PADDLING PERFORMANCE IN RECREATIONAL AND COMPETITIVE JUNIOR SURFERS

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Submitted in the fulfilment of the requirements of the degree of Doctor of Philosophy

APRIL, 2009
ABSTRACT

Purpose: The primary purpose of this thesis was to investigate surf-paddling performance, the surf popup manoeuvre (i.e., prone to standing position) and maximal-leg power in junior male recreational and competitive surfers. Four independent studies were conducted with the aims to: i. Develop reliable testing methods of assessing maximal-paddling performance in surfers (Study 1), ii. Determine the aerobic power and paddling economy in junior male recreational surfers (SurfersREC) and junior male competitive surfers (SurfersCOMP) (Study 2), iii. Measure maximal-paddling performance and the accumulated O\(_2\) (AO\(_2\)) deficit of a 30-s Wingate Anaerobic Test for paddling (WAnT\(_\text{PADDLING}\)) in SurfersREC and SurfersCOMP (Study 3), and iv. Characterise the timing and magnitude of the vertical ground reaction forces produced during a surf popup manoeuvre in SurfersREC and SurfersCOMP, measure maximal-leg power in SurfersREC and SurfersCOMP, and measure the influence of paddling on the popup maneuver and maximal leg power in SurfersREC (Study 4).

Methods: All subjects were junior male surfers aged 16-20 yr. SurfersCOMP were members of the Australian Junior National Team and had been competing nationally for a minimum of 2 yr in national age-group events. SurfersREC had been surfing for a minimum of 4 yr and participating in surfing at least 2 session/wk, but had not participated in competitive surfing events, other than their local board-riding events (< 6 event/yr). Participation numbers for each group included; i, Study 1: eleven SurfersCOMP (17 ± 1 yr, 61.9 ± 3.1 kg, 173 ± 2 cm), ii, Study 2: eight SurfersREC (18±2 yr; 66.8±13 kg, 175±10.3 cm) and eight male SurfersCOMP (18±1 yr; 68.0±11.7 kg, 172.9±9.6 cm), iii, Study 3: eight SurfersREC (18±2 yr, 66.7±6.3 kg, 169±10 cm) and eight SurfersCOMP (18±1 yr, 68.9±47 kg, 170±5 cm), iv, Study 4: ten SurfersREC (17±1 yr, 68.2±6.2 kg, 179±5 cm) and ten SurfersCOMP (17 ± 1 yr, 62.9±9.9 kg, 172±8cm). All paddling tests were performed on a stationary swim-bench ergometer with pulmonary gas exchange measured breath-by-breath using a metabolic measurement system. Aerobic power was
determined using an incremental-paddling test to exhaustion and paddling economy measured during paddling at four, 3-min constant-load work stages. Anaerobic power was measured from a 10-s maximal-paddle test and the 30-s WAnT<br>PADDLING test. The AO₂ deficit was determined during the WAnT<br>PADDLING as a measure of the contribution of the anaerobic energy systems to the total energy demand of the test. The timing and magnitude of the vertical ground reaction forces produced during the popup were measured on an inground force plate. Maximal vertical jump height was measured on the force plate and used as a measure of leg power. Relationships between paddling, the popup, and leg power were investigated before and after 25 min of paddling on the swim-bench ergometer, designed to replicate a competitive surfing heat.

**Results:** Study 1 established that peak power determined during a 10-s maximal-paddling test on a swim-bench ergometer is a reliable method both trial-to-trial (r = 0.995, p < 0.001) and day-to-day (r = 0.983, p < 0.001) to determine maximal-paddling power in surfers. Study 2 showed that there were no differences between SurfersREC and SurfersCOMP for peak O₂ uptake (2.5 ± 0.5 L/min vs. 2.6 ± 0.4 L/min, respectively) and economy (21.8 ± 3.1 % vs. 23.8 ± 4.0 %, respectively). There were no significant correlations between aerobic power and economy with surfing experience (number of yr surfing) or frequency (session/wk). During submaximal constant-load paddling blood lactate was greater in SurfersREC (2.4 ± 0.9 mmol/L) compared to SurfersCOMP (1.6 ± 0.5 mmol/L). In Study 3 peak power (SurfersREC = 292 ± 56 W vs. SurfersCOMP = 404 ± 98 W, p = 0.014), mean power (SurfersREC = 236 ± 59 W vs. SurfersCOMP = 335 ± 74 W, p = 0.010), and the AO₂ deficit (SurfersREC =1.14 ± 0.38 L vs. SurfersCOMP = 1.60 ± 0.31 L, p = 0.022) determined during the 30-s WAnT<br>PADDLING were all greater in SurfersCOMP when compared to SurfersREC. No differences were observed between SurfersREC and SurfersCOMP for peak O₂ uptake (2.5 ± 0.2 L/min vs. 2.7 ± 0.1 L/min, respectively) and paddling economy (19.6 ± 6.9 % vs. 21.1 ± 4.9 %). Significant correlations were observed between surfing experience and frequency with the WAnT<br>PADDLING peak power and AO₂ deficit. Consistent with study 2, from the incremental paddling test no
correlations were observed between surfing experience and frequency and peak O₂ uptake and paddling economy. Study 4 revealed no differences between SurfersREC and SurfersCOMP in the timing and magnitude of the vertical ground reaction forces produced during the popup manoeuvre. There were no differences in the leg power as a measure of jump height between SurfersREC (38.2 ± 4.7 cm) and SurfersCOMP (40.0 ± 9.2 cm). Following 25 min of intermittent surfboard paddling there was a decrease (t = 4.553, p = 0.001) in maximal vertical jump height in SurfersREC (post paddle = 34.0 ± 5.1 cm).

Conclusions:

No differences in aerobic power and paddling economy between SurfersCOMP and SurfersREC and a greater anaerobic power and accumulated O₂ deficit in SurfersCOMP compared to SurfersREC suggests that the measures of anaerobic performance are more closely related to surfing ability than measures of aerobic performance. No correlations between aerobic power and paddling economy with surfing experience and participation frequency, but significant correlations between anaerobic power and the accumulated O₂ deficit with surfing experience and participation frequency reveal that measures of anaerobic performance are more closely associated with surfing experience and participation frequency than measures of aerobic performance. A decrease in maximal vertical jump height following surfboard paddling suggests that paddling may influence leg power possibly necessary for subsequent wave-riding performance. Collectively these findings suggest that recreational and competitive surfing results in significant changes in the anaerobic energy system, more so that the aerobic energy system and than a bout of paddling can reduce leg power.
DECLARATION

This work has not previously been submitted for a degree or diploma in any university. To the best of my knowledge the thesis contains no material previously published or written by another person except where due reference is made in the thesis itself.

_________________________  ______________________
Signed                      Dated
LIST OF PUBLICATIONS

The following submissions for publication are listed in support of this thesis:


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ACKNOWLEDGMENTS

Thank you to the people who have supported the development of this PhD thesis.

Thank you to PhD supervisor Dr Clare Minahan, for guidance and assistance with the experimental design, testing methods and paper and thesis writing. To PhD secondary supervisor A/P Lewis Adams and final project supervisor A/P Wendy Gillearrd, thank you for help with editing and compiling the final product. Thank you to all the staff at Surfing Australia, past and present, specifically Martin Grose and past Head Coach Sasha Stocker for their enthusiasm to expand the field of Exercise Science in Surfing.

Thank you to Dr Surendran Sabapathy for supporting with research ideas, lab-testing and thesis writing. Thank you to fellow research students Troy Cross, Travis Teves, and Martin Frank for hands-on assistance with data collection. Thank you to those who have helped with technical support, to Mark Andrews from Applied Motion Research, Anna Boehm from Griffith University and Robert Baglin and Cameron Phillips from Southern Cross University.

A heart felt thank you to Alicia Loveless for guidance through the PhD potholes, proofreading and moral support in the end stages of the PhD. Thank you to Greg Loveless and Sue Loveless for unconditional love and encouragement throughout every step of the PhD and university journey.

Finally, a loving thank you to Serge Benhayon, Miranda Smith and everyone with Universal Medicine, for continuously presenting love and nothing but truth, inspiring me to be all That I Am in all that I do – Not be all that I do and abandon who I am.

Danielle
In 1999, at a university open day, a well established Professor and Head of the Physiotherapy and Exercise Science Department passed on a piece of insight to a fresh faced 17 year old. The Professor said with a grin of encouragement “you’ll do fine at the university here on the Gold Coast, as long as you don’t spend too much time surfing or hanging on the beach”. Ten years later I can confidently respond “sorry Professor, on this one occasion you were wrong”.

Surfboard riding (Surfing) was once considered a leisure activity for the ‘beach hippies’ of the 60’s and 70’s. Forty years later it is now a highly competitive international sport with an estimated 4 million participants spread across all continents and supported by many millions of dollars in competition prize money and sponsorship. The growth of surfing has seen an increase in participation numbers, competition standards and surfing performance. As with other elite sports, the improvements in performance have occurred through substantial advances in equipment design and improvements in the biomechanical, physiological and psychological profile of surfboard riders (surfers). Although technical advances are clearly documented, there is a paucity of scientific evidence relating to the human performance aspects of the sport. The lack of research in this field probably relates to the young age of the sport, which was introduced to Australia in the early 1910’s but did not achieve significant participation levels until the 1950’s. Further, research on surfing is complex due to the many uncontrollable variables that influence surfing performance. These include the geographical and environmental conditions of the ocean, such as the type of ocean floor (sand, rock, reef), wave size and direction, wind speed and direction and tide and current movements.

Exercise science research in surfing began in the 1980’s, with exercise physiologist Brian. J. Lowden publishing a series of papers investigating the physical attributes, movement patterns, and common injuries of competitive surfers. Following the
conclusion of Lowdon’s research, the early 1990’s produced only a few articles, mainly investigating injury patterns in recreational and competitive surfers. Only in the last 5 years have we seen a resurgence in publications in surfing physiology and surfing biomechanics. In particular, A. Mendez-Villanueva, a Spanish researcher who completed the first PhD in surfing physiology published a number of papers, including a review of the ‘Physiological Aspects of Surfboard Riding Performance’, which covered the exercise science research undertaken in surfing up until 2005.

With the limited amount of scientific research on surfing, the physiological and biomechanical factors important for optimal surfing performance are still unclear. Such information is valuable for surfing instructors and coaches, as well as health professionals, to help target strategies for exercise training and performance improvement as well as for the prevention and management of injuries. This PhD thesis reports on scholarly and research activity aimed at expanding the understanding of the key physiological and biomechanical determinants of surfing performance.

