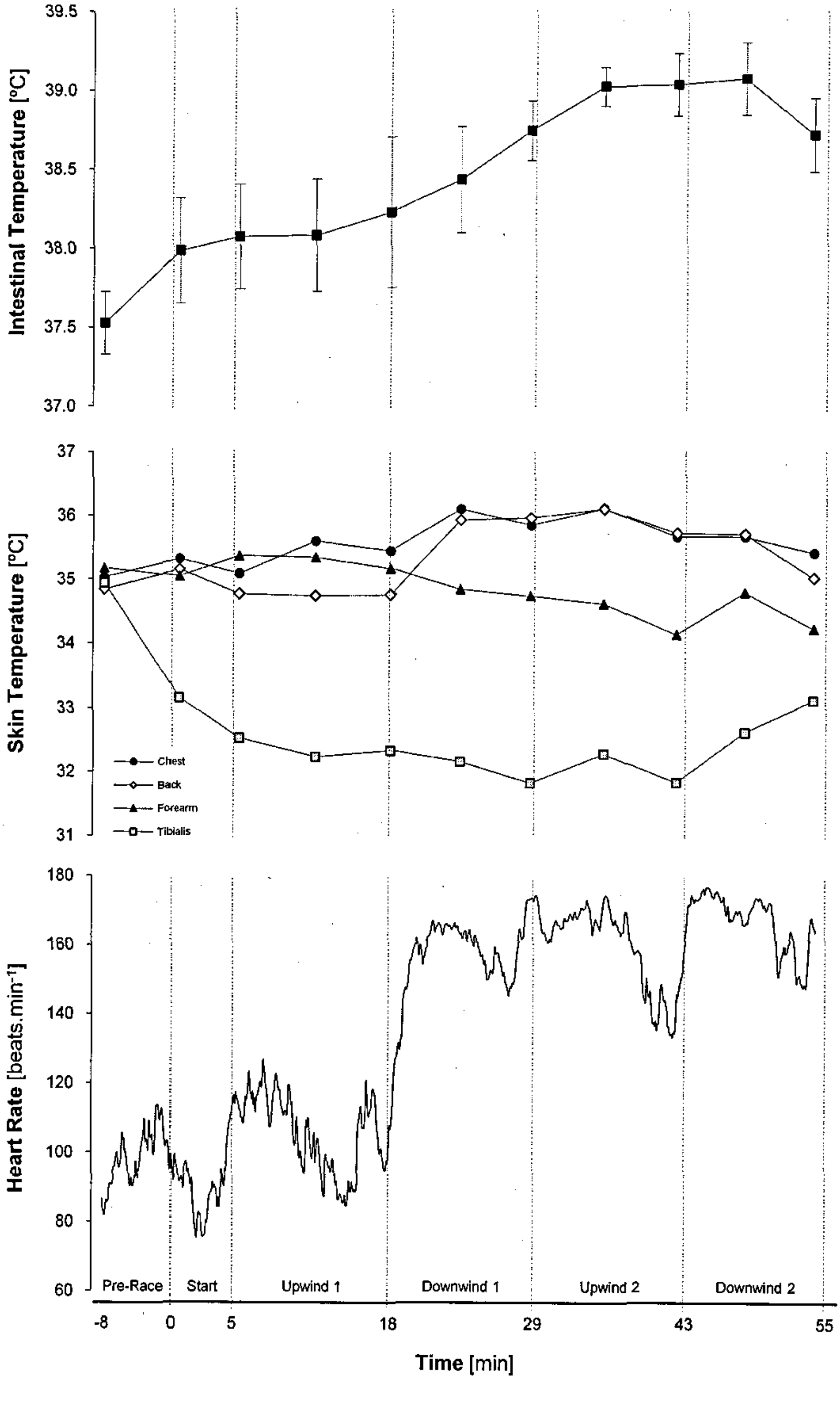


Figure 7.1 Mean intestinal temperature, skin temperature and heart rate for *bowmen* during an America's Cup yacht race (n=4)

For all athletes mean sweat loss during sailing (150 min) was 2.24 ± 0.89 L (range: 0.74 to 3.95 L), equivalent to a sweat rate of 0.96 ± 0.38 $L \cdot h^{-1}$ (range: 0.32 to 1.69 $L \cdot h^{-1}$). Assuming that no sweat was lost during the periods before and after competition, sweat rate during racing (100 min) was 1.34 ± 0.58 $L \cdot h^{-1}$ (range: 0.44 to 2.40 $L \cdot h^{-1}$). Crew position influenced absolute (ANOVA, $P<0.001$; Table 7.4) and relative sweat loss (ANOVA, $P<0.001$). Specifically, the *afterguard* (1.03 ± 0.25 L) lost significantly less sweat than the *bowmen* (3.01 ± 0.52 L), *grinders* (2.78 ± 0.83 L) and *utilities* (2.11 ± 0.55 L). Relative to body mass the *bowmen* (3.7 ± 0.9%) lost more sweat than the *afterguard* (1.2 ± 0.3), *trimmers* (2.4 ± 0.8) and *utilities* (2.3 ± 0.6) (Table 7.4). A modest correlation was found between peak T_{core} and fluid loss ($r=0.48$, $P=0.02$), but surprisingly no significant association was found with fluid intake.

Table 7.4 Sweat loss, fluid intake and major sweat electrolyte concentrations during America's Cup yacht racin

	All [n=32]	[Range]	Bowmen [n=6]	Grinders [n=8]	Utilities [n=6]	Trimmers [n=6]	Afterguarc [n=6]
Sweat loss [L]	2.24 ± 0.89	[0.74 - 3.95]	3.01 ± 0.52	2.78 ± 0.83	2.11 ± 0.55	2.07 ± 0.58	1.03 ± 0.25
Sweat loss [% of BM]	2.4 ± 1.0	[0.8 - 5.2]	3.7 ± 0.9[b]	2.6 ± 0.7	2.3 ± 0.6	2.4 ± 0.8	1.2 ± 0.3[c]
Fluid intake [L]	1.60 ± 0.77	[0 - 2.58]	1.88 ± 0.64	2.00 ± 0.69[e]	1.53 ± 0.46	1.65 ± 0.60	0.77 ± 0.90
Sweat loss replaced [%]	72 ± 41	[0 - 192]	62 ± 17	71 ± 13	79 ± 32	77 ± 23	73 ± 89
Dehydration [%]	0.7 ± 0.8	[-1.3 to 2.5]	1.5 ± 0. 9[f]	0.6 ± 0.4	0.7 ± 0.7	0.5 ± 0.3	0.1 ± 1.0
Mean sweat electrolyte concentration							
Sodium [$mmol \cdot L^{-1}$]	27.2 ± 9.2	[12.0 - 43.5]	34.0 ± 9.7	26.0 ± 10.4	28.8 ± 5.1	24.4 ± 6.4	23.3 ± 10.9
Chloride [$mmol \cdot L^{-1}$]	19.0 ± 6.1	[8.3 - 31.5]	23.7 ± 5.8	18.9 ± 7.0	20.8 ± 1.3	15.8 ± 4.1	15.7 ± 7.2
Potassium [$mmol \cdot L^{-1}$]	4.3 ± 0.8	[1.6 - 5.6]	4.3 ± 0.4	4.6 ± 0.3	4.3 ± 0.8	4.7 ± 0.6	3.4 ± 1.1
Magnesium [$mmol \cdot L^{-1}$]	0.35 ± 0.07	[0.23 - 0.51]	0.39 ± 0.08	0.35 ± 0.07	0.36 ± 0.08	0.33 ± 0.07	0.33 ± 0.05

Sweat loss was calculated from the change in body mass after correcting for fluid and solid intake and urine volume. Dehydration is expressed as the percentage change in body mass due to fluid loss.

Differences between crew positions: [a] Afterguard lower than bowmen, grinders and utilities; [b] Bowmen higher than utilities, trimmers and afterguard; [c] Afterguard lower than bowmen, grinders and trimmers; [d] Afterguard lower than bowmen, grinders and utilities; [e] Grinders higher than afterguard; [f] Bowmen higher than afterguard. All comparisons P<0.05.

Fluid intake was influenced by crew position (ANOVA, $P<0.05$), with the *grinders* consuming more fluid than the *afterguard* (2.00 ± 0.69 *vs.* 0.77 ± 0.90 L; Bonferroni, $P<0.05$), and fluid intake was also highly correlated to sweat loss ($r=0.74$, $P<0.001$). The proportion of sweat loss replaced by the whole crew was 72 ± 41% (ranging from 0 to 192%) and was similar for all crew positions (ANOVA, $P=0.96$). Dehydration of the crew ranged from -1.3 to 2.5% and was affected by sailing position (ANOVA, $P<0.05$), with the *bowmen* dehydrating significantly more than the *afterguard* (1.49 ± 0.89 *vs.* 0.04 ± 1.02%; Bonferroni, $P<0.05$).

Ten athletes had a pre-race urine osmolality greater than 900 $mOsmol \cdot kg^{-1}$ (and specific gravity greater than 1.025; Table 7.5), and the majority of *grinders* (7/8) were > 890 $mOsmol \cdot kg^{-1}$. Urine specific gravity significantly increased post-race (1.019 ± 6 to 1.022 ± 8; Paired *t*-test, $P=0.03$), however, no change was observed in serum osmolality. Serum sodium and chloride concentrations were unaffected by racing, however the serum potassium concentration was significantly lower after sailing ($P<0.001$).