The thesis is presented in six parts: Chapter 1 provides an overview of the background knowledge of surfing physiology. The history and movement patterns of surfing are introduced and the physiological demands of surfing and the physiological characteristics of surfers explored. The research aims of the thesis are presented in the final section of chapter 1. Chapters 2, 3, 4 and 5 describe four original experimental studies that address each of the research aims. Each of these chapters includes independent Introduction, Methods, Results and Discussion sections. Chapter 2 reports ‘Two reliable protocols for assessing maximal-paddling performance in surfboard riders’ (Study 1). Chapter 3 discusses the ‘Peak aerobic power and paddling economy in recreational and competitive junior surfers’ (Study 2). Chapter 4 presents ‘Maximal-paddling performance in recreational and competitive junior surfers’ (Study 3) and Chapter 5 reports the final study ‘Surfboard riding popup manoeuvre and leg power in recreational and competitive junior surfers’ (Study 4). Chapter 6 concludes with the
thesis discussion and conclusions, summarising the findings of all four studies and discussing the relevance of this research to the existing scientific literature on surfing.
CHAPTER 1

BACKGROUND
1.1 AN INTRODUCTION TO SURFING

A brief history

The activity of surfboard riding (surfing) can be described as the action of an individual riding a floatable vessel on the broken or unbroken section of a wave, as it moves towards the shore. For the purpose of the research in this thesis, surfing refers solely to stand up surf board riding on a short board, without a paddle. Surfing originated in the Pacific Islands of Tahiti, Polynesia and Hawaii and was an important cultural and recreational activity (Kampion & Brown, 1997). Due to religious and cultural changes around early 1800’s surfing was suppressed on many of the main Pacific islands. It wasn’t until the early 1900’s that the Olympic champion, Hawaiian swimmer Duke Kahanamoku, introduced surfing to the western cultures in California and Australia (Kampion & Brown, 1997). By 1914, a number of Australians were giving surf riding displays at beaches in South East Queensland and Sydney, giving rise to the new and exciting sport of surfing in Australia.

In 1964 the first international competitive events were run, later leading to the development of an international governing body for surfing, the Association of Surfing Professionals (ASP) to manage these events. There are now two branches of the ASP, ASP International and ASP Australasia. ASP International manage the world competitive circuit called the World Championship Tour (WCT), for the top 50 male and top 30 female surfers worldwide. ASP Australasia manage two other international competitive circuits called the World Qualifying Series (WQS) and the Professional Junior circuit (Pro Junior), which are for open age and junior surfers (under 21) respectively, who are trying to qualify for the WCT. Events run all year across five continents and the WCT surfers have access to more than $4,000,000 in prize money. The last five years has seen the development of National Surfing Organisations in most major surfing countries (e.g. Australia, USA, Hawaii, Brazil, Japan, Portugal) to
manage and foster recreational and competitive surfing participation in their country. In more recent years, Surfing High Performance Centres have been set up to focus on the long term athlete development of talented juniors, who now have access to multimillion-dollar sponsorship contracts, even before the age of 18.

The last 40 years of surfing has seen great advances in technology, coaching expertise and training techniques, to meet the needs of surfers wanting to improve performance. Most scientific research and funding have focused on developing better surfing equipment, (e.g. boards and wetsuits) or monitoring geographical or environmental conditions that influence the surf. A much smaller amount of resource has been directed towards examining the human factors that influence surfing performance. These include the surfer’s physiological make up, biomechanical considerations related to the event, tactical skill, and psychological and mental aptitude for success in this sport (Mendez-Villanueva & Bishop, 2005a).

**Epidemiology**

There is lack of data about participation numbers in surfing, both worldwide and in Australia. It was estimated that in 2002 there were approximately five to seven million surfers worldwide (Frisby & Mckenzie, 2003) and in 2004 a figure of more than 2.1 million was reported for the United States alone (Darrow, 2005). More recently, in 2006 it was estimated that 14 % of urban-dwelling Australians participate in the sport of surfing (Sweeney, 2006). Currently competitive surfing has the profile, funding and athlete income of other highly competitive international sports. The increase in surfing participation was forecasted 20 yr ago (Renneker, 1987), with the current popularity driven by commercialisation and the appeal of the surfing lifestyle (Everline, 2007; Nathanson et al., 2007).
The action of surfing

Surfing can be characterised as comprising of three fundamental components i. Lying prone on the surfboard and paddling (paddling), Figure 1.1; ii. The motion of pushing up from a prone to standing position (popup) Figure 1.2, and iii. Standing on the surfboard and riding a wave (wave riding), Figure 1.3. A surfer is required to undertake each component independently in order to successfully surf a wave towards the shore. The process of paddling out from shore, catching a wave, popping up and wave riding towards shore is repeated many times during a recreational or competitive surfing session. The amount of time spent paddling, taking off and wave riding are all influenced by the equipment used, the environmental conditions, the physiological characteristics of the surfer and the purpose of the surfing session. Environmental conditions such as swell size, wind direction, currents present and time between wave sets all play a highly significant role in the characteristics of a surfing session.

A competitive surfing event consists of heats lasting for 20-40 min, with two to four surfers competing against one another. A surfer can perform one to six heats on the one day of a competition, depending on the length of the event which can range from one to fourteen days. Each wave caught by the surfer in the total heat time will be given a score out of 10 and the top two scores added to give the final score for the surfer for that heat. Typically a surfer will aim for two to four quality waves and catch anything from 2 to ~12 waves per heat. It is unclear exactly how many events a professional surfer will compete in a year, but this can range from 8 to ~25 events per year depending on the programs of the competitive circuits, the age or level of performance of the surfer and the nature of any sponsorship requirements.
Figure 1.1 a. Example of a recreational surfer paddling lightly into wave catching position; b. Example of a recreational surfer paddling maximally to catch a wave.

Figure 1.2 a. Example of a recreational surfer at the beginning of a popup manoeuvre; b. Example of a recreational surfer at mid-point of the popup manoeuvre.

Figure 1.3 a. and b. Example of recreational surfer’s wave riding.
A recreational surfing session can vary from 20 min to 4 h and consist of 0 to ~50 wave rides. The features of a recreational surfing session strongly depend on the geographical and environmental conditions, equipment used, number of surfers in the water, and the surfer’s intentions and motivations. For example, surfing a wave breaking close to the shore (beach break), alone, a surfer may catch >10 waves in 30 min and do only short bouts of paddling. By contrast, surfing a headland (point break) that has a strong current and many other surfers, a surfer may spend 30 min paddling continuously and waiting to catch a single wave.

**Movement patterns of a surfing session**

The time motion analysis of six, state-level ex-competitive surfers during a typical 1 hr surfing session (taken as surfing at a beach break with swell size, wind direction, tide and number of other participants in the water uncontrolled) (Meir *et al.*, 1991) found that wave riding accounts for only 5 % of the total surfing session, despite a mean number of 20.6 waves ridden (Meir *et al.*, 1991). The majority of the surfing session included board paddling and stationary board sitting, accounting for 44 % and 35 % of the total surfing session, respectively. The remaining 16 % of the session included miscellaneous activities such as duck diving, wading and board retrieval. Thus the two most important components of a one hour recreational surfing session, wave riding and board paddling, accounted for 3 min and 26 min respectively.

During competition, wave riding is the most critical component of the surfing session as the surfers are judged and scored on this activity. Time motion analyses by Mendez-Villanueva *et al.* (2006) reported that the movement patterns of forty-two male professional surfers, recorded during heats at an international contest, were similar to the results reported for the recreational surfing session analysed by Meir *et al.* (1991). Surfers were observed to be paddling, remaining stationary and wave riding for 51 %, 42 % and 3.8 % of the total 25-min heat, respectively (Mendez-Villanueva *et al.*, 2006). During competitive surfing, miscellaneous activity such as walking and board retrieval
only accounted for 2.5 % of the 25-min heat, which is less than the 16 % of miscellaneous activity observed during recreational surfing. The reduction in miscellaneous activity and small increase in board paddling observed during competitive surfing compared to recreational surfing may be due to different surf conditions, but is more likely due to the greater demand to ride several quality waves during competition. No analysis has been performed on the velocity of movement of the board during paddling or wave riding.

1.2 THE PHYSIOLOGY OF SURFING

Surfing experience, frequency and physical attributes of surfers

Some recreational surfers are known to spend the same amount of time surfing per wk as competitive surfers (Lowdon et al., 1983). Lowdon et al. (1983) found that a sample of 346 surfers of different age, experience and competence surfed from one to four hr, once to four times per wk. A further study by Lowdon et al. (1987a) found that a group of 97 international-level surfers spent an average of 4 to 7 h surfing per day for 5 or more days per wk. Table 1.1 summarises the literature investigating participation patterns in competitive surfers. Comparing these patterns in the late 1990’s with those for the early 2000’s shows a trend for competitive surfers to be increasing surfing activity by one more day per wk. There are no reported values for the amount of time recreational or competitive surfers spend undertaking additional exercise training (dry-land training).
<table>
<thead>
<tr>
<th>Study</th>
<th>Age</th>
<th>Body Mass (kg)</th>
<th>Height (cm)</th>
<th>Surfing (days/wk)</th>
<th>Surfing (hr/day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lowdon &amp; Pateman (1980a) International surfers</td>
<td>22±3 yr (n = 76)</td>
<td>68.0±7.2</td>
<td>173.6±5.9</td>
<td>NR</td>
<td>NR</td>
</tr>
<tr>
<td>Lowdon et al. (1987a) International surfers</td>
<td>22±4 yr (n= 79)</td>
<td>NR</td>
<td>NR</td>
<td>5.2±1.3</td>
<td>3.7±1.1</td>
</tr>
<tr>
<td>Lowdon et al. (1989) National surfers</td>
<td>21±1 yr (n = 12)</td>
<td>70.5±5.1</td>
<td>177.7±7.2</td>
<td>5.0±1.4</td>
<td>2.3±0.6</td>
</tr>
<tr>
<td>Meir et al. (1991) Ex competitive surfers</td>
<td>21±3 yr (n = 6)</td>
<td>68.9±5.7</td>
<td>175.8±5.5</td>
<td>NR</td>
<td>NR</td>
</tr>
<tr>
<td>Mendez-Villanueva et al. (2005b) European level surfers</td>
<td>26±3 yr (n = 7)</td>
<td>67.0±4.3</td>
<td>172.1±4.9</td>
<td>6.3±0.8</td>
<td>NR</td>
</tr>
<tr>
<td>Mendez-Villanueva et al. (2005b) Regional level surfers</td>
<td>27±4 yr (n = 6)</td>
<td>71.1±2.6</td>
<td>174±4.7</td>
<td>6.0±0.9</td>
<td>NR</td>
</tr>
<tr>
<td>Chapman et al. (2008) International surfers</td>
<td>24±4 (n=21)</td>
<td>72.9±8.0</td>
<td>174±9.0</td>
<td>NR</td>
<td>NR</td>
</tr>
</tbody>
</table>

NR: Not reported. Values presented are means±SD
In 1980, Lowdon determined the Heath-Carter somatotypes of 76 male and 14 female international surfboard riders (Lowdon, 1980). Male surfers had a balance mesomorph (2.57, 5.20, 2.64) and the female surfers a central mesomorph (3.89, 4.06, 2.64) and it was concluded that the male surfers somatotype closely resemble those of world class swimmers, water polo players, divers and rowers. Further suggestions have been that the physical attributes ideal for a high-performance surfer are a smaller stature and lower body mass compared to other aquatic athletes such as swimmers (Lindsay Carter & Ackland, 1994; Mendez-Villanueva & Bishop, 2005a).

Table 1.1 summarises the physical characteristics of surfers reported in various studies. There appears to be a trend for the body mass of the competitive male surfers to be increasing from Lowdon’s earlier investigations in 1980 to more recent studies in 2008 (Chapman et al., 2008). An increase observed in the mean age amongst the WCT team surfers, observed from 1978 to 2005 (Association of Surfing Professionals, 2006), may be associated with the trend for increasing body mass in competitive surfers. However, more recent studies have had small subject numbers, which may not represent the normal surfing population, so no clear conclusions can be drawn. An in-depth investigation of the physical characteristics and the Heath-Carter somototypes of current competitive surfers will allow accurate comparisons and scientific conclusions about changes in the body physique and composition of surfers in the last 25 yr.

**Physiological demands of a surfing session**

The physiological demands placed on the body during surfing can be characterised as primarily upper body (board paddling), primarily lower body (wave riding), or whole body (popup). Board paddling consists of the surfer lying prone with their trunk hyperextended at all spinal segments to allow the circumduction of the arms during the paddling action (Everline, 2007; Lowdon & Pateman, 1980; Renneker, 1987). Paddling takes up approximately 50% of a surfing session (Meir et al., 1991; Mendez-Villanueva et al., 2006) and is extremely important, as wave riding cannot be achieved without it.
Board paddling during a surfing session can be divided into short-duration paddling bouts, or long-duration paddling bouts. Lowdon (1982) suggested that short-duration paddling is explosive and required when paddling out through a heavy break or to catch a wave, and usually occurs in intermittent spurts of less than 60 s. Mendez-Villanueva et al. (2006) determined that during competition heats ~60 % of all paddling bouts are between 1 and 20 s and ~33 % of all paddling bouts are between ~21 and 90 s. Although the intensity of the paddling performed during a recreational or competitive surfing session has never before been measured, it is likely that short duration paddling bouts between 1 and 20 s are at a moderate- to high-intensity (around or above the lactate threshold). Long duration paddling bouts between 91 and 180 s accounted for only ~10 % of all paddling bouts. It is likely that paddling bouts between 91 and 180 s are performed at a light- to moderate-intensity (below the lactate threshold). The long-duration paddling is undertaken when paddling from the shore line to the back of the break (wave catching zone) at the beginning of the surfing session, changing positions in the surf (break location) and paddling back out after the surfer has caught a wave.

Once the surfer has caught a wave and is moving with the energy of the wave, they stand up by pushing down onto the board with their arms and simultaneously moving their body up and legs forward to stand up (figure 1.2b). The physiological or biomechanical characteristics of a successful popup manoeuvre have never before been investigated. However, the techniques used and the velocity of the popup movement are likely to vary with surfing experience, equipment used and the characteristics of the wave being caught. Following the popup, the surfer continues to ride along the wave standing on their board.

The stance of the surfer during wave riding is described as a semi squat position with between 30-80 degree knee flexion (Everline, 2007), with one foot at the rear of the board and the other at the mid region. Mendez-Villanueva & Bishop (2005a) suggested that the physiological skills relevant to wave riding are dynamic balance (reactive and
proactive balance), force development, flexibility, reaction time, coordination and muscular strength as well as a good aerobic and anaerobic power. Everline (2007) further suggested that ankle dorsiflexion, and rotation of the hips and shoulders are also important factors contributing to successful completion of surfing manoeuvres. Nevertheless, there are few research studies that have clearly identified the contribution of each of these skills to surfing performance.

The intensity and duration of the work rate required during a surfing session has not been clearly defined. However, ~50 % of a surfing session is paddling, and ~60 % of all paddling is less than 20 s in duration (Mendez-Villanueva et al., 2006). Therefore, it is reasonable to suggest that a large percentage (~30 %) of the total time of a surfing session is spent paddling for short durations. Further, it is likely that short duration paddling is at a moderate to high-intensity paddling, in contrast to long duration paddling (>90 s) which is likely to be performed at a low to moderate paddling intensity. Long duration paddling accounts for ~5 % of the total time of a surfing session (Mendez-Villanueva et al., 2006). The examination of the physiological responses during a surfing session may provide further insight into the physiological demands or work-intensities of a surfing session.

**Physiological responses to a surfing session**

Meir et al. (1991) measured heart rate (HR) in six, state-level competitive surfers during 1 h of recreational surfing. Periods of high-intensity exercise were present with peak HR equalling 95 % (171 bpm) of maximum HR (Maximum HR; 180 bpm) determined during incremental paddling to exhaustion on a swim-bench ergometer. The mean HR for the whole session was 135 bpm, equivalent to 75 % of maximum HR. The mean HR taken over all periods of paddling and while stationary represented 80 % and 71 % of Maximum HR, respectively. The total times spent paddling and stationary were 44 % and 35 % of the total time surfing. The relatively high HR when stationary suggests that these stationary periods were relatively short, separated by either intermittent paddling
or wave riding. The HR of the wave-riding period (5 %) of a surfing session was not tested.

The time motion analysis study by Mendez-Villanueva et al. (2006) and the HR observations by Meir et al. (1991) made no distinction between high-intensity and light-intensity paddling of the total paddling period (50 %) of a surfing session. Therefore, is unclear what portion of a total surfing session is undertaken at a low-intensities (i.e., <60 % peak HR) and what portion is high-intensities (i.e., >80 % peak HR). Moreover, the exact contribution of either oxidative or non-oxidative metabolism to energy production during a recreational or competition surfing session is not clear. The assessment of peak aerobic power and anaerobic power/capacity in experienced surfers may provide a greater understanding of the importance of oxidative and non-oxidative metabolism in surfing.

1.3 METABOLIC ENERGY SYSTEMS IN SURFING

To understand energy expenditure during a recreational or competitive surfing session it is necessary to have an understanding of skeletal muscle metabolism during exercise. The immediate energy source for the actin-myosin cross-bridge activity of muscle contraction is derived from adenosine triphosphate (ATP) (Equation 1). At rest the intramuscular concentration of ATP is relatively small at around 5-6 mmol·kg$^{-1}$ (Kemp et al., 2007). Subsequently, continuous exercise and muscle contraction (e.g., board paddling and wave riding) requires the constant regeneration of ATP. The metabolic pathways that maintain ATP resynthesis include i, the degradation of creatine phosphate (CP) in the absence of O$_2$ (ATP-CP system), ii, the break down of muscle glycogen in the absence of O$_2$ resulting in the bi-product lactate (anaerobic glycolysis) and iii, the degradation of carbohydrates and lipids in the presence of oxygen (oxidative metabolism).
Equation 1.1 ATP use in energy production

\[ \text{ATP} + \text{H}_2\text{O} \rightarrow \text{ADP} + \text{Pi} + \text{H} + \text{energy} \]

ATP: adenosine triphosphate; H$_2$O: water; ADP: adenosine diphosphate; Pi: inorganic phosphate; H: hydrogen.

Non-oxidative energy systems

The predominant energy yielding pathways for high-intensity short-duration (<30 s) exercise is the ATP-CP system (Equation 1.2) and anaerobic glycolysis (Equation 1.3) (Withers et al., 1991), both occur in the absence of O$_2$, therefore termed non-oxidative energy pathways or systems. A small amount of ATP for high-intensity short-duration exercise is also produced in the non-oxidative myokinase reaction (Equation 1.4), with the concurrent bi-product of adenosine monophosphate (AMP).

**Equation 1.2 Resynthesis of ATP via non-oxidative degradation of CP**

\[ \text{ADP} + \text{CP} + \text{H}^+ \rightarrow \text{ATP} + \text{creatine} \]

ADP: adenosine diphosphate; CP: phosphocreatine; H$^+$: hydrogen ion; ATP: adenosine triphosphate.

**Equation 1.3 Resynthesis of ATP via non-oxidative degradation of muscle glycogen**

\[ \text{Glycogen} + 3\text{ADP} \rightarrow 2\text{lactate} + 2\text{H}^+ + 3\text{ATP} \]

ADP: adenosine diphosphate; H$^+$: hydrogen ion; ATP: adenosine triphosphate.

**Equation 1.4 Non-oxidative production of ATP from ADP**

\[ 2\text{ADP} \rightarrow \text{ATP} + \text{AMP} \]
ADP: adenosine diphosphate; ATP: adenosine triphosphate; AMP: adenosine monophosphate.

The ATP-CP system and anaerobic glycolysis provide approximately 15 mmol ATP⋅kg dry mass\(^{-1}\)⋅s\(^{-1}\) over the first 6 s of sprint exercise, with 50% of the ATP supplied from the degradation of CP (Gastin, 2001). The ATP-CP system is the fastest energy pathway to respond to an increased demand in ATP, reaching its maximum immediately and beginning to decline after only 1.3 s (Brooks, 2000). A total depletion of ATP does not occur, even in extreme exercise conditions. In contrast, there is almost a complete depletion of CP stores, which is most likely a limiting factor of the capacity of the ATP-CP system (Bogdanis et al., 1995).

The energy available through anaerobic glycolysis is significantly greater than the ATP-CP system, reaching its maximal rate at around 5 s, which can then be maintained for several seconds (Gastin, 2001). The maximum rate of ATP resynthesis of anaerobic glycolysis is up to 100 times that of the resting ATP resynthesis rate (Brooks, 2000). Continuous anaerobic glycolysis can result in the accumulation of the metabolites H\(^+\) and K\(^+\) which may negatively influence the activity of glycolytic enzymes (Allen et al., 2007). Subsequently, the rate of anaerobic glycolysis is limited by either the inhibition of glycolytic enzymes, changes in the activation or force generating capacity of individual cross-bridges or alteration of the ability of the sarcoplasmic reticulum to load and release Ca\(^{2+}\) (Allen et al., 2007). Continuous high-intensity exercises also results in an increase in the intramuscular concentrations of the glycolysis by-product lactate. The measurement of intramuscular lactate and blood lactate concentration is therefore considered to be indirectly associated with exercise intensity and duration. The measurement of blood lactate concentration during or following a surfing session may help to quantify relative exercise intensity during a recreational or competitive surfing session.
The non-oxidative energy systems are necessary to regenerate ATP for short, intense bouts of surfing activities such as paddling onto a wave, wave-riding, bouts of high-intensity paddling and duck diving to get out through the break. Subsequently, an individual’s maximal power and capacity during a bout of intense exercise is a reflection of the maximal rate (power) and total amount (capacity) of their non-oxidative energy systems.