For the whole crew the sodium concentration of sweat was 27.2 ± 9.2 $mmol \cdot L^{-1}$ (range: 12.0 to 43.5 $mmol \cdot L^{-1}$), the rate of sodium loss was 0.6 ± 0.4 $g \cdot h^{-1}$ (range: 0.1 to 1.7 $g \cdot h^{-1}$) and the total NaCl loss during sailing was 3.8 ± 2.4 g (range: 0.7 to 10.0 g). There was a significant main effect for potassium concentration between positions ($P=0.02$), specifically the *afterguard* were less than *trimmers* and *grinders* ($P<0.03$). Moreover, the absolute loss of sweat electrolytes was related to crew position (ANOVA, $P<0.01$ for sodium, potassium, chloride and magnesium), with the *afterguard* losing significantly less sweat electrolytes than other positions, specifically less than the *bowmen* for all electrolytes ($P<0.05$; Table 7.4). Across the whole crew, the rate of sweat loss was strongly related to mean sweat sodium and chloride concentrations ($P<0.001$), but no relationship was found for magnesium or potassium.

There was no relationship between body surface area and mean T_{core} ($P=0.92$) or sweat rate ($P=0.38$). Peak heart rate was significantly related to both peak T_{core} ($r=0.53$, $P=0.01$) and fluid loss ($r=0.61$, $P<0.001$).

Table 7.5 Serum electrolytes and osmolality, and urine specific gravity and osmolality pre and post America's Cup yacht racing [n=32]

	Pre Race	Post Race
Serum Electrolytes		
Sodium [$mmol \cdot L^{-1}$]	142 ± 2	142 ± 2
Potassium [$mmol \cdot L^{-1}$]	4.3 ± 0.3	4.1 ± 0.3 **
Chloride [$mmol \cdot L^{-1}$]	102 ± 1	102 ± 2
Serum osmolality [$mmol \cdot L^{-1}$]	286 ± 3	286 ± 3
Urine osmolality [$mOsmol \cdot kg^{-1}$]	772 ± 224	807 ± 285
Urine specific gravity	*1019 ± 6*	*1022 ± 8 **

Significantly different to pre-race ($P<0.05$; ** $P<0.001$)*

7.4 Discussion

This is one of the first field studies to report body temperature responses, concurrent with fluid and electrolyte balance in elite professional athletes. The main findings suggest that America's Cup sailors may at times be at risk of heat related illness and experience considerable fluid and electrolyte losses during racing, similar to the magnitude reported during other high-intensity intermittent team sports. The effects are specific to the role of the athlete, with *bowmen* at greatest degree of both hyperthermia and dehydration. In addition, downwind sailing involves significantly greater thermal strain than upwind sailing, which may have implications for clothing selection and race management strategies.

While sailing in hot environmental conditions, such as the 32°C in this study, thermal radiation can be increased by the reflective surfaces of the water and sails, as well as via the heat gain from the boat deck which is usually black or dark in color (Nielsen 1990).

Hence, overall heat gain from the environment may be high, which increases the thermoregulatory strain when combined with the prolonged exercise such as during America's Cup yacht racing. The duration of the races in the current study were less than that of official America's Cup yacht races (11.2 and 5.6 *vs.* 22.4 km). Despite a moderate subjective rating of race intensity (2.7/5.0) and a relatively low number of race manoeuvres (tacks and gybes, 24 *vs.* ~ 80 during strenuous racing), the mean heart rate for all athletes was still relatively high (62% of HR_{max}). The T_{core} for all athletes at the end of racing (38.4 ± 0.4°C; n=23) was similar to that previously reported in field studies involving other prolonged intermittent sports (Bergeron et al. 2006; Edwards and Clark 2006; Godek et al. 2006). The T_{core} of professional American football players (NFL) reached 38.7°C (n=8) at the end of a 2 h high intensity preseason training session (Godek et al. 2006), while a semi-professional soccer team had T_{core} of 38.7°C (n=7) at the end of a 90 min competitive match (Edwards and Clark 2006). In this study *grinders* had the highest body mass and lowest BSA-to-mass ratio, and with the high work demands of grinding (Bernardi et al. 2007b; Neville 2008) they may have been expected to have the greatest rise in T_{core} (Godek et al. 2006). However, the athletes with the lowest body mass and greatest BSA-to-mass ratio, *bowmen*, reported the greatest peak T_{core} (39.2°C; range: 39.0 to 39.5°C). It has been well established that T_{core} in excess of 39°C can negatively impact on sport specific skill (Dawson et al. 1985; Sunderland and Nevill 2005) and exercise capacity (Nybo 2008). Therefore, it is possible that the performance of the *bowmen* could have been compromised in this study, and this crew position may be at risk of hyperthermia-related heat illness in more demanding race conditions. It is interesting to note that even the least physically demanding positions, the *afterguard*, experience elevated peak T_{core} (~38.2°C) which may be attributed to the environmental conditions as well as the athlete's selection of clothing.

The fact that several athletes lost skin temperature sensors as a result of contact with boat-hardware and sails, underscores the difficulties of field studies. The low T_{tibia} compared to the other regional skin temperatures may reflect clothing selection, as most athletes wore long sleeve tops and shorts, allowing greater evaporative cooling of the lower limb, or the intensive upper body work involved in big-boat sailing.

The higher T_{core} and heart rate observed during the downwind legs of the race are likely to be due to the different environmental conditions and work demands between upwind and the downwind sailing. Two important differences are the AWS, which is the actual wind speed on the boat resulting from a combination of the true wind speed and the speed of the boat (Whiting 2007), and the direction of the waves (which typically run with the wind and/or sea current). In this study the AWS was almost 4-times greater upwind than downwind, and sailing upwind into the waves produced a continuous spray of water over the boat. Both these factors promote evaporative and convective cooling and the athletes' (those on deck) sensation of being "cold and wet" when sailing upwind. In contrast, the reduced AWS downwind combined with a high humidity after becoming wet during the upwind legs resulted in the athletes feeling "hot and uncomfortable" when sailing downwind. The greater physical work required to gybe the larger downwind sails (Bernardi et al. 2007b) may also be a contributing factor to the increased thermal strain as evident by the marked increase in heart rate and T_{core} of the *bowmen* (the position primarily responsible for gybing the downwind sails).

There are little data available on fluid loss during sailing, with no reports in the published literature on big-boat sailing. The mean rate of sweat loss in the current study (~0.9 $L \cdot h^{-1}$) was higher than that reported during amateur Dinghy sailing (0.4 $L \cdot h^{-1}$) (Slater and Tan 2007), largely due to the extended data collection period (5 h *vs.* 2 h of competition). Due to the nature of sailing, accurate measurements are only possible when the athletes are on the dock (land based); hence the data collection period during the current study (150 min) was considerably longer than the competition period (100 min). If one was to assume that the majority of the fluid loss occurred during racing, then the rate of sweat loss may have been substantially greater (~1.3 $L \cdot h^{-1}$). Few studies have accurately measured fluid loss in elite athletes during training or competition. In intermittent team sports, soccer has received the greatest attention, with reports indicating mean sweat losses of ~1.1 $L \cdot h^{-1}$ during competition (Broad et al. 1996; Maughan et al. 2007b), which is similar to that of the current study. Sweat loss was highly variable between athletes with some having lost as much as 4.0 L. The America's Cup class rule allows for rehydration fluids to be stored on the yacht independent of the technical weight restrictions, hence the opportunities for fluid intake during racing are greater than for many field sports where *ad libitum* hydration is limited to stoppages in play. Therefore fluid consumption is restricted only by storage space on the deck and opportunities to drink between work bouts during racing. It is not surprising that fluid intake was highly correlated to sweat loss.

Grinders consumed the most fluid while racing, possibly because they are relatively stationary compared to the *bowmen* and *utilities*, and therefore have better access to fluids throughout the race. Fluid intake on average replaced 72% of sweat loss, with *bowmen* replacing the least fluid (62%). This may be a contributing factor to their elevated T_{core} as greater fluid replacement may assist in attenuating the rise in T_{core} (Maughan 1999; Howe and Boden 2007), although this was not confirmed in this study. The level of dehydration was highly variable between individuals (range: -1.3 to 2.5%) and between positions, with *bowmen* displaying the greatest dehydration (1.5%). It has been shown that dehydration of 1.5% can reduce intermittent exercise performance (Maxwell et al. 1999), sport specific skill performance (Edwards et al. 2007) and cognitive function (Gopinathan et al. 1988). B*owmen* often find it difficult to drink during specific periods of the race due to the continuous nature of their activities and their opportunities for fluid replacement may be dependent on race intensity. Although there was a change in urine indices of hydration status post-exercise, there was no significant change in serum osmolality between pre- and post-sailing. Similar observations have been reported previously during prolonged exercise (Francesconi et al. 1987), and may be a result of acclimatization, as well as the duration between measurements allowing for the adjustment of plasma volume. The determination of fluid balance during exercise assesses only the change in hydration status of an individual. Clearly any pre-exercise fluid deficit could exacerbate the body water deficit that occurs during exercise. Therefore, the "actual" fluid deficit of the ten athletes which were considered dehydrated before sailing (urine osmolality > 900 $mOsmol \cdot kg^{-1}$) (Shirreffs and Maughan 1998) may have been more severe than indicated by the change in fluid balance during racing (Maughan et al. 2007b). The consequence of pre-exercise fluid deficit as seen in the majority of *grinders* can be a substantial reduction in performance; Armstrong et al (Armstrong et al. 1985) found a 2% pre-exercise reduction in body mass caused a 5% decrement in 1500 m track running times. Both fluid intake and fluid loss were not related to pre-sailing measures of hydration status, suggesting that pre-exercise hydration status is not the primary factor affecting fluid intake and loss during sailing, but other factors such as opportunities to drink are likely also important. Although data from the present study relates specifically to big-boat match-racing, the results have important implications to sailors competing in other in-shore classes such as Olympic class and Dinghy sailing, where the athletes are often at risk of hypohydration as a result of underestimating fluid requirements (Mackie and Legg 1999).