**Oxidative energy system**

During low- to moderate-intensity exercise almost all ATP is produced by the oxidative energy system. The oxidative energy system involves the metabolism of carbohydrates (Equation 1.4) and lipids (Equation 1.5) in the presence of O$_2$. Muscle glycogen, blood glucose and free fatty acids (FFA) are the major substrates derived from intramuscular triglyceride reserves and adipose tissue, used in the resynthesis of ATP. In extreme cases when carbohydrate availability is inadequate the oxidation of amino acids from muscle protein may also contribute to overall energy metabolism during exercise. The amount and type of substrate used for ATP resynthesis during oxidative metabolism is determined by the exercise intensity and duration. Lactate produced from the non-oxidative degeneration of glycogen may also be used as a substrate for oxidative metabolism (Gladden, 2008). The oxidative energy system has a large capacity for energy production but takes approximately 2 min to function fully (Gastin, 2001). Therefore, the oxidative energy system would be active during the total duration of a surfing session, and the primary energy supply for low- to moderate-intensity continuous paddling, such as paddling from shore line to the back of the break, paddling between breaks and paddling into wave-catching position.
Equation 1.5 Resynthesis of ATP via oxidative metabolism of carbohydrates

\[
\text{Glucose} + 6\text{O}_2 + 36\text{ADP} \rightarrow 6\text{CO}_2 + 6\text{H}_2\text{O} + 36\text{ATP}
\]

\(\text{O}_2\): oxygen; \(\text{ADP}\): adenosine diphosphate; \(\text{CO}_2\): carbon dioxide; \(\text{H}_2\text{O}\): water; \(\text{ATP}\): adenosine triphosphate.

Equation 1.6 Resynthesis of ATP via oxidative metabolism of lipids

\[
\text{Palmitate} + 23\text{O}_2 + 130\text{ADP} \rightarrow 16\text{CO}_2 + 16\text{H}_2\text{O} + 130\text{ATP}
\]

\(\text{O}_2\): oxygen; \(\text{ADP}\): adenosine diphosphate; \(\text{CO}_2\): carbon dioxide; \(\text{H}_2\text{O}\): water; \(\text{ATP}\): adenosine triphosphate.

**Contribution of non-oxidative and oxidative energy systems in surfing**

Energy is derived from each of the three metabolic pathways during all exercise activities (Gastin, 2001). The duration of maximal exercise at which equal contributions are derived from the anaerobic and aerobic energy systems appears to occur between 1 to 2 min and most probably around 75 s (Gastin, 2001). Characterising the relative contribution of each of the three energy systems during a specific activity or sport (e.g., surfing) allows for further understanding about the metabolic requirements for the sport and the development of activity specific performance tests and training techniques to better monitor and/or improve energy metabolism for the activity.

It is evident that a typical surfing session would be fuelled by both the non-oxidative and oxidative energy systems. However, it is unclear what the comparative contribution of the non-oxidative and oxidative energy systems is to a surfing session. The relative time spent paddling (45 %), sitting (40 %) wave riding (5 %) and miscellaneous activity (10 %) has been defined (Meir *et al.*, 1991; Mendez-Villaneuva *et al.*, 2006), but it is unclear what relative time is spent high-intensity paddling or low-intensity paddling. An understanding of the relative contribution of the non-oxidative and oxidative energy
system will allow sports scientists and surf fitness trainers to have a greater understanding about the physiological requirements necessary for a surfing session.

**Surf-specific characteristics influencing energy metabolism**

There are several unique features of surfing that may alter the metabolic responses among surfing sessions. These surf-specific characteristics are unlike other activities or sports of similar intensities that have relatively stable external or environmental conditions. Environmental factors (i.e. swell conditions, weather, water temperature and tide) are the most obvious external factors that alter the relative contribution of the non-oxidative and oxidative energy systems among surfing sessions. For example, an increase in wave height of 1-2 foot, an increase in wind speed, change in wind direction, and a running current can instantly increase the physical demand required to paddle out through the surf or to maintain wave catching position.

The biomechanics of surfboard paddling (prone with back hyperextended, figure 1.1a) is unique to surfing and may influence energy metabolism when compared to other upper body exercise (e.g. swimming and arm cranking). Lying prone may increase pulmonary ventilation and perfusion (Kaneko *et al.*, 1966; Suzuki *et al.*, 2008) as well as stroke volume and cardiac output (Rowland *et al.*, 2009; Beveg-Ard *et al.*, 1960). While lying prone, there is a reduction in the gravitational gradients of blood flow, preventing the need to mobilize gravity-dependent blood from the lower extremities. Additionally, during surfboard paddling the buoyancy of the surrounding water may further eliminate the influence of gravitational forces on blood flow.

Hyperextension of the back is most likely adopted to improve vision of the oncoming waves. Hyperextension of the back may change paddling biomechanics and muscle recruitment patterns during paddling. For example, hyperextension may result in an increased recruitment of back extensor muscles or a change in the kinematics of the larger torso muscles (e.g. latissimus dorsi, obliques or lower trapezius muscles).
Whether back hyperextension influences surfboard paddling performance is unknown. A change in kinematics and/or increased recruitment of large back muscles during hyperextension may influence paddling performance by i, increasing maximal power due to increased muscle recruitment ii, delay muscle fatigue in the arms or iii, result in an increased $O_2$ consumption due to the recruitment of a larger muscle mass. Regardless, the increased recruitment of back muscles would increase the metabolic cost and may change the contribution of the energy systems when compared to other aquatic sports such as swimming which involve a more streamlined position and less activation of back extensor muscles.

The fibre type composition of the upper body (arms and shoulders) is predominantly composed of the non-oxidative type II muscle fibres (Mavidis et al., 2007). Further, upper-body anaerobic exercise tests are relatively more non-oxidative when compared to lower body exercise tests (Calbet et al., 1997; Parolin et al., 1999; Rohrs et al., 1990; Withers et al., 1991). Therefore, anaerobic power may be a defining factor for the upper body activity of surfboard paddling.

Water temperature and protective or thermal clothing will also have a significant influence on energy metabolism during surfing, as demonstrated during other ocean activities such as diving (Tomikawa et al., 2008; Noakes, 2000). The interactions between surf-specific characteristics (i.e. paddling biomechanics and water temperature) and energy metabolism during a surfing session cannot be investigated in any detail until the relative contribution of the oxidative and non-oxidative energy systems during a typical surfing session is known and surf-specific reliable testing methods developed.

**Method of assessment of non-oxidative power and capacity**

Methods to quantify non-oxidative energy release are complex as non-oxidative ATP production is an intracellular process with little reliance on central processes and no need for $O_2$. A universally accepted non-invasive method of directly assessing non-
oxidative metabolism does not exist. However, there are a number of well accepted exercise performance measures associated with the non-oxidative energy systems that are commonly used as an indirect measure of non-oxidative energy release by sports scientists.

Anaerobic power and anaerobic capacity are two common terms used to describe the performance of the non-oxidative energy systems. **Anaerobic power** is the maximum amount of energy that can be generated per unit time and is critical for success in many sports that require the development and short-term maintenance, of high power outputs (Brooks *et al.*, 2000). Paddling maximally to catch a wave is an example of the anaerobic power necessary for surfing. At high power outputs, anaerobic power is only sustainable for brief periods of time. Measurements of anaerobic power can be made by quantifying the peak power achieved during a maximal effort of an explosive movement (e.g., vertical jump, shot put) or a maximal-intensity sprint in a dynamic form of exercise (e.g., cycling or paddling).

The 30-s Wingate Anaerobic Test (WAnT) is well accepted as a reliable and valid method (Bar-Or, 1987) of measuring and comparing short-term maximal-exercise performance among groups of untrained children (Dotan & Bar-Or, 1980), adults (Dotan & Bar-Or, 1983; Minahan *et al.*, 2007), and athletes (Tanaka *et al.*, 1993; Zajac *et al.*, 1999). The peak power, mean power and fatigue index (absolute difference between the highest and the lowest work rate expressed as a percent of the highest work rate) achieved during a 30-s WAnT are all commonly used as indices of anaerobic energy production. The peak power of the 30-s WAnT is a reliable measure of an individual’s anaerobic power, but there is speculation as to whether or not performance variables of the 30-s WAnT indicate an individual’s anaerobic capacity (Minahan *et al.*, 2007; Scott *et al.*, 1991).

**Anaerobic capacity** is the total amount of energy obtainable from both non-oxidative energy systems (ATP-CP system and anaerobic glycolysis). The maximal accumulated
O₂ deficit, blood lactate measures and various power output measures from maximal intensity dynamic exercise testing have all been used as measures of an individual’s anaerobic capacity (Jacobs, 1986; Minahan et al., 2007; Scott et al., 1991). In 1920 the concept of the accumulated oxygen (AO₂) deficit was introduced (Krogh & Lindhard, 1920) and has since been used as a means to reliably (Weber & Schneider, 2001) determine anaerobic energy production in various populations (Weber, 2004; Weber et al., 2006; Weber & Schneider, 2000). The accumulated oxygen deficit is described as the difference between the AO₂ demand of a given amount of exercise and the total O₂ uptake (L) that is measured during the exercise bout. Therefore, the AO₂ deficit is the amount of energy that is derived anaerobically from the ATP-CP system and anaerobic glycolysis.

The reliable measurement of the AO₂ deficit at supramaximal intensities (intensities above the power output at which peak O₂ uptake is achieved) can be performed using methods described previously by Medbo and colleagues (Medbo & Tabata, 1989, Medbo & Burgers, 1990). Briefly, an O₂ uptake-power relationship is determined for the individual being tested. This is achieved by measuring the O₂ uptake (L·min⁻¹) for four to six submaximal constant load work stages lasting between 3 and 10 min in duration. The O₂ uptake and corresponding power values achieved for the constant load work stages are then used to depict the O₂ uptake-power relationship for the subject (Figure 1.4a). The O₂ uptake for each work stage is taken as the average value of the last 30 s or 60 s of each work stage. The linear regression of the O₂ uptake-power relationship is extrapolated to estimate the total estimated O₂ demand (AO₂ demand: L) for a given amount of time for a maximal effort exercise test, such as a 30-s WAnT (Medbo & Burgers, 1990) or supramaximal constant load exercise (Weber & Schneider, 2001). The aerobic contribution (AO₂ uptake) to the maximal effort exercise test is determined by summing the values of O₂ uptake (L) measured during the test. The AO₂ deficit (anaerobic contribution) is then calculated by subtracting the AO₂ uptake from the AO₂ demand (Figure 1.4b).
Method of assessment of oxidative capacity

The oxidative energy release from the combustion of carbohydrates and fats is readily quantified, as there is a direct relationship between the oxygen uptake measured at the mouth and the whole-body aerobic production of ATP (Whipp & Wasserman, 1972). Aerobic power is defined as the amount of oxygen the body can use during a specified period of time (Brooks et al., 2000). Aerobic power is a function of the capacity of the cardio-respiratory system and the ability to remove and utilize oxygen from circulating blood. Aerobic power is expressed either as an absolute rate in litres of O\(_2\) per min (L\(\cdot\)min\(^{-1}\)) or as a relative rate in mL of O\(_2\) per kg of bodyweight per min (mL\(\cdot\)kg\(\cdot\)min\(^{-1}\)).
The latter index is often used to compare the endurance performance of individuals or athletes across various activities or sports. An individual’s peak aerobic power in any mode of exercise is determined during incremental intensity exercise to exhaustion and is often termed **peak \( O_2 \) uptake**. Peak \( O_2 \) uptake is widely accepted as the single best measure of cardiovascular performance and maximal aerobic power. Therefore, an individual’s peak \( O_2 \) uptake in a specific activity is an accurate measure of their ability to perform aerobically in that activity.

As indicated earlier the oxidative energy system does not respond efficiently to rapid changes in exercise intensity or to short bouts of high-intensity exercise (Brooks *et al.*, 2000). For this reason, the aerobic energy pathway is the primary source of energy for low to moderate intensity, long duration activity, such as a 5 km run or 5-min paddle out towards the back of a surfing break. As exercise intensity increases (running speed or paddling speed) there is a point at which the contribution of the non-oxidative energy system will increase significantly. The point at which blood lactate concentrations begins to continuously increase is identified as the **lactate threshold** (LT), which occurs when lactate is produced faster than it can be removed.

**Economy** is another common measure associated with the performance of the aerobic energy system. Economy is a ratio of the external work performed by an individual (watts (W) or Kilojoules (kJ)) to the amount of \( O_2 \) they take up (L) when completing an activity. The \( O_2 \) uptake required and the economy for a task such as surfboard paddling would be determined during constant load paddling at a known work intensity.

### 1.4 PHYSIOLOGICAL CHARACTERISTICS OF SURFERS

**Peak \( O_2 \) Uptake of Surfers**

Six studies have investigated the peak \( O_2 \) uptake of male surfers employing a variety of exercise modes including leg cycling (Lowdon & Pateman, 1980; Patterson, 2002),
tethered board paddling (Lowdon et al., 1989), arm cranking (Lowdon et al., 1989), arm paddling on a swim-bench ergometer (Meir et al., 1991), and arm paddling on a modified kayak-ergometer (Mendez-Villanueva & Bishop, 2005a), presented in Table 1.2. The reported peak O$_2$ uptake values of surfers ranges from 40 mL·kg·min$^{-1}$ to 54 mL·kg·min$^{-1}$, with a group of ex-competitive surfers having one of the highest values. One study found no significant difference in the aerobic power between national level surfers and regional level surfers, both measured on a modified kayak-ergometer (Mendez-Villanueva & Bishop, 2005a). Although the data for surfing is limited, there appears to be no relationship between aerobic power and competitive surfing status, suggesting that aerobic power may not make a significant contribution to surfing performance in competitive surfers. No studies have documented maximal aerobic power in recreational surfers.
<table>
<thead>
<tr>
<th>Study</th>
<th>Participants</th>
<th>Mode of testing</th>
<th>Peak O$_2$ Uptake (mL·kg·min$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lowdon &amp; Pateman (1980)</td>
<td>76 male and 14 female international surfers (competitive) (22±3 yr)</td>
<td>Cycle ergometry</td>
<td>66 (estimated)</td>
</tr>
<tr>
<td>Lowdon et al. (1989)</td>
<td>12 male college surfers (competitive) (21±1 yr)</td>
<td>Tethered board paddling</td>
<td>40</td>
</tr>
<tr>
<td>Lowdon et al. (1989)</td>
<td>12 male college surfers (competitive) (21±1 yr)</td>
<td>Arm cranking</td>
<td>42</td>
</tr>
<tr>
<td>Meir et al. (1991)</td>
<td>6 male recreational surfers (ex-competitive) (21±3 yr)</td>
<td>Swim bench ergometry</td>
<td>54</td>
</tr>
<tr>
<td>Patterson, (2002)</td>
<td>61 South African competitive surfers (34±6 yr)</td>
<td>Not reported</td>
<td>55</td>
</tr>
<tr>
<td>Mendez-Villanueva &amp; Bishop</td>
<td>7 male competitive (European level) (26±3 yr)</td>
<td>Modified kayak ergometry</td>
<td>50</td>
</tr>
<tr>
<td>Mendez-Villanueva &amp; Bishop</td>
<td>6 male competitive (Regional level) (27±4 yr)</td>
<td>Modified kayak ergometry</td>
<td>48</td>
</tr>
</tbody>
</table>
Although there is no apparent relationship between paddling aerobic power and competitive surfing status, Mendez-Villanueva *et al.* (2005b) found that peak power developed during incremental paddling until exhaustion and paddling intensity at which 4 mmol·L⁻¹ of blood lactate concentration is reached are significantly correlated with surfing status.

**Lactate Threshold of Surfers**

Mendez-Villanueva *et al.* (2005b) measured the power output during incremental paddling at which blood lactate concentrations [La⁻] rise above 4 mmol·L⁻¹ (LT₄). The power output at which 4 mmol·L⁻¹ of blood [La⁻] occurred was significantly higher in National level surfers when compared to regional level surfers. Peak power achieved at peak O₂ uptake and LT₄ were also strongly correlated (r = -0.67, P = 0.01; r = -0.57, P = 0.03) with the surfers ranking according to their performance in the most recent surfing season. A higher peak power achieved at peak O₂ uptake may suggest other measures of aerobic power (e.g., exercise economy) are more sensitive indices of performance.

**Paddling Economy of Participants in Upper Body Aquatic Sports**

No study has investigated the paddling economy of surfers, either on a swim-bench ergometer or on a surfboard in the water. Nevertheless, the importance of swimming economy for swimming performance is highly recognised (Fernandes *et al.*, 2006). Swimming economy has only been measured during tethered swimming or swimming in a flume; no study has investigated swimming economy on a swim-bench ergometer. A greater economy of surf paddling may allow a surfer to paddle for longer periods before reaching fatigue, or possibly at higher exercise intensities with less effort. However, it is unclear whether or not surfboard paddling has any influence of surfing performance, or whether there are any relationships between surfing status and board paddling economy.
Anaerobic Power of Participants in Upper Body Aquatic Sports

The maximal anaerobic power of surfers has not previously been studied. Upper body power of swimmers has previously been assessed on a biokinetic swim bench during either 10-s, 30-s or 60-s of maximal paddling (Rohrs et al., 1990; Swaine, 2000) or surf-life saving board paddling (Morton & Gastin, 1997). Only one study has measured peak power of competitive swimmers during a 30-s maximal paddle on a swim-bench ergometer (Rohrs et al., 1990). Significant correlations were found between the 30-s peak power developed on the swim-bench ergometer and swimming velocity for time trials at 22.86 m, 45.72 m and 91.44 m (Rohrs et al., 1990). Morton et al. (1997) also found significant correlations between mean power achieved during a 60-s maximal surf-life saving board paddle and 75 m and 140 m paddling time trials. Results from these studies suggest that upper body anaerobic power and a maximal-paddling performance test on a swim-bench ergometer may be a good predictor of athletic performance in upper body aquatic sports.

A study by Patterson (2002) investigated a series of physical tests in 61 competitive South African surfers, including the determination of peak anaerobic power using a 30-s WAnT test protocol. Group means for maximum power, average power and fatigue index were 979.2 ± 163.8 W, 86.8 ± 118.2 W and 30.6 ± 9.8 % respectively. No article was written, only an abstract which did not report the mode of exercise used by the surfers during testing. However, the relative peak power achieved (14.0 W·kg⁻¹) is consistent with values reported for lower body cycle ergometry 30-s WAnT (13.3 ± 0.3 W·kg⁻¹) in recreationally active males (Weber et al., 2006) and greater than values reported for upper body 30-s WAnT arm ergometry (9.3 ± 0.3 W·kg⁻¹) in recreationally active males (Weber et al., 2006). No precise conclusions can be drawn about the anaerobic power of the surfers in Patterson’s study due to the absence of important details in the abstract that has been published, such as equipment and methods used. It remains unclear whether upper body anaerobic capacity is an important contributing factor for surfboard paddling performance, or surfing performance.
1.5 NEUROMUSCULAR FUNCTION AND BIOMECHANICS DURING SURFING

There are no scientific papers examining optimal biomechanical or neuromuscular characteristics of any of the three components of surfing. Everline (2007) provided a qualitative assessment of short-board performance surfing suggesting that wave riding demands superior fine motor skill and the adoption of a posture, which is dominated by isometric fixation of the legs and torso with a significant level of rear-knee valgus stress applied when performing manoeuvres (Everline, 2007). The article gives an observational description of various manoeuvres performed whilst wave riding; however, there is limited detail about the kinematics and biomechanics of such manoeuvres.

Neuromuscular and biomechanical characteristics of surfers

In line with the paucity of publications on the neuromuscular function and biomechanics of a surfing session, there is also little scientific literature available on the neuromuscular characteristics of the surfers themselves. Chapman et al. (2008) evaluated postural control in highly competitive and intermediate surfers and a group of healthy active non-surfers. Systematic differences in balance abilities existed between competitive surfers and active individuals. When in an upright stance and performing general cognitive tasks, competitive surfers produced a significantly greater sway path length (SPL) and area of the 95th centile ellipse (AoE) compared to intermediate surfers and controls. Chapman suggested that prolonged balance training in a dynamic environment appears to allow a flexible strategy to be used where centre of pressure migration can be relatively large but still remain safely within the base of support. Chapman suggested that the greater SPL and AoE shown by competitive surfers during mental tasks was the result of a strategy for disengaging co-contraction and a confounding cognitive-motor coupling activated by secondary visuospatial tasks.
Neuromuscular fatigue and surfing

The level of whole body or muscular fatigue developed during paddling and wave riding during a recreational or competitive surfing session is unknown. Further, it is unclear whether there is a relationship between upper body paddling and lower body wave-riding performance. Considering that a 1 h recreational surfing session consisting of ~50% paddling and is associated with mean and maximum HR of ~70% and ~80% peak HR values (Meir et al., 1991), it is reasonable to suggest that such a surfing session would result in some level of central and/or peripheral fatigue.

Fatigue developed during exercise is commonly considered as the point at which the exercising muscle fails to maintain the required force (Edwards, 1981), or fails to continue working at a given exercise intensity (Booth & Thomason, 1991). However, this is probably simplistic as the maximal force generating capacity of a muscle starts to decline once exercise has commenced and before the muscle fails to perform the required task (Gandevia, 2001). Therefore fatigue can be characterised as a continuous decrease in the force generating capacity in a given task.