The loss of electrolytes was considerable and similar to other sports (Stofan et al. 2002; Maughan et al. 2007b), with some individuals losing as much as 10 g of NaCl. The concentration of sweat electrolytes was highly variable between individuals, but with no consistent pattern between crew positions. Both the mean sodium and chloride concentrations were lower than that reported in American football (Stofan et al. 2002) and soccer (Maughan et al. 2007b), and may be an indication of the athletes being well acclimatized to the hot Mediterranean conditions (Buono et al. 2007). In addition, mean concentrations of sweat sodium and chloride were strongly related to the rate of sweat loss, indicating reduced electrolyte re-absorption at high rates of sweat loss (Morgan et al. 2004). Serum potassium concentration was significantly reduced post-sailing; similar results have been found in competitive Dinghy sailors (Stieglitz 1993). The loss of serum potassium post-exercise reflects the intensity of the activity (Sjogaard 1996) and occurs as a consequence of numerous factors including, losses in sweat and urine (Schamadan and Snively 1967) and rapid post-exercise re-absorption by skeletal and cardiac muscle (Lindinger and Sjogaard 1991).

It is important to note that the work intensity and duration of sailing are likely to be greater during official races, which would increase the physiological and thermoregulatory stress. Higher environmental temperatures would also increase the thermoregulatory demands on the sailors during racing. Finally, as the work intensity of sailing is probably largely dependent on the wind speed (Neville 2008), it might be assumed that in windier conditions the work intensity, thermoregulatory stress, and magnitude of hyperthermia and dehydration would be more pronounced than we have documented. However, the increased evaporative cooling from higher wind speeds during upwind sailing may help to dissipate the greater metabolic heat produced by the sailors in these conditions. When comparing positions, *bowmen* experienced the greatest physiological and thermoregulatory strain during racing (Figure 7.1). Not only did *bowmen* have the highest heart rate and T_{core}, but despite being the smallest athletes they recorded the greatest absolute sweat and sweat electrolyte losses as well as the lowest relative sweat loss replaced. This can be attributed to their high work rate downwind as well as the high thermal stress below deck. B*owmen* can spend up to a third of the race below deck, packing, moving and connecting sails, where the temperature and humidity are considerably greater than on deck and compounded by minimal air flow. B*owmen* are usually below deck during most of the second upwind leg (due to having to repack the downwind sails after the initial downwind leg) with less exposure to the greater AWS and evaporative cooling of upwind sailing that may explain their rise in heart rate and greater T_{core} (Figure 7.1). These results have implications for clothing choice, as the majority of *bowmen* in the current study wore

Gore-Tex® spray tops over their standard race shirts to prevent getting wet on the bow of the boat. However, of noteworthy consideration is that attempting to stay dry may be less important than staying cool in order to prevent attenuations in performance or the risk of heat illness. Strategies aimed at attenuating the rise in T_{core}, such as the use of 'ice jackets' could be employed before races and between races on two-race days (Webster et al. 2005).

7.4.1 *Conclusions*

This is the first study to quantify the thermoregulatory response of elite professional sailing. The America's Cup is widely considered the pinnacle of yacht racing and the sailors, particularly *bowmen*, are of greater risk of greater risk of hyperthermia as well as high rates of fluid and electrolyte losses during racing which may impair performance and lead to heat illness. These findings have important implications for medical support, which should be encouraged to monitor early signs of heat illness (Howe and Boden 2007) particularly during two-race days, where preventative measures such as 'ice jackets' could be employed between races as an effective means of reducing T_{core}. Downwind sailing results in significantly greater cardiovascular and thermal strain compared with upwind, and the cold and wet conditions of upwind sailing may be important in attenuating the rise in T_{core}. Hence, sailors should avoid 'overdressing' while sailing upwind. Fluid and electrolyte losses can be high and are specific to the individual. Sailors should be encouraged to drink regularly and would benefit from individualized hydration and electrolyte replacement strategies before, during and immediately after racing. These results may also have implications for fabric and garment selection (light weight and highly breathable), race management (in reducing the time that *bowmen* spend below deck packing spinnakers), and boat design (which should aim to reduce below deck temperature and increase ventilation), however further investigation is required.

CHAPTER 8

THE DEMANDS OF TRAINING:

IMMUNE STATUS, FATIGUE AND ILLNESS

8.1 Introduction

Upper respiratory infections (URI) are the most common medical complaint of athletes (Robinson and Milne 2002; Neville et al. 2006) and can negatively affect training and performance (Pyne and Gleeson 1998). For example, during a two year training period prior to the 31st America's Cup, 40% of all illnesses were URI and accounted for 60% of illness related days absent from sailing (Neville et al. 2006). In addition, elite athletes seem to be more susceptible to URI than recreationally active or sedentary individuals (Spence et al. 2007), with the risk of illness increasing during periods of heavy training and competition (Peters and Bateman 1983; Novas et al. 2003; Libicz et al. 2006). This increased susceptibility to URI is thought to be largely due to a depression of immune system function as a result of multifactorial stress including physiological, psychological, environmental and behavioral (Dawes 1972; Tomasi et al. 1982; Cohen et al. 1999; Calder and Jackson 2000) (see Gleeson (2007) for review).

Approximately 95% of all infections are initiated at the mucosal surfaces (Bosch et al. 2002), which are protected by antimicrobial proteins of which secretory immunoglobulin A (IgA) is the most abundant (Brandtzaeg 2003). Secretory IgA provides an immunological barrier by neutralizing and preventing viral pathogens from penetrating the body through the mucosal surfaces (Mazanec et al. 1993; Lamm 1997). In the buccal cavity, the synthesis and secretion of salivary IgA (s-IgA) responds almost instantaneously to stress (Bosch et al. 2002), resulting in transitory fluctuations in concentration and secretion rate (Stone et al. 1987b).

Elite athletes are frequently exposed to exercise stress, and the effects of both acute and chronic exercise on s-IgA have been well documented (Tomasi et al. 1982; Mackinnon et al. 1993b; Gleeson et al. 2000b; Novas et al. 2003; Libicz et al. 2006) and appear to depend on the fitness level of the individual as well as the training load. In elite athletes, s-IgA concentration and secretion rate decrease after a bout of strenuous exercise, of either high volume (Nieman et al. 2002) or maximal intensity (Fahlman et al. 2001), or during prolonged periods involving repeated bouts of strenuous training (Libicz et al. 2006). Much of the immunology research in athletes has concentrated on post-exercise salivary immunity when athletes seem to experience a transitory decrease in s-IgA for up to 24 h post-strenuous training or competition. It is during this "open window" period of immune depression (Pedersen et al. 1994) when athletes are thought to be at greatest risk of URI. However, there are few longitudinal studies that have examined the relationship between immune depression and the incidence of URI (Mackinnon et al. 1993a; Gleeson et al. 1999b; Novas et al. 2003; Fahlman and Engels 2005) and these typically have had a low number of subjects or low sample collection frequency. Nevertheless, an absolute s-IgA concentration of less than 40 $mg \cdot L^{-1}$ (Gleeson et al. 1999b) and an absolute s-IgA secretion rate of less than 40 $\mu g \cdot min^{-1}$ (Fahlman and Engels 2005) have been reported to be associated with increased incidence of URI in athletes.

Large within and between subject variations in s-IgA concentration have been reported in elite rowers and swimmers, recreationally active and sedentary individuals (Nehlsen-Cannarella et al. 2000; Francis et al. 2005). This variation implies that the secretion of s-IgA may be specific to the individual and their recent environmental exposure. Therefore regular monitoring should be carried out to obtain well controlled basal values to determine individual reference data. These variations in values also call into question the validity of studies that report only a limited number of measured samples (Gleeson et al. 1999a). Furthermore, consensus regarding the control of factors known to affect basal s-IgA has yet to be determined, such as: the residual effects of exercise, nutrition status (fasted vs non fasted), circadian rhythms and caffeine ingestion (see (Gleeson et al. 2004b) for review). These inconsistencies in methodology have led to inconsistancies in the literature and make it difficult to compare studies (Shephard 2000). Furthermore, in determining URI, the majority of studies have used self-reported illness diaries and so it has been difficult to confirm the reported incidence of URI (Spence et al. 2007), and may be prone to inconsistency and over-reporting (Gleeson et al. 2004b). Few studies have used clinical diagnosis to confirm the presence of URI.

The overall aim of this study was to examine the relationship between s-IgA and URI in a relatively large cohort of athletes over a prolonged period of time (weekly samples for 50 weeks). The specific objectives were: to document the within and between athlete variability in resting s-IgA; examine the relationship between s-IgA and URI, and whether s-IgA values indicated the presence or imminent onset of URI; and to investigate the relationships of subjective fatigue rating and physical stress (sailing and training load) with s-IgA.

8.2 Methodology

8.2.1 *Participants*

Thirty eight elite America's Cup Yacht Racing athletes (mean ± SD: age 36 ± 7 years, body mass 92 ± 12 kg, body fat 14 ± 4 % and *arm ergometer* VO_2max 50 ± 5 $ml \cdot min^{-1} \cdot kg^{-1}$) were studied over 50 weeks of sailing and training. The subjects were all professional athletes contracted to one of the top four America's Cup teams, with their collective experience and success including: 20 Olympic Games representations, 8 Olympic medals, 90 World Championship titles and more than 100 America's Cup campaigns.

8.2.2 *Experimental Design*

A prospective longitudinal study design was used to collect saliva samples, illness reports, training load and fatigue ratings over an 18-month sailing and training preparation period prior to the 32nd America's Cup held in Valencia, Spain in 2007. Informed consent was obtained from all athletes and the study was conducted within the team's normal training and competition schedule and overseen by the team's sports science and medical support staff. The study was approved by the Loughborough University Ethical Advisory Committee.

8.2.3 *Athletes' Work Load*

The athletes' week typically consisted of 6 training days and one day of rest. Their working day was typically between 8 and 14 h in duration, beginning at 08:00 h with approximately 1 h of land-based strength and conditioning exercise ('training') followed by meetings and preparing the boats for sailing. The volume of sailing varied between 3 to 7 h per day whereafter, 1 to 3 h of boat maintenance was carried out. This was followed by further meetings and on some occasions an additional short bout of strength and conditioning exercise.

8.2.4 *Sailing and Training Data*

In order to calculate an index of overall sailing and training load, the product of volume and intensity was ranked on a scale of 1 to 5 (1 = very low load; 5 = very high load) for sailing and training separately. These were combined for the cohort with a weighting of 2/3 for sailing and 1/3 for training to provide an index of combined sailing and training load.

8.2.5 *Saliva Collection*

Saliva samples were collected weekly at 07:45 h in a fasted state, the day after a rest or no training day ensuring a minimum of 38 h rest after the previous training session. Whole mixed saliva samples were collected prior to training and breakfast or coffee (Bishop et al. 2006) 5 min after consuming 250 ml of water. Athletes sat quietly with their head tilted forward and passively dribbled (with minimal orofacial movement) approximately 1 ml of unstimulated saliva into a pre-marked specimen container. Samples were placed in a pre-cooled insulated container and taken directly to the laboratory for analysis.

8.2.6 *Saliva Analysis*

Saliva samples were analysed for s-IgA concentration within 2 h of collection. Salivary IgA concentration was determined by means of immunonephelometry using a BN ProSpec analyser (Dade-Behring Marburg GmbH, Marburg, Germany). In summary, IgA in human saliva forms immune complexes in an immunochemical reaction with specific antibodies. These complexes scatter a beam of light passed through the sample. The intensity of the scattered light is proportional to the concentration of IgA in the sample. The result is evaluated by comparison with a standard of known concentration. The reagents used were N Antiserum to Human IgA (Dade Behring Marburg GmbH, Marburg, Germany), produced by immunization of rabbits with highly purified human immunoglobulin A with Sodium azide (< 1 $g.L^{-1}$) added as a preservative and N Diluent (Dade Behring Marburg GmbH, Marburg, Germany), which contains Phosphate buffered saline and sodium azide (< 1 $g.L^{-1}$) as a preservative. Samples were assayed in duplicate after being brought to room temperature and spun at 14,000 rpm for 6 minutes. Supernatant was recovered and transferred to a sample cup. After a 1:5 dilution with N-Diluent, sample and antiserum were incubated for 6 minutes prior to immunocomplexes measurement using a 380 nm light beam. The within-run coefficients of variation (CV) for each assay were on average 1.6% and the mean between-run CV was 3.7% with a total CV of 4%. The limit of sensitivity was 14 $mg{\cdot}L^{-1}$. Contaminated samples or those containing sputum were excluded from analysis.

8.2.7 *Illness Reports*

Respiratory illness and infections were recorded by the team's Physician, who was present during all data collection and team training sessions. An URI was only recorded if the athlete required medication (either systemic or antibiotic) and missed at least one sailing or training session as a result of the illness (Neville et al. 2006). Medical consultations, allergies and the prescription of vitamin supplementation or prophylactic treatment were not considered an URI episode. A recurring illness was defined as "any URI occurring within one week of a previously recorded episode" and excluded from analysis.

8.2.8 *Fatigue Rating*

A simple three scale subjective fatigue rating questionnaire was completed at the same time as saliva collection during the last 30 weeks of the study period. The questionnaire asked: "How rested do you feel?" to which there were three answers: "worse than normal", "normal" or "better than normal".

8.2.9 *Statistical Analysis*

Data are expressed as mean ± SEM, and the level of significance was set at $P < 0.05$. The reliability of s-IgA was calculated within and between subjects with the coefficient of variation (CV). Independent samples *t* test was used to identify differences between athletes in high and moderate physically demanding roles. Pearson's product moment correlations were used to determine the strength of relationships.

The mean s-IgA concentration for each individual was calculated as the mean of all No URI values (i.e. s-IgA values were excluded from the mean when a URI episode was present), and individual relative s-IgA was calculated as percentage of this mean value. Paired samples *t* test was used to assess any differences between s-IgA during URI and No

URI. Relative s-IgA concentrations before, during and after URI were compared with repeated measures ANOVA and a Bonferroni post-hoc test to analyse where any differences lay. These procedures were also used to compare s-IgA for different ratings of fatigue. Analyses were performed using SPSS version 14.0 for Windows.

The incidence of low s-IgA values (< 40% and < 70% of an individual's mean) was calculated in the weeks before, during and after URI. The probability of low s-IgA leading to URI within 3 weeks (Predictability of URI), when URI was not present or recent (i.e. excluding during URI or 1-week post-URI) was calculated as the number of samples during pre-URI as a percentage of pre- and No URI.

8.3 Results

Over the 50-week study period 1,424 saliva samples were analysed, with a mean s-IgA concentration of 136 ± 3 $mg \cdot L^{-1}$. Salivary IgA concentration was highly variable within-subjects, with a mean coefficient of variation (CV) of 48%. The difference in the mean value between the lowest and the highest individual was almost 10 fold (35 ± 4 $mg \cdot L^{-1}$ vs. 314 ± 27 $mg \cdot L^{-1}$; Figure 8.1A) and the between-subjects CV was 71%. The s-IgA concentration of athletes with sailing roles of moderate and high physical demands were similar (moderate: 149 ± 20 $mg \cdot L^{-1}$; high: 127 ± 12 $mg \cdot L^{-1}$).

A total of 102 incidents of URI were recorded, resulting in 129 weeks of infection with symptoms ranging from 1 to 3 weeks in duration. The incidence of URI was on average 2.7 ± 0.3 infections per athlete over the 50-week period (Figure 8.1B), and was similar for athletes in roles with moderate (2.9 ± 0.5) and high (2.5 ± 0.4) physical demands.

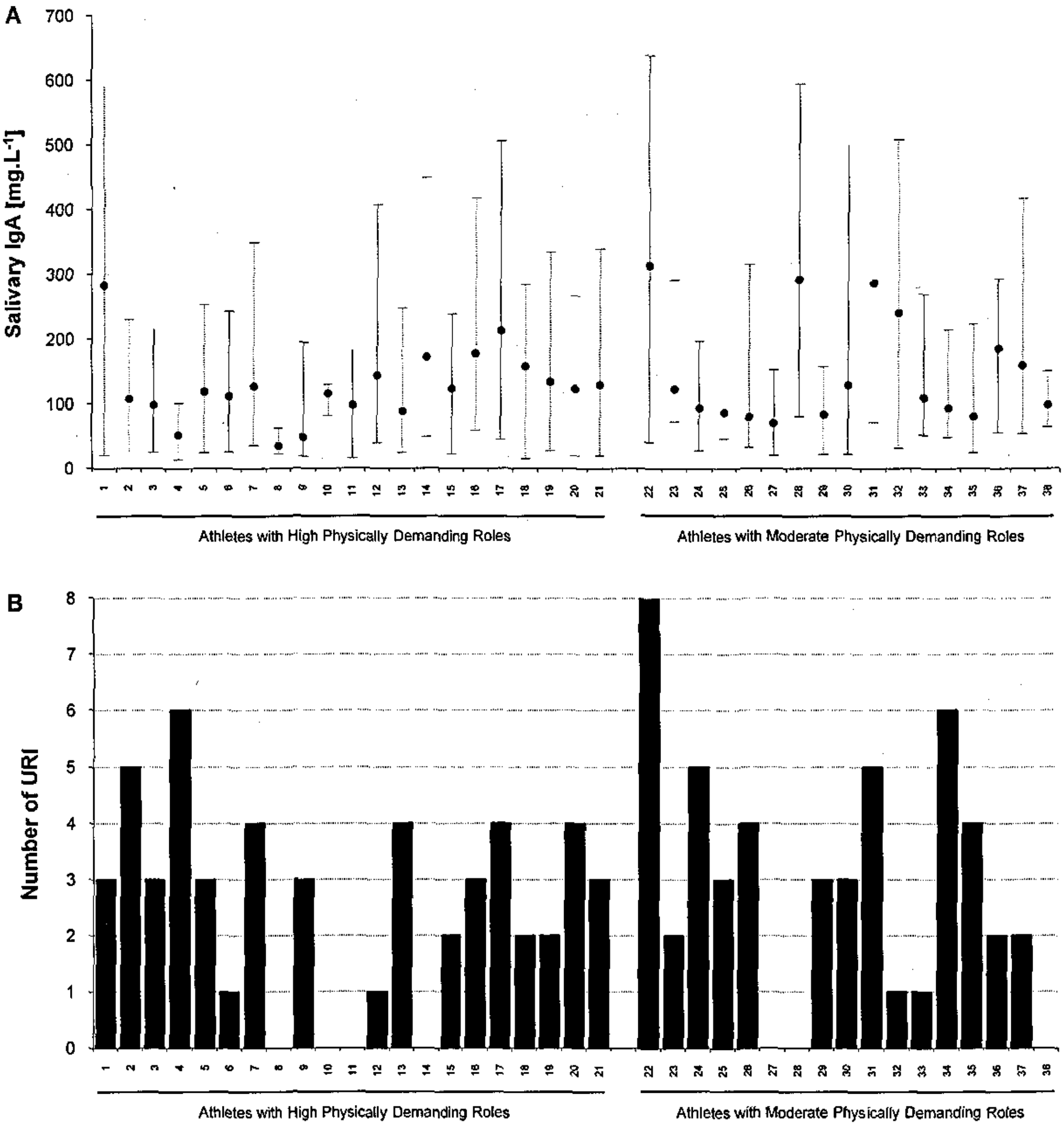


Figure 8.1 Saliva IgA concentration (**A**, *mean ± range) and the number of Upper* Respiratory Infections (**B**) for each athlete over the 50 weeks