It is reasonable to assume that a decrease in upper or lower body strength and power may influence a surfer’s ability to paddle onto waves, popup and/or ride waves with correct technique and the strength and stability necessary to maintain balance. Mendez-Villanueva & Bishop (2005a) were the first to suggest that fatigue induced during upper body paddling might impair the fine motor skills necessary for high performance surfing (Mendez-Villanueva & Bishop, 2005a). Further research is needed to identify what level of fatigue is developed during paddling and what influence this may have on a surfer’s ability to catch waves, popup and wave ride.
Indirect measures of fatigue

The causes of fatigue are complex, involving both peripheral and central mechanisms. It is difficult to indirectly measure an exact level of fatigue of an athlete since fatigue is continuously developing during exercise, with the rate of development depending on the intensity and duration of the exercise (Gandevia, 2001). In the sports science community, fatigue is typically investigated by changes in various measures of athletic performance. A decrease in maximal voluntary contraction, torque, rate of force development or vertical jump height (Lattier et al., 2004; Skurvydas et al., 2002) as well as changes in neuromuscular activity (Lepers et al., 2000) and coordination (Billaut et al., 2005) are all commonly used to monitor fatigue or its effect on performance following exercise.

To date there has been no research investigating the lower body strength, power or fine motor skills necessary for surfing and more particularly for wave riding. Therefore, there are no surf specific methods available to make such measurements and to investigate the influence of fatigue on surfing performance. The development of such methods and protocols would help to establish baseline values and investigate whether or not fatigue developed from upper body paddling impairs the fine motor skills necessary for high performance surfing, as hypothesised by Mendez-Villanueva & Bishop (2005a).
1.6 THESIS AIMS AND SIGNIFICANCE

Thesis Aims

**Study 1 (Chapter 2):**
To develop reliable testing methods of assessing maximal-paddling performance in surfers.

**Study 2 (Chapter 3):**
To determine the aerobic power and paddling economy of junior male recreational and competitive surfers.

**Study 3 (Chapter 4):**
To measure maximal-paddling performance and the accumulated AO$_2$ deficit of a 30-s Wingate Anaerobic Test for paddling in junior male recreational and competitive surfers.

**Study 4 (Chapter 5):**
To characterise the timing and magnitude of the vertical ground reaction forces produced during a surf popup manoeuvre and measure maximal-leg power in junior male recreational and competitive surfers. To investigate relationships between surfboard paddling, the popup and maximal-leg power in junior male recreational surfers.

**Thesis Significance**

A rapid growth in the international surfing industry and the increasing competitive standards has led to a need for continuous advances in technology, coaching expertise and training techniques, to help improve surfing performance and to prevent and better manage injuries. There has been little attention on the development of surf specific
scientific measures of surfing performance and the assessment of physiological and biomechanical characteristics of surfers. Also, the relationship between surfboard-paddling performance and wave-riding performance is unclear. The development of reliable and valid surf specific tests will advance surfing research and the performance testing of surfers. The investigation of aerobic power, anaerobic power, leg power and the popup manoeuvre in recreational surfers, as well as competitive surfers will help to identify surf specific physiological characteristics that are related to surfing status. A greater understanding about the physiological characteristics related to surfing performance will help to develop surf-specific training techniques to improve performance, reduce injuries and possibly increase the level of enjoyment in the sport for beginners, intermediate and competitive surfers.
CHAPTER 2

TWO RELIABLE PROTOCOLS FOR ASSESSING MAXIMAL-PADDLING PERFORMANCE IN SURFBOARD RIDERS


2.1 INTRODUCTION:

Surfboard riding (surfing) is an internationally recognised and highly-competitive professional sport. Advances in equipment and competition standards have resulted in the need for new coaching expertise and training techniques to help improve surfing performance and prevent injuries. Surfboard paddling takes up the largest proportion (~44-50%) of total surfing time with only 5-8% of total time spent wave riding (Meir, et al., 1991; Mendez-Villanueva et al., 2006). Wave riding cannot be performed without paddling; first to get from the shoreline to the wave break, and second to successfully catch a wave. However, during surfing competition, paddling has no influence on the judges’ score. As a result, surfboard paddling has received little attention in scientific research.

Previous studies use tethered board paddling (Lowdon et al., 1989), arm cranking (Lowdon et al., 1989), swim-bench ergometers (Meir et al., 1991), and modified kayak ergometers (Mendez-Villanueva et al., 2005), to investigate peak aerobic power during surfboard paddling. Despite previous interest in the aerobic energy demands of surfboard riding, no previous study has assessed maximal-paddling performance in surfboard riders. As surfers are frequently required to paddle maximally for several seconds to catch waves or paddle out through wave sets, such performance is an important physical characteristic. Greater maximal-paddling ability would: i. Improve the surfer’s chance of catching a wave, or ii. Allow the surfer to assume the ideal position in the surf for wave riding. Therefore, the assessment of maximal-paddling performance could be important for monitoring improvements in surfing performance, or examining physiological adaptations to training.

One way to evaluate maximal-intensity exercise is to measure external power output. This approach has been undertaken with other aquatic athletes, such as swimmers and surf lifesavers where measures during swim-bench front crawl (Swaine, 2000) and
knee-board paddling (Morton & Gastin, 1997) were reliable. However, it is not known if swim-bench ergometry can be used to assess maximal-paddling performance with similar reliability in surfers given their unique upper-body paddling technique (i.e., hyperextension of the trunk and lack of hip drive). Currently, swim-bench ergometers are the most sport-specific devices available for surfboard paddling.

The purpose of the present study was to examine the test-retest reliability of peak power output measured during maximal-intensity paddling on a swim-bench ergometer in competitive male surfers. A secondary purpose of the present study was to develop an equivalent field test to assess maximal-paddling performance in surfers that can be administered easily.

2.2 MATERIALS AND METHODS

Subjects

Eleven competitive male surfers (age 17 ± 1 yr, body mass 61.9 ± 3.1 kg, and stature 173 ± 2 cm) participated in the study. Each participant had been surfing for at least 4 yr and had qualified to compete in junior state titles in the last 12 mo. The study was approved by the Griffith University Human Research Ethics Committee and written informed consent was obtained from each participant as well as parental/guardian consent when surfers were under 18 yr.

Experimental design

Surfers underwent two days of laboratory testing and two days of field testing. Surfers practised with the testing equipment on a separate day before the laboratory testing commenced. The laboratory test consisted of 10 s of maximal-intensity paddling performed on a swim-bench ergometer. Peak power output (W) was recorded from the
digital display unit on the ergometer and used as the key performance indicator. Surfers completed six trials of the laboratory test over two days, completing three trials each day. The field test consisted of 10 s of maximal-intensity paddling performed on the surfers' personal surfboard in a 25-m swimming pool. Peak speed (m·s⁻¹) was measured using a custom made speed probe (SP5000, Applied Motion Research, Gold Coast, AUS). Trial-to-trial reliability of peak speed was determined under two conditions: i. Arm paddling only (non-kicking), and ii. Simultaneous arm paddling and leg kicking (kicking). Field testing was conducted over two days with three trials of the non-kicking condition on one day and three trials of the kicking condition on another day. Testing was randomised to minimise order effect. The impact of leg kicking on paddling speed was determined by comparing peak speed of the two testing conditions.

Similar testing procedures were used for the laboratory-, and field-testing protocols. A 5-min warm up was performed that comprised 3-min light-intensity continuous paddling, followed by a 30-s rest and three, 5-s maximal-intensity paddling efforts replicating the test start. Each 5-s effort was separated by a 30-s rest. The warm up was followed by a 10-min rest and three, 10-s maximal-intensity paddling trials; each trial separated by 10 min of rest. Testing was performed at, or as near as possible to, the same time of day, with the four testing days separated by 48 to 72 h. The same instructions were used for each trial with the surfers verbally encouraged to paddle as hard as they could for the whole trial. Surfers were not informed of the elapsed trial time. Verbal encouragement lasted 11-12 s before the command of “stop” was given, to prevent the surfer from slowing down prematurely.
Laboratory-testing equipment

The wind-braked swim-bench ergometer used in the present study (Figure 2.1) was a classic Vasa Swim Ergometer (Vasa, Inc., Essex Junction, VT, USA) that is similar to the biokinetic swim-bench ergometer previously described by Sharp et al. (1982). Biokinetic swim-bench ergometers are neither isotonic nor isokinetic as the force and speed of the arm pulling varies and is not constrained at a predetermined setting (Sharp et al., 1982). Biokinetic swim-bench ergometers have been described as a semi-accommodating resistance device that can be preset to a regulation speed that provides constant acceleration in proportion to the force applied by the user (Sharp et al., 1982).

Figure 2.1 Example of a surfboard rider during paddling on the swim-bench ergometer.

The swim-bench ergometer used in the present study consisted of hand paddles attached to two pull ropes induced rotation of the isokinetic-resistance device. The external power output of each separate arm pull is determined from two suitably mounted force transducers on each hand pulley that measure tensile forces, distance through which
these forces act, and the duration of the application of force. When force is applied to
the hand paddles, the pull-rope pays out a velocity which ranges up to maximum,
termed the maximum pull velocity (MPV). The resistance unit on the swim-bench
ergometer provided seven MPV settings. Power output was calculated and continuously
fed back to the surfer via a digital display unit. The display unit had no memory storage,
so the duration of each trial was video recorded and played back to obtain 1-s power
output values. The paddling ergometer was calibrated before testing using methods
previously described (Sharp et al., 1982).

Pilot testing previously performed in our laboratory determined the optimal MPV
setting (of the seven settings), necessary to achieve peak power output. Pilot testing
consisted of twenty recreational male surfers (age 21 ± 1 yr, body mass 76.1 ± 0.16 kg)
undertaking six, 10-s maximal-intensity paddling trials, performed at three MPV
settings (2, 4 and 7). Two trials were performed at each of the three MPV settings and
testing was undertaken over two days, completing three trials each day, each separated
by a 10-min rest. The body mass of the twenty surfers ranged between 58.5 and 86.0 kg.
To determine the interaction between body mass, MPV setting and peak power output,
the results were split according to body mass; < 70 kg (n = 5), 70-80 kg (n = 7) and > 80
kg (n = 8). Results showed that the highest peak power output for all three body mass
groups was achieved at the highest MPV setting (Figure 2.2). Consequently an MVP
setting of 7 was used for all surfers in the present study. It is not known if a higher MPV
setting would have resulted in further increases in peak power output, as a higher MPV
setting was not available on the present ergometer.
Figure 2.2 The group mean values of peak power output determined during three 10-s maximal-intensity paddling tests performed at three resistances (1, 4, 7) in twenty recreational male surfers grouped according to body mass. *Different from peak power output in the same group at the other two resistances.

Field-testing equipment

A speed probe was used to determine peak speed of the surfer during the 10-s field tests. The speed probe determined speed by measuring displacement via a 10-cm circumference, machined wheel. A non-stretch line (tether) was wrapped around the wheel and then attached to the surfer’s waist (the wheel was wide enough that the line did not wrap onto itself). The surfer entered the pool with the tether attached, and lay on their board with their feet just off the pool wall to prevent a push off. The test began when the chief investigator gave the command of, “On your marks, go!” As the surfer progressed, the pull on the line forced the wheel to spin. The faster the wheel spins, the greater the displacement or distance paddled. The distance that the tether travels, and the time in which it travels, is measured by an infrared light that passes over ten drill holes (1 cm apart) situated around the circumference of the wheel. As the wheel spins,
the infrared light measures the number of holes passed (distance) and the time between each hole (time). The analogue output from the wheel is then converted into a digital signal recorded onto a personal computer using custom designed software that calculates speed from distance and time (Sports Studio 2005, Applied Motion Research, Gold Coast, AUS). Figure 2.3 displays an example of the field-testing set up.

The speed achieved by one surfer performing a 10-s maximal-intensity paddling trial (field) is displayed in Figure 2.4. The wave-like motion of the speed curve is because of the alternate arm paddling of the surfer and therefore the small oscillation in speed with each stroke. Speed is greatest at the end of each paddle and least just before the hand re-enters the water, similar to that of swimming. Speed values were averaged into 1-s intervals with peak speed taken as the highest 1-s value achieved over the 10-s period of the trial.

Figure 2.3 Example of a surfboard rider during a 10-s maximal-paddling test performed in a 25-m swimming pool paddling on a surfboard.
The output results for one individual surfer completing a 10-s maximal-paddling trial performed in the swimming pool is displayed in Figure 2.4. The wave like motion of the velocity curve is due to the alternate arm paddling of the surfer and therefore the small oscillation in velocity with each stroke. Velocity is greatest at the end of each paddle and least just before the hand re-enters the water, similar to that of swimming. Velocity values were averaged into 1-s intervals with peak velocity taken as the highest 1-s value achieved over the 10-s period of the trial.

**Figure 2.4** The speed of one competitive male surfer during a 10-s maximal-intensity paddling test performed on a surfboard in a 25-m swimming pool.

**Data analysis**

Means (± SD) values were calculated for physical characteristics, peak power output, and peak speed. ANOVA with repeated-measures for Day and Trial was used compared peak power output across all six laboratory tests. A second ANOVA with repeated measures for Condition and Trial was used to compare peak speed during the non-kicking and kicking field tests. When differences were detected, pairwise comparisons
with Bonferroni adjustments were performed to determine their source. The effect size of the difference was calculated as the standardised mean difference between the two groups i.e., \((\text{mean of kicking} - \text{mean of non-kicking})/\text{standard deviation of kicking}\).

Trial-to-trial reliability was determined from intraclass correlation coefficients for all six trials of laboratory testing and all three trials of field testing in each condition. The coefficients for Trial 1 and Trial 2 performed on Day 1 both for laboratory testing and field testing were determined to investigate trial-to-trial reliability. Day-to-day reliability for laboratory testing was determined by calculating coefficients for peak power output measured for Trial 1 on Day 1 of testing and Trial 1 on Day 2 of testing. Statistical significance was set at \(P < 0.05\). Intraclass correlation coefficients are highly sensitive to heterogeneity of the sample (Hopkins, 2000), therefore the change in mean and typical error were also determined to assess the reliability of the two testing methods. The change in mean and typical error were also expressed as a percentage of their respective means using log-transformed data. Typical error and change in mean values were chosen to characterise reliability because of the reasons outlined by Hopkins (2000, p. 15) in which he concluded that ‘observed values and confidence limits of the typical error and change in mean are necessary and sufficient to characterise the reliability of a measure’.
2.3 RESULTS:

Reliability of lab testing

There were no differences in peak power output among all six trials performed during laboratory testing (F = 1.063, p = 0.364), as illustrated in Figure 2.5. Table 2.1 presents the intraclass correlation coefficients, change in mean and typical error for peak power output calculated for Trial 1 and Trial 2 (trial-to-trial) as well as Trial 1 and Trial 4 (day-to-day) of laboratory testing. The intraclass correlation coefficient of all six trials was not notably different to the coefficient calculated for peak power output determined during Trial 1 and Trial 2 only. Similarly, the intraclass correlation coefficient associated with Trial 1 and Trial 4 was greater than 0.90. The group mean value for the change in mean and typical error were all less than 6%.

![Figure 2.5](image)

**Figure 2.5** The group mean (± SD) values of peak power output determined during six 10-s maximal-intensity paddling tests performed on a swim-bench ergometer in eleven competitive male surfers. Six trials were performed over two days; three trials per day.
Table 2.1 Measures of reliability determined for peak power output obtained during maximal-intensity paddling ergometry in eleven competitive male surfers.

<table>
<thead>
<tr>
<th></th>
<th>ICC</th>
<th>Change in mean</th>
<th>Typical error</th>
</tr>
</thead>
<tbody>
<tr>
<td>All 6 trials</td>
<td>0.992</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Trial 1 –</td>
<td>0.995</td>
<td>10.9 W</td>
<td>6.9 W</td>
</tr>
<tr>
<td>Trial 2</td>
<td></td>
<td>4.4 – 17.5 W</td>
<td>4.8 – 12.1 W</td>
</tr>
<tr>
<td></td>
<td>Mean (%)</td>
<td>3.8%</td>
<td>2.6%</td>
</tr>
<tr>
<td></td>
<td>Confidence limits (%)</td>
<td>1.3 – 6.5%</td>
<td>1.8 – 4.6%</td>
</tr>
<tr>
<td>Trial 1 –</td>
<td>0.983</td>
<td>20.2 W</td>
<td>14.9 W</td>
</tr>
<tr>
<td>Trial 4</td>
<td></td>
<td>6.0 – 34.5 W</td>
<td>10.4 – 26.2 W</td>
</tr>
<tr>
<td></td>
<td>Mean (%)</td>
<td>5.7%</td>
<td>3.7%</td>
</tr>
<tr>
<td></td>
<td>Confidence limits (%)</td>
<td>2.1 – 9.5%</td>
<td>2.6 – 6.4%</td>
</tr>
</tbody>
</table>

Six 10-s paddling trials were performed over two days; three trials each day. Trial-to-trial reliability (All 6 trials, Trial 1 – Trial 2) and day-to-day reliability (Trial 1 – Trial 4) was assessed. 95% confidence limits were calculated. % values were derived from log-transformed data.

Reliability of field testing

There were no differences in peak speed among the three trials for kicking (F = 0.154, p = 0.858) and across the three trials for non-kicking (F = 0.204, p = 0.661). The intraclass correlation coefficient for peak speed measured during all three trials for kicking was > 0.90 that was similar to the intraclass correlation coefficient calculated for the three non-kicking trials (Table 2.2). There was no substantial change in the coefficient when only speed values from Trial 1 and Trial 2 were included in the calculation for both the kicking and non-kicking conditions. The change in mean and typical error were all less than 1% for peak speed from Trial 1 to Trial 2 for each condition.
Table 2.2 Measures of reliability determined for peak speed obtained during maximal-intensity paddling performed by eleven competitive male surfers in a swimming pool.

<table>
<thead>
<tr>
<th></th>
<th>ICC</th>
<th>Change in mean</th>
<th>Typical error</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Non-kicking trials</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>All 3 trials</td>
<td>0.993</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Trial 1 – Trial 2</td>
<td>0.985</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean (W)</td>
<td></td>
<td>&lt; 0.00 m·s⁻¹</td>
<td>0.01 m·s⁻¹</td>
</tr>
<tr>
<td>Confidence limits (W)</td>
<td></td>
<td>-0.01 – 0.02 m·s⁻¹</td>
<td>0.01 – 0.03 m·s⁻¹</td>
</tr>
<tr>
<td>Mean (%)</td>
<td></td>
<td>0.2%</td>
<td>0.8%</td>
</tr>
<tr>
<td>Confidence limits (%)</td>
<td></td>
<td>-0.6 – 1.0%</td>
<td>0.6 – 1.5%</td>
</tr>
<tr>
<td><strong>Kicking trials</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>All 3 trials</td>
<td>0.996</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Trial 1 – Trial 2</td>
<td>0.995</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean (W)</td>
<td></td>
<td>&lt; 0.00 m·s⁻¹</td>
<td>0.02 m·s⁻¹</td>
</tr>
<tr>
<td>Confidence limits (W)</td>
<td></td>
<td>-0.01 – 0.02 m·s⁻¹</td>
<td>0.01 – 0.03 m·s⁻¹</td>
</tr>
<tr>
<td>Mean (%)</td>
<td></td>
<td>-0.2%</td>
<td>0.8%</td>
</tr>
<tr>
<td>Confidence limits (%)</td>
<td></td>
<td>-0.9 – 0.6%</td>
<td>0.6 – 1.5%</td>
</tr>
</tbody>
</table>

Three 10-s paddling only trials (non-kicking) were performed on one day and three 10-s paddling and kicking trials (kicking) were performed on a separate day. 95% confidence limits were calculated. % values were derived from log-transformed data.

Impact of leg kicking on surfboard-paddling speed

We found no interaction between Trial (1, 2, and 3) and Condition (kicking and non-kicking) (F = 0.957, p = 0.821). There was no main effect for Trial (F = 1.092, p = 0.355) but there was an effect for Condition (F = 21.731, p < 0.001), such that the mean peak speed for the kicking condition (1.89 ± 0.04 m·s⁻¹) was greater than (p < 0.001, effect size = 4.00) the mean peak speed for the non-kicking condition (1.73 ± 0.03 m·s⁻¹), see Figure 2.6.
Figure 2.6 The group mean (± SD) values of peak speed determined during six 10-s maximal-intensity paddling tests performed in a 25-m swimming pool in eleven competitive male surfers. Three paddling trials were performed whilst arm paddling only (non-kicking) and three with simultaneous arm paddling and leg kicking (kicking). * Different from kicking, (p < 0.001).

2.4 DISCUSSION

The present study found that peak power output measured during maximal-intensity surfboard paddling on a swim-bench ergometer is reliable in competitive male surfers. Peak power output determined for the group of eleven male surfers did not change across six, 10-s maximal-intensity paddling trials and there was no change in the intraclass correlation coefficient when calculated for the first two trials (r = 0.995) compared with the value calculated for all six trials (r = 0.992). Furthermore, we established that peak power output could be determined reliably (r = 0.983) on separate days. We conclude that there is good trial-to-trial and day-to-day reliability in peak
power output for surfboard paddling determined during swim-bench ergometry in competitive male surfboard riders.