There was no relationship between an athlete's mean s-IgA and his number of URI (r = 0.11). When s-IgA values were normalised to each individual's mean, relative s-IgA concentration was 28% lower during URI than when there was no URI (P < 0.005; Figure 8.2). For the cohort, the number of URI in each week was inversely related to the mean weekly relative s-IgA concentration (Figure 8.3). The four lowest weekly mean relative s-IgA values (< 70%) were recorded during the pre-season training period (March and April) and three of these weeks were coincident with the highest incidence of URI. Relative s-IgA declined progressively during the 3 weeks prior to URI, being significantly lower during URI in comparison to 4 weeks prior, before returning to above baseline by 2 weeks following URI (Figure 8.4).

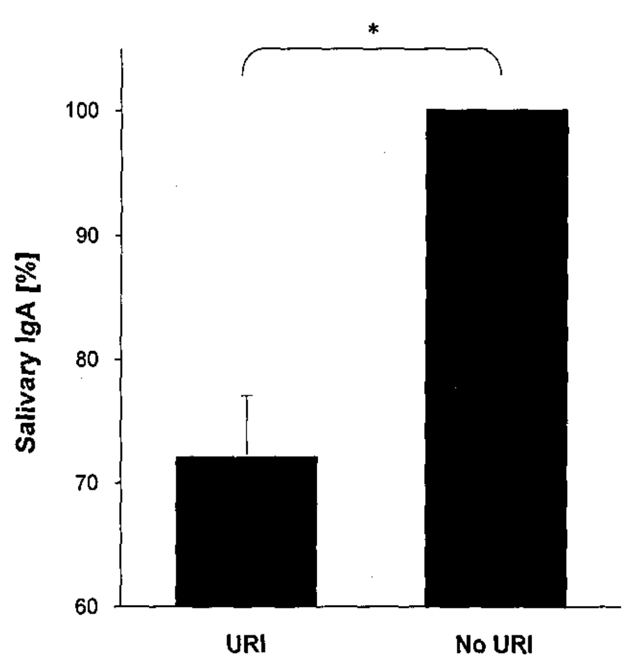


Figure 8.2 Saliva IgA concentration during URI (72 ± 5 %) and No URI (100 ± 0 %). Data are mean ± SEM of 31 athletes that reported an infection, with each individual's relative s-IgA values averaged for URI or not. * P < 0.005

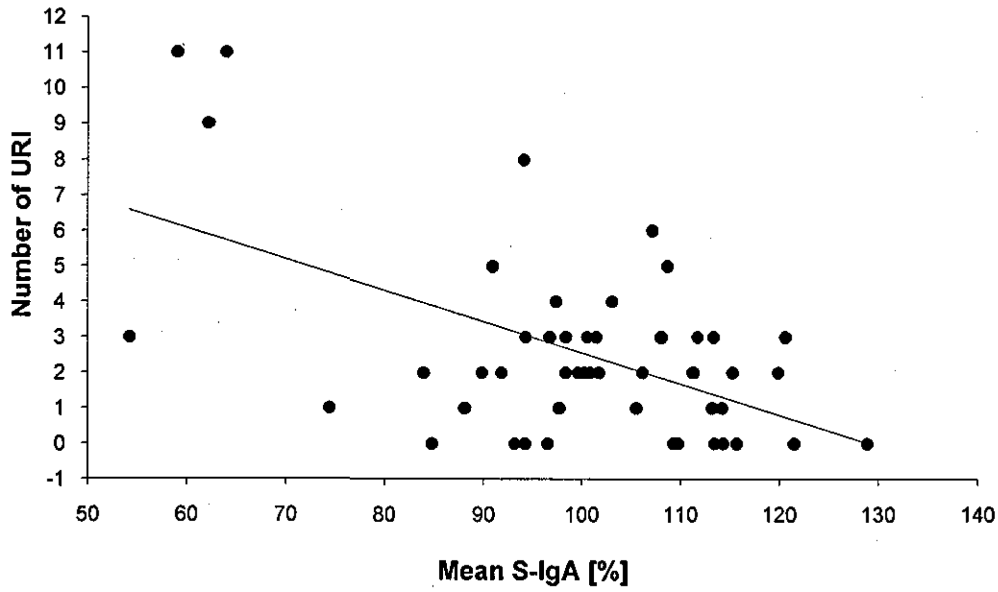


Figure 8.3 Scatter plot of the weekly number of URI within the subject cohort and salivary IgA (mean of relative values for each individual) (r=0.54, r^2=0.29, n=50, P<0.005).

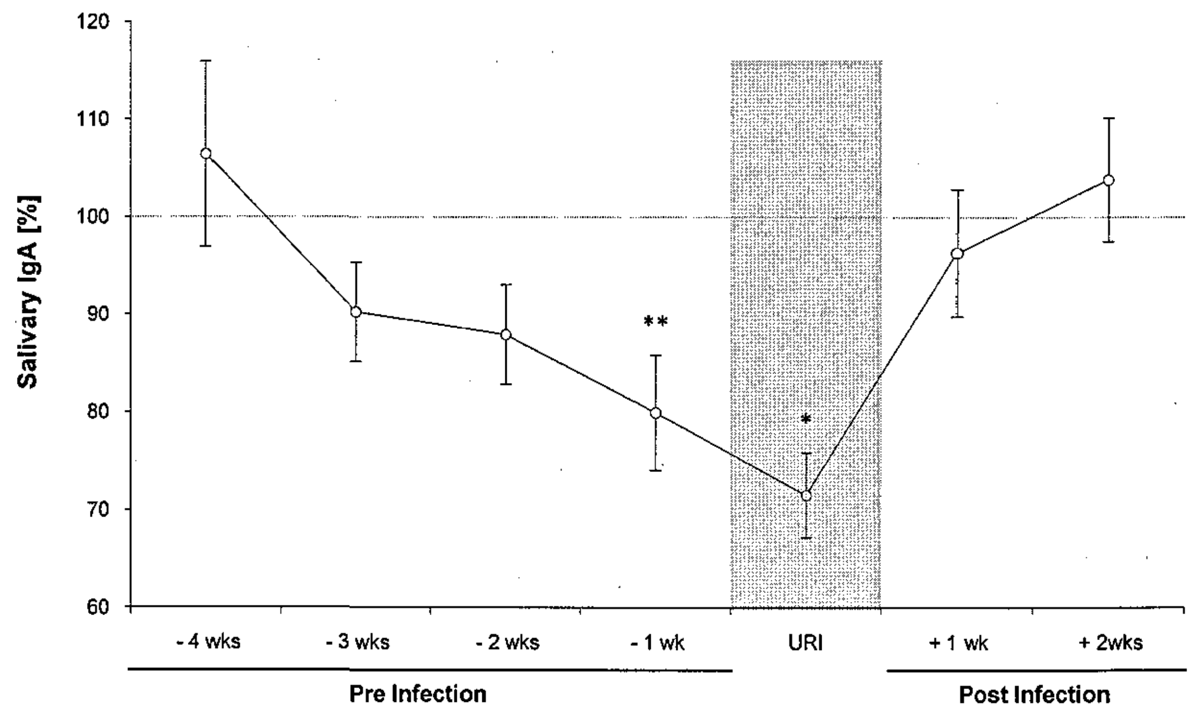


Figure 8.4 Salivary IgA concentration for each week pre, during and post all infections (n=102). Data are mean ± SEM of individual relative s-IgA (percentage of No URI mean values). * URI significantly different to -4weeks, +1week, +2weeks, P<0.005; ** -1week significantly different to +2weeks, P<0.005.

The frequency of low s-IgA values (< 40% of an individual's mean healthy value) was higher in the weeks prior to, during and immediately after URI, than when no URI was present or imminent, being almost 6-fold greater in the week before infection (Table 8.1). When an individual did not have an URI or was not recovering from an URI, a low relative s-IgA value (< 40%) suggested a 48% chance (23/48) of contracting an URI within 3 weeks, compared with a 28% chance (74/263) of URI for relative s-IgA values of less than 70%. However, during the 3 weeks prior to URI, 89% and 65% of s-IgA values were greater than 40% and 70% of relative s-IgA, respectively.

Table 8.1 Number and incidence of low relative salivary IgA values (<70% and <40% of an individual's healthy average) before, during and after URI.

	Total number of s-IgA samples	Number (% incidence) of s-IgA <70%	Number (% incidence) of s-IgA <40%
No URI	1020	189 (18.5)	25 (2.5)
3weeks pre-URI	56	12 (21.4)	3 (5.4)
2weeks pre-URI	71	25 (35.2)	8 (11.3)
1week pre-URI	83	37 (44.6)	12 (14.5)
During URI	109	52 (47.7)	15 (13.8)
1week post-URI	85	21 (24.7)	10 (11.8)
Predictability of URI* (%)		28	48

*****The Predictability of URI was calculated as the percentage of values below each threshold that led to URI within 3 weeks, when URI was not present or recent (i.e.: excluding during URI and 1 week post-URI).*

The mean total sailing and training exposure for each athlete over the 50 weeks was 986 h, (749 h sailing; 237 h training) and the mean weekly combined sailing and training load ranged from 2.0 to 4.4. No relationship was found between weekly combined sailing and training load and URI (r = 0.002). However, a significant correlation was found between the weekly sailing and training load and the weekly percentage of relative mean s-IgA concentration (r = 0.41, Figure 8.5).

There was a difference between the athletes' relative s-IgA concentration according to their fatigue rating, with s-IgA being significantly different for each of the fatigue ratings: "better than normal" 131 ± 8%; "normal" 103 ± 4%; "worse than normal" 69 ± 5% ($P < 0.005$, Figure 8.6).

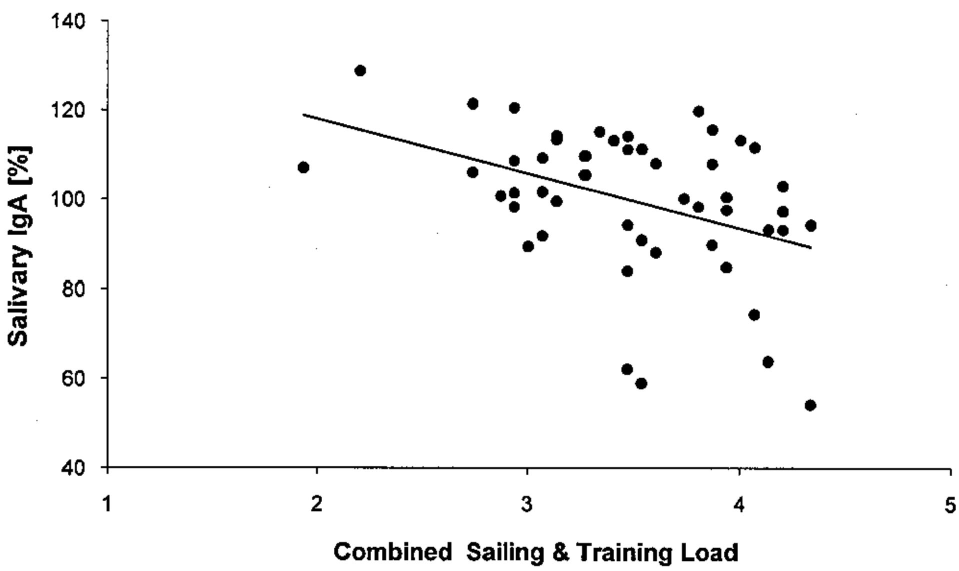


Figure 8.5 Scatter plot of the weekly salivary IgA, mean relative values, and the combined sailing and training load (r=0.41, r^2=0.17, n=50, $P<0.005$).

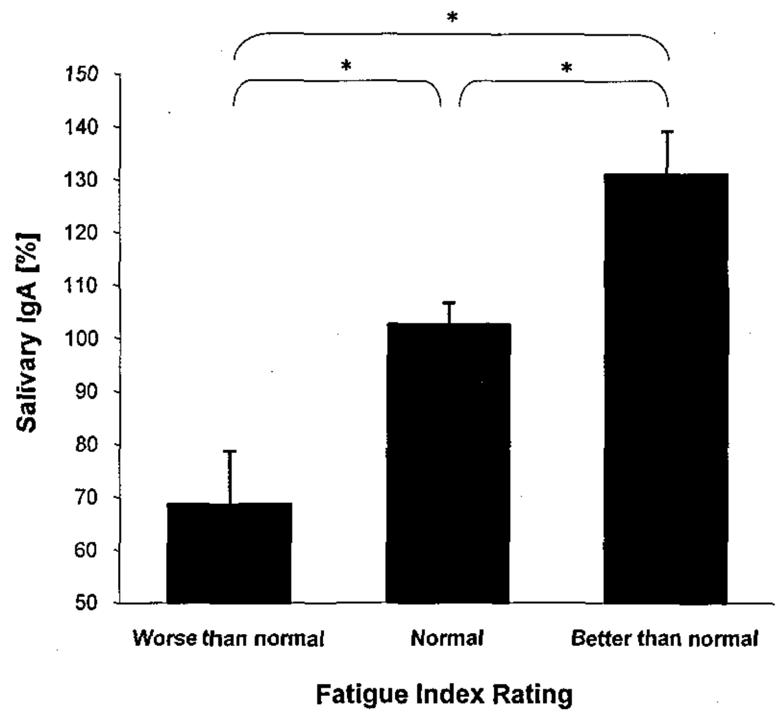


Figure 8.6 Salivary IgA concentration for different fatigue ratings. Data are mean ± SEM of 38 athletes, with each individual's relative s-IgA values averaged for each rating. * s-IgA for each rating significantly different to the other two (n=38, P<0.005).

8.4 Discussion

This is the largest salivary immunology study on elite athletes to date. The main findings suggest that the relative s-IgA concentration is associated with, and can help to predict URI in elite athletes. For the cohort, relative s-IgA determined a substantial proportion of the variability of URI incidence. The typical decline in an individual's relative s-IgA over the 3 weeks before URI appears to pre-empt and contribute to URI risk, with the level of risk related to the extent of the decline in s-IgA, independent of the absolute concentration. In addition, the s-IgA of elite athletes is highly variable, both within and between subjects, and is related to the athlete's perception of underlying fatigue. These results suggest that regular monitoring of resting s-IgA may benefit athletes and coaches in determining the risk of URI and fatigue in elite athletes.

The mean s-IgA concentration in the current study is similar to that reported by several previous studies in exercise immunology (Tharp 1991; Halson et al. 2003; Sari-Sarraf et al. 2006). However, the differences between studies are extensive, with some studies having a 15-fold greater (Nieman et al. 2006) mean s-IgA concentration than others (Mackinnon et al. 1993b). These differences could be attributed to variations in methodology, assay assessment techniques, control for basal resting values, different cohorts of subjects and large between-subject variability. It is therefore difficult to make comparisons between studies (Shephard 2000), particularly with respect to absolute values of s-IgA.

The volume of sailing per week was greater (almost 30%) than that reported during the 31st America's Cup (Neville et al. 2006), as was the ratio of sailing to training volume (Neville et al. 2006). This was possibly due to the more favourable sailing conditions at the venue of the 32nd America's Cup. The correlation between the combined sailing and training load and the athletes' weekly s-IgA was in accordance with previous reports (Tomasi et al. 1982; Nieman et al. 2002; Novas et al. 2003; Fahlman and Engels 2005; Libicz et al. 2006; Nieman et al. 2006).

The incidence of URI (2.7 episodes per 1,000 h sailing and training) was similar to that previously reported in America's Cup yacht racing (Neville et al. 2006), with a similar incidence for athletes in sailing roles with high and moderate physical demands.

The large within-subject variation in the current study (CV: 48%) concurs with results found in elite level rowing (Nehlsen-Cannarella et al. 2000) and swimming (Francis et al. 2005). Elite athletes have been reported to have greater within-subject variability than recreationally active or sedentary individuals (Francis et al. 2005), which may be due to the many stressors encountered as a result of high training loads and competition. These variations may be characteristic of the individual and their response to recent circumstances, and may indicate that some athletes are more susceptible (or adaptable) to stress than others. This variation was despite carefully controlling for a range of factors known to influence s-IgA. In fact, the methodological care with which samples were collected in standardised conditions (after a rest day, at a consistent time of day, in a fasted state and without caffeine ingestion) was one of the strengths of the current study. Many studies have not controlled for factors known to influence the concentration of s-IgA such as the residual effects of exercise (Francis et al. 2005), large data collection windows (Francis et al. 2005; Sari-Sarraf et al. 2007a) and caffeine ingestion (Gleeson et al. 1999b; Novas et al. 2003). Other factors known to influence s-IgA which have not been controlled for in previous studies include, time of day and circadian rhythm effects (Dawes 1972) and nutritional status (Gleeson and Bishop 2000). Whilst many of these inconsistencies may explain some of the discrepancies found in the literature, even when well controlled for in this study, there was still a large within-subject variability, which highlights the complex nature of the mucosal immune system. Saliva samples were collected 38 h post-exercise to ensure that the athletes were well rested and exclude any residual effects of exercise; hence, these results are related to the resting status of the individual and should not be compared with the effects of acute stress or temporal changes in s-IgA.

Another factor affecting baseline values is sample size (Hopkins 2000). The current study collected up to 50 samples for each athlete, which is considerably more than the range of 2 to 13 samples in most previous longitudinal studies (Tharp 1991; Mackinnon et al. 1993a; Mackinnon et al. 1993b; Gleeson et al. 1999a; Gleeson et al. 1999b; Gleeson et al. 2000b; Pyne et al. 2000; Klentrou et al. 2002; Fahlman and Engels 2005; Francis et al. 2005; Libicz et al. 2006). With s-IgA being highly variable, the smaller the number of samples, the less likelihood of detecting a real change (Hopkins 2000), which could account for some of the inconsistencies in the literature. In addition, a low number of samples may result in values having a large influence on the correlation coefficient, thereby increasing the risk or chance effect of a significant correlation.

The large between-subjects variability in s-IgA concentration found in this study (CV: 71%) concurs with previous reports (Nehlsen-Cannarella et al. 2000; Francis et al. 2005) and strongly indicates that resting values of s-IgA are specific to the individual. Hence, it is the aetiology of this variability which may provide important answers to athletes' susceptibility to illness.

No association was found between the absolute mean s-IgA concentration of each athlete and the incidence of URI, indicating that athletes with low s-IgA concentration were no more at risk of URI than athletes with high values. This is contrary to previous reports, which have suggested that an absolute concentration of $< 40\ mg \cdot L^{-1}$ (Gleeson et al. 1999b) or an absolute rate of secretion of $< 40\ \mu g \cdot min^{-1}$ (Fahlman and Engels 2005) may increase the risk of URI. Based on these previous reports, the athlete with the lowest mean s-IgA concentration (35 ± 4 mg·L^{-1}) in the current study would be at chronic risk of infection, when in fact this athlete reported no incidence of illness during the study, and coincidently, the athlete with the highest mean value (314 ± 27 mg·L^{-1}) reported the greatest number of URI (8). Based on these data, relative values are the preferable methods of expressing resting s-IgA and provided sufficient resting samples are measured, will provide a valid baseline for each individual.

A main finding of this study was the association between s-IgA and URI, where the weekly mean relative s-IgA concentration was negatively related to the incidence of URI (r = -0.54, $P < 0.005$). This indicates that on a group basis the weekly mean s-IgA determines a substantial proportion (29%) of the variation in URI incidence. Hence, monitoring group s-IgA may assist coaching staff in identifying periods of high risk in order to apply appropriate intervention (see (Pyne et al. 2000) for a review of intervention strategies). Previously, the relationship between s-IgA and URI in athletes has been less than convincing, with only a few studies having suggested an association (Mackinnon et al. 1993a; Gleeson et al. 1999a; Gleeson et al. 1999b; Fahlman and Engels 2005). These results are therefore important in confirming that s-IgA plays an important role in the incidence of URI and that the changes in s-IgA within an individual may be either directly responsible for URI risk, or may be a surrogate measure for some other immune system function. Interestingly, the lowest weekly s-IgA values for the group occurred during the first 6 weeks of training after a 2-month winter off-season period, and coincided with the highest weekly incidence of URI. This is likely to be a combined result of changes in environment, increased sailing and training load, changes in diet, psychological stress associated with returning to the competitive team environment and exposure to pathogens during public travel on return to the team venue (Pyne et al. 2000).

On an individual basis there was also a difference in s-IgA concentration (~30%) between when an athlete had URI and when no URI was present. When the time course of s-IgA was examined in the weeks before, during and after an URI episode, it showed that there was a progressive decline in s-IgA during the 3-weeks prior to URI and a subsequent return to baseline within 2-weeks following URI. The cause and effect relationship as inferred by Mackinnon et al. (Mackinnon et al. 1993a), where the decrease in s-IgA prior to infection could be the result of the incubation period prior to expression of URI symptoms, is unlikely to apply to the findings of the present study, as the incubation period of URI is usually only 1 to 3 days (Department of Health 2005). Therefore, it is postulated that the reduction in s-IgA in the weeks prior to URI is a contributing factor to the subsequent incidence of URI. It seems that, on average, a 30% reduction in relative s-IgA from healthy values may increase the risk of URI, which is further supported by the increased frequency (2.5-fold) of s-IgA values less than 70% of an individual's mean healthy value during the week prior to URI when compared with times when no infection was present. The results further suggest that the greater the drop below an individual's mean healthy s-IgA concentration, the greater the risk of URI.

An important finding of this study was that for individual athletes low relative s-IgA concentrations were associated with an increased risk of URI. For example: when an athlete was healthy (did not have URI or was not recovering from URI), a low s-IgA value (< 40% of an individual's mean healthy value) suggested a 48% chance of contracting an URI within 3 weeks, compared with a 28% chance when values were below 70% of an individual's healthy mean s-IgA concentration. Therefore, the lower the s-IgA value below baseline, the greater the probability of contracting an URI. However, it should be noted that 38% of URI were not preceded by values below baseline and only 11% of URI were preceded by values < 40%. Hence, the absence of low s-IgA values was no guarantee of remaining healthy, indicating the multifactorial nature of immunity, and that factors other than reduced s-IgA alone contribute to the risk of infection.

No significant relationship was found between sailing and training load and the incidence of URI, which is contrary to previous reports in a number of different sports, including: elite level swimming (Spence et al. 2007), elite tennis (Novas et al. 2003) and endurance running (Peters and Bateman 1983; Nieman 2000). This may be due to the difficulty in accurately determining the total work load that each individual is exposed to, as athletes are often required to perform large volumes of work over and above the physical requirements of sailing and training, including: boat maintenance, sail packing, boat sanding, as well as the psychological stress of design and performance meetings .

As fatigue is common in athletes during periods of heavy training and competition, the relationship between salivary immunity and recovery is of great interest. To our knowledge, this is the first report of subjective fatigue being associated with relative s-IgA concentration. The results suggest that a simple fatigue rating reflects immune status to some extent, and appears to validate the use of a simple subjective questionnaire in monitoring underlying fatigue and recovery of athletes. These findings also imply that an athlete's underlying fatigue or psychological state may have a major influence on s-IgA in addition to the combined sailing and training load.

8.4.1 *Conclusions*

The results of this study confirm the role of s-IgA in the incidence of URI in elite athletes. The weekly mean relative s-IgA concentration for the cohort was negatively related to the incidence of URI, indicating that on a group basis the weekly mean s-IgA determines a substantial proportion of the variation in URI incidence. No association was found between the absolute mean s-IgA concentration of each athlete and the incidence of URI, indicating that athletes with low mean s-IgA concentration were at no greater risk of infection. Consequently, relative values are the preferred means of expressing basal s-IgA concentration. The large within and between subjects variability strongly indicates that basal values of s-IgA are specific to the individual and a relatively large number of samples are required to determine baseline values. Elucidating the aetiology of this variability would enhance our understanding of athletes' susceptibility to illness. The reduction in s-IgA in the weeks prior to URI appears to be a contributing factor to the subsequent incidence of URI, with the magnitude of the decrease related to the risk of URI. Furthermore, a simple fatigue rating appears to reflect changes in salivary immunity. The results presented in this study point to the need for frequent monitoring of well controlled resting s-IgA in elite athletes. If the results are rapidly available, they may assist athletes and their support staff in identifying periods of high URI risk so that appropriate preventative strategies can be applied. Furthermore, the use of a simple fatigue questionnaire can provide coaches with valuable information on the underlying fatigue status of the athlete.

CHAPTER 9

GENERAL DISCUSSION

9.1 General Discussion and Recommendations

This thesis comprises the most comprehensive series of studies on a specific class of sailing to date. The broad spectrum of studies presented herein addresses fundamental questions on the competition and performance analysis, physiology, biomechanics, thermoregulation, immunology, and health of elite professional sailors, and highlights the unique nature of this sport. The results of each of the six studies are novel and contribute to the applied and clinical sports science literature.

It is evident that the physiological demands of America's Cup yacht racing are high and the athletes are well adapted (or selected) for the unique demands of this sport. The race analysis described in Chapter 3 has substantially improved our knowledge of America's Cup sailing. For example quantifying the activity pattern of *grinders* with work bouts lasting on average 5.5 ± 5.4 s and work:rest ratio typically 1:6 was essential in understanding the physiological requirements of this role. The observation that a higher standard crew were grinding for less time, and thus completing manoeuvres more quickly than a lower ranked team, seemed to highlight the importance of effective grinding to the speed of manoeuvres, and likely overall race performance. However, other technical factors such as the rate of turn or the trimmer's 'cast-off', could also explain the quicker manoeuvres of highly ranked teams. It would, therefore, be interesting to measure the actual power output of *grinders* during racing, and more carefully examine how this relates to the speed of manoeuvres. This would involve on-board power measurement, a technical challenge that has not yet been achieved within America's Cup sailing. It would also be interesting to determine more precisely, the activity profiles of other positions during racing, such as the *bowmen*.

The differences in strength and strength endurance between teams of different standard reported in Chapter 3, highlights the importance of athlete fitness and training in America's Cup yacht racing. Specifically, the high strength and body mass of *grinders* is not surprising, considering the absolute power requirements of this position. Although grinding is predominantly an anaerobic activity, the frequency of bouts indicates a high provision for aerobic energy is also involved. This is evident from the remarkably high levels of peak power, substantially above any previously recorded, and the concomitant high aerobic power documented in Chapter 4. This also poses a challenge for their conditioning, where both maximal power and endurance are required.

As identified in the race analysis, the activity pattern of grinding during racing is varied. This variability includes the load, crank velocity, duration and direction of grinding. Therefore part of the objective of the research herein has been to identify factors which may contribute to improved grinding performance. For example, the determination of the linear torque-crank velocity and parabolic power-crank velocity relationships during maximal standing arm-cranking are important in understanding the optimal velocity for grinding performance (Chapter 4). 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 the development of efficient gear change mechanisms. For example, it would be highly beneficial if it were mechanically possible to maintain optimum crank velocity (125 rpm) in the forward direction without stopping to change gear, such as the use of a 'crash-box' gear change system. The issue of grinding direction was not considered in the current work, but is clearly another important variable with respect to optimising grinding performance. Whilst it would be useful for future work to consider the physical and technical optimisation of grinding backwards, given the documented superiority of grinding in the forward direction, the development of on-board winch technology to facilitate purely forwards grinding may supersede the utility of this research avenue.

In addition, the influence of crank length and crank-axle height on performance is clear and it is suggested that America's Cup teams consider these results in the design of grinding pedestals. Optimal crank-axle height was between 50 and 60% of stature (950-1150 mm for the cohort in Chapter 5), while a crank-axle height of <50% of stature, which is typically used on America's Cup yachts, resulted in substantially reduced performance (>7%). Hence it may be highly beneficial for America's Cup teams to reconsider the grinding pedestal ergonomics. The optimal crank length for maximal power was 12.3% of arm-span (241 mm for the athletes studied in Chapter 5), which is similar to the 250 mm crank lengths used in the America's Cup. However, these findings suggest that standard cycling crank lengths (170-175 mm), commonly used in arm-crank ergometry, are inappropriate for maximal arm-cranking performance, and casts doubt on the validity of previous maximal arm-crank studies.

Grinding technique also plays an important role in optimising performance. Restricted leg movement during standing arm-cranking increased the physiological strain of this activity. Therefore, a purely stabilising role of the lower limbs is discouraged and it is recommended that *grinders* make dynamic use of the legs to decrease cardiovascular and metabolic responses to this exercise. It is possible that greater lower limb activity than was typical in the normal grinding, reported in Chapter 6, could be beneficial to grinding performance, however further investigation is needed to better understand the relationship between lower extremity function and grinding performance. Furthermore, the contribution of the lower limb is only one aspect of grinding technique and other issues of interest include the sequential pattern of muscle activation and recruitment, and how body segments in the upper and lower-body interact during the different phases of the movement. In addition, determining lower back load in relation to grinding technique and/or arm-crank configuration could elucidate the aetiology of lumbar spine injuries.
The contribution of the lower limbs to grinding underscores the importance of lower limb conditioning for grinders. With the majority of positions characterised by specific activities or skills, it is logical that each sailors' training and conditioning reflect the requirements of their role. As clearly identified in this study, *grinders* require considerable whole body strength and power training in order to develop muscle mass. They also require a substantial volume of high intensity arm-crank training, and multi-joint explosive training to develop force generation from the proximal kinetic chain. Quantifying the influence of specific training interventions on upper body power and endurance may be useful in understanding the adaptations of these elite athletes. In addition, the identification of grinding activity cycles during racing in Chapter 3 may benefit the prescription of specific training intervals.

A principle finding in Chapter 7 was the substantial thermoregulatory strain during racing. This is the first study to comprehensively report the unique environmental extremes of in-shore yacht racing. Downwind sailing resulted in significantly greater cardiovascular and thermal strain compared with upwind, and the cooler and wet conditions of upwind sailing may in fact be an important part of racing in attenuating the rise in body temperature. B*owmen* in particular are at greater risk of hyperthermia and high fluid and electrolyte losses during racing,which may impair their performance and even lead to heat illness. It seems that dressing in an attempt to stay dry may be less important than staying cool during upwind sailing in order to prevent attenuations in performance or the risk of heat illness. These results may also have implications for fabric and garment selection, where light weight, highly breathable and waterproof garments could be beneficial. Race management (reducing the time that *bowmen* spend below deck), and boat design (reducing below deck temperature and increasing ventilation) may also assist in attenuating the thermal strain. Medical support should be encouraged to monitor early signs of heat illness particularly on days with two races, where preventative measures such as 'ice jacket cooling' could be employed before and after races as an effective means of reducing core temperature. Furthermore, the results suggest that sailors (particularly *bowmen*) should be encouraged to drink regularly and would benefit from individualized hydration and electrolyte replacement strategies.

It is evident that fatigue is common to America's Cup athletes, even in well resourced teams (Neville et al. 2008) as a result of the high volume of work and sailing involved. This may be further exacerbated in less well resourced teams, where athletes are typically required to take on multiple roles within the team due to the limited number of support staff. Consequently, the athletes' ability to prioritise on their athletic performance may be compromised. As fatigue and illness are common in athletes during periods of heavy training and competition, the relationship between salivary immunity and fatigue and illness was of great interest. The findings of this study suggest that a simple fatigue rating correlates with immune status to some extent, and appears to validate the use of a simple subjective questionnaire in monitoring underlying fatigue and recovery of athletes. These findings also imply that an athlete's underlying fatigue may have a major influence on s-IgA in addition to the combined sailing and training load. Coaches and support staff may benefit from such a simple measurement tool in identifying underlying fatigue in athletes. Furthermore, the relationship between the weekly mean relative s-IgA concentration and the incidence of URI is an important finding, indicating that on a group basis the weekly mean s-IgA determines a substantial proportion of the variation in URI incidence. The fact that the reduction in s-IgA in the weeks prior to URI appears to indicate the subsequent incidence of URI, makes this a useful tool. If the results are rapidly available, s-IgA could assist athletes and their support staff in identifying periods of high URI risk so that appropriate preventative strategies can be implemented. These findings advocate frequent monitoring of well controlled resting s-IgA in elite athletes and may have important implications for clinical health as well.

It is clear that the high work loads are part of the nature of this sport and largely unavoidable, underscoring the importance of prudent athlete management. The number of full-time sports science/medical support staff typically employed by teams (usually one full-time staff for up to 30 athletes) is clearly inadequate and detrimental to the performance, health and competitive longevity of the athletes, not to mention the effectiveness of the support. Ideally teams should employ one sports science/medical support staff for every 5-7 athletes, and include expertise in areas such as, medical support, physiotherapy and rehabilitation, exercise science, strength and conditioning, nutrition and hydration and psychology.

9.2 Further Research

A number of areas of suggested future research have been identified:

1. Measure the actual power output of *grinders* during racing, and more carefully examine how this relates to the speed of manoeuvres

2. Determine the activity profiles of different positions during racing by means of kinematic analysis and energetic/metabolic measures

3. Evaluate the sequential pattern of muscle activation/recruitment during arm-cranking/grinding, and how body segments in the upper and lower-body interact during the different phases of the movement

4. Assess if greater lower limb activity than was typical in the normal grinding is beneficial to grinding performance

5. Investigate the physical and technique differences between grinding forwards and backwards

6. Quantify the influence of specific training interventions on upper body power and endurance of *grinders*

7. Specifically determine the aetiology of lower back injuries in relation to grinding technique and or arm-crank configurations

8. Determine the influence of fabric/garment choice on thermoregulatory strain and comfort during sailing

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Appendix 1. America's Cup Defenders and Challengers from 1851 to 2007, [name of boat/team].

Year	#	Defender	Result	Challenger
2009	33rd	Switzerland [Alinghi]		Currently under litigation
2007	32nd	Switzerland [Alinghi]	5-2	New Zealand [Team New Zealand]
2003	31st	New Zealand [Team New Zealand]	0-5	Switzerland [Alinghi]
2000	30th	New Zealand [Team New Zealand]	5-0	Italy [Prada Challenge]
1995	29th	United States [Young America]	0-5	New Zealand [Black Magic]
1992	28th	United States [America^3]	4-1	Italy [Il Moro di Venezia]
1988	27th	United States [Stars & Stripes]	2-0	New Zealand [NZ Challenge]
1987	26th	Australia [Kookaburra III]	0-4	United States [Stars & Stripes]
1983	25th	United States [Liberty]	3-4	Australia [Australia II]
1980	24th	United States [Freedom]	4-1	Australia [Australia]
1977	23rd	United States [Courageous]	4-0	Australia [Australia]
1974	22nd	United States [Courageous]	4-0	Australia [Southern Cross]
1970	21st	United States [Intrepid]	4-1	Australia [Gretel II]
1967	20th	United States [Intrepid]	4-0	Australia [Dame Pattie]
1964	19th	United States [Constellation]	4-0	England [Sovereign]
1962	18th	United States [Weatherly]	4-1	Australia [Gretel]
1958	17th	United States [Columbia]	4-0	England [Sceptre]
1937	16th	United States [Ranger]	4-0	England [Endeavour II]
1934	15th	United States [Rainbow]	4-2	England [Endeavour]
1930	14th	United States [Enterprise]	4-0	Northern Ireland [Shamrock V]
1920	13th	United States [Resolute]	3-2	Ireland [Shamrock IV]
1903	12th	United States [Reliance]	3-0	Ireland [Shamrock III]
1901	11th	United States [Columbia]	3-0	Ireland [Shamrock II]
1899	10th	United States [Columbia]	3-0	Ireland [Shamrock]
1895	9th	United States [Defender]	3-0	England [Valkyrie III]
1893	8th	United States [Vigilant]	3-0	England [Valkyrie II]
1887	7th	United States [Volunteer]	2-0	Scotland [Thistle]
1886	6th	United States [Mayflower]	2-0	England [Galatea]
1885	5th	United States [Puritan]	2-0	England [Genesta]
1881	4th	United States [Mischief]	2-0	Canada [Atalanta]
1876	3rd	United States [Madeleine]	2-0	Canada [Countess of Dufferin]
1871	2nd	United States [Columbia]	4-1	England [Livonia]
1870	1st	United States [Magic]	1-0	England [Cambria]
1851		United States [America]	1-0	England [Aurora]