Maximal-paddling performance has not been assessed in surfers of any standard (Mendez-Villanueva & Bishop, 2005). Maximal-intensity surfboard paddling might be a major determinant of a surfer’s ability to catch a wave and assume the ideal position for wave riding. The present study demonstrates that peak power output achieved on the swim-bench ergometer (mean of six trials = 348 ± 23 W) is similar to peak power output observed in competitive swimmers (304 ± 22 W) (Swaine, 2000) and surf lifesavers (326 ± 29 W) (Morton & Gastin, 1997), measured during 30-s all-out front-crawl swimming and 60-s all-out knee-board paddling (surf lifesavers) on similar swim-bench ergometers. Upper-body peak power output of competitive swimmers and surf lifesavers is probably among the highest of any sportsman given the nature and energy demands of their sports. Therefore, the similar peak power output values observed in the present study for competitive surfers suggests that surfing also requires high upper-body power output.

The ability to reliably measure peak power output for paddling will enable coaches and exercise scientists to: i. Estimate maximal-intensity exercise capability, ii. Monitor changes in peak power output as a result of training, iii. Establish a goal for a rehabilitation program, iv. Use test results as a motivational tool, and v. Establish normative values for varying standards of surfing ability. In addition, a reliability study that provides anticipated change in mean values or typical error confidence limits for the measurement of peak power output during paddling allows coaches to identify physiologically meaningful changes.

The day-to-day reliability reported for peak power output on the swim-bench ergometer in the present study are comparable to values reported in studies that have investigated repeated sprints during leg cycling on a cycle ergometer (typical error values ranging
between 3.1-7.3%), as summarised in a meta-analytical review on the reliability of power in physical performance tests (Hopkins et al., 2001). To the best of our knowledge, only one study has investigated the trial-to-trial reliability of front-crawl paddling on a swim-bench ergometer in which two tests were performed and a change in mean value was reported as 6.9% (Swaine, 2000). No previous study has reported day-to-day reliability of a swim-bench ergometer.

An increase in peak power output of 53% has been reported for surf lifesavers after 10 wk of high-intensity surfboard training (Morton & Gastin, 1997). The present study suggests that smaller changes in peak power output observed in competitive surfers after an intervention (e.g., training) could be considered “worthwhile” (as defined by Hopkins, 2004) given the typical error value of 3.7% reported here for day-to-day reliability during laboratory testing. For example, an increase in peak power output of 1.9% (i.e., half the typical error), or about 6 W, could be considered to be “reasonably confident of a worthwhile change” (Hopkins, 2004). However, surfers should improve by about 7.4% (i.e., double the typical error), or about 20 W, from an initial peak power of 300 W. Nevertheless, this error value was derived from a small group of competitive male surfers. Thus, no firm conclusions can be made about worthwhile changes in peak power output when monitoring individual surfers.

It is unclear how upper-body peak power output measured on a swim-bench ergometer translates or relates to the actual speed of movement of the surfer through the water. A paddling test that can easily and quickly be performed in any swimming pool might be a useful tool for sport scientists or surfing coaches who might not have access to swim-bench ergometry. This is the first study to assess surfboard-paddling performance in the water. Peak speed for surfboard paddling in flat-water (swimming pool) was highly reliable in competitive male surfboard riders. The mean peak speed determined for the group of eleven male surfers did not change across three, 25-m maximal-intensity paddling trials under two conditions (non-kicking and kicking).
The present study determined the peak speed of surfboard paddling in the water under two conditions: i. Simultaneous paddling and kicking (kicking), and ii. Paddling only (non-kicking). Whereas measures from both were reliable, peak speed was greater when kicking than paddling only. There are three situations in surfing where a surfer will kick their legs while paddling to: i. Secure a wave, ii. Move away from the impact zone of a wave set (where the waves are crashing or dumping), and iii. Arrive in the take-off zone in competition to receive priority for the next wave. In contrast, a surfer will not kick when paddling from the shoreline to the wave-catching position, (typically at the back of the braking waves), or when moving into the best position to wait for a wave as they do not require high speeds and kicking could increase their fatigue.

Kicking while paddling was 0.16 m·s\(^{-1}\) faster than non-kicking. For a 5-10 s burst necessary for catching a wave, this is an increase in distance of between 0.8 to 1.6 m. Therefore, a surfer competing for the best take-off position will move 0.8 to 1.6 m further when kicking for 5-10 s. An increase in distance from 0.8 to 1.6 m could be the difference between reaching a wave before another surfer or not. The first surfer to stand up on the wave during competition gets priority for that wave. Therefore, we suggest that kicking while paddling could improve a surfer’s chance of getting into the ideal position for catching a wave compared to paddling only.

The present study demonstrates that peak speed of surfboard paddling with no kicking is 92% of the speed of simultaneous arm paddling and kicking in competitive male surfers. This highlights the importance of upper- and lower-body contributions to peak power output in surfing. Further, the percent difference in performance between non-kicking and kicking might be more useful than absolute speeds to compare results between surfers. Comparing absolute values of speed between surfers is difficult because the combined effects of volume and dimensions of the surfboard and the stature and body mass of the surfer greatly influence the resultant speed of the overall system.
The dimensions and volume of the surfboard in relation to the surfer’s stature and body mass need to be controlled to make accurate comparisons between the two testing methods or among individual surfers for field testing. This is unlike laboratory-testing results that can accurately and easily be compared between individuals by, for example, expressing peak power output values relative to body mass (W·kg$^{-1}$). Nevertheless, trial-to-trial reliability of measures from the laboratory test can be compared with the trial-to-trial reliability of those from the field test via change in mean values, typical error scores, and typical error confidence limits for both tests, expressed as a percentage of the mean. Field-test measures had a smaller change in mean, typical error, and confidence limits than those from laboratory testing. The smaller typical error scores and change in mean values for field testing suggests that this test has greater sensitivity to assess smaller or physiologically meaningful changes in maximal-paddling performance than its laboratory equivalent.

**Concluding Remarks**

The ability of a surfer to accelerate quickly from a stationary position and achieve high-paddling speeds could be related to their ability to catch bigger waves, faster waves, or waves that are hard to paddle onto (waves breaking slowly, strong winds, or waves with less energy). We can only hypothesize about the relationship between peak power output and paddling speed with the ability to catch a wave. However, the development of a reliable laboratory and field test for the assessment of peak power output for paddling in surfboard riders has provided new tools and methods to undertake further research in this area. Such research should include the: i. Characterisation of maximal-intensity exercise capabilities and economy of surfboard paddling in surfers of different standard, ii. Characterisation of the kinematics of surfboard paddling both in the laboratory and in the field, and iii. Determination of the influence of body position, stroke rate, underwater-paddling technique, and board dimensions on muscle
recruitment patterns of board paddling. Such research could help investigate surfers’ upper-body injuries that are attributable to board paddling, or help identify the influence of maximal-intensity exercise and/or paddling economy on performance. Finally, the dimensions and volume of the surfboard in relation to surfers’ stature and body mass should always be considered or controlled when undertaking field-based research in this area.
CHAPTER 3:

PEAK AEROBIC POWER AND PADDLING ECONOMY IN JUNIOR COMPETITIVE AND RECREATIONAL SURFERS
3.1 INTRODUCTION:

The most recent evidence suggests that approximately 5-7 million people participate in surfboard riding (surfing) worldwide (Frisby & Mckenzie, 2003) and there are more than 2.1 million surfboard riders (surfers) in the United States alone (Darrow, 2005). Furthermore, Sweeney (2006) reported that about 14% of urban-dwelling Australians participate in the sport of surfing. Despite the emerging profile of surfing as one of the world’s most popular and competitive professional sports (Booth, 2005), there is a paucity of research examining the physiological characteristics of surfers (Mendez-Villanueva & Bishop, 2005a).

The activity of surfing can be described as the action of an individual riding a floatable vessel on the broken or unbroken section of a wave, as it moves towards the shore. Surfing comprises of three main tasks: i. Lying prone on the surfboard and paddling (paddling), ii. The motion of pushing up from a prone to standing position (pop up), and iii. Standing on the surfboard and riding a wave (wave riding). The process of paddling out from shore, popping up, and wave riding is repeated many times during a recreational and/or competitive surfing session.

Performance during surfing is dependent on equipment and environmental conditions as well as an individual’s skill, psychological and mental aptitude, and physical fitness (Mendez-Villanueva & Bishop, 2005a). The contribution of each of these variables to overall performance is not completely understood. However, given that approximately 50% of total surfing time is spent board paddling and only 5% wave riding (Meir et al., 1991; Mendez-Villanueva et al., 2006), it is surprising that only three previous papers have examined board-paddling ability in surfers (Lowdon et al., 1989; Meir et al., 1991; Mendez-Villanueva et al., 2005b).
Peak O$_2$ uptake in competitive surfers has been measured during upper-body incremental exercise on an arm-cranking ergometer (Lowdon $et$ $al.$, 1989), during tethered board-paddling (Lowdon $et$ $al.$, 1989), on a swim-bench ergometer (Meir $et$ $al.$, 1991), and on a modified kayak-ergometer (Mendez-Villanueva $et$ $al.$, 2005b). The reported peak O$_2$ uptake of competitive surfers varies among studies (Table 3.1), with values ranging from 40 to 55 mL·kg$^{-1}$·min$^{-1}$. The range of testing equipment, and methodology employed, make it difficult to compare peak O$_2$ uptake values among studies and render conclusions about any differences in aerobic power that might exist between surfers of varying ability questionable.

Mendez-Villanueva $et$ $al.$ (2005b) found no significant difference in peak O$_2$ uptake for paddling (modified kayak-ergometer) measured in European top-level competitive surfers when compared to regional-level competitive surfers. These findings suggest no difference in peak aerobic power for paddling between competitive surfers of varying ability. However, while peak O$_2$ uptake was not different between the two groups, Mendez-Villanueva $et$ $al.$ (2005b) reported that the European top-level surfers reached a significantly higher peak power output (W) during the incremental paddling test when compared to the regional-level surfers (155 ± 37 W vs. 118 ± 27 W, respectively). The ability to produce a greater peak power output at the end of an incremental-exercise test with the same peak O$_2$ uptake may be associated with an increased ability to produce energy anaerobically, or improved exercise economy. The anaerobic capacity and/or paddling economy of surfers participating in the study by Mendez-Villanueva $et$ $al.$ (2005b) were neither measured nor discussed.
<table>
<thead>
<tr>
<th>Study</th>
<th>Reported standard of subjects (surfers) (gender, sample size, mean age±s)</th>
<th>Mode of exercise</th>
<th>Peak $O_2$ uptake (mL·kg$^{-1}$·min$^{-1}$±s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lowdon <em>et al.</em>, 1989</td>
<td>Competitive – college (men, n = 12; 21±1 yr)</td>
<td>Treadmill running</td>
<td>56.3±3.9</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Tethered board paddling</td>
<td>40.4±2.9</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Arm crank ergometry</td>
<td>41.6±4.0</td>
</tr>
<tr>
<td>Meir <em>et al.</em>, 1991</td>
<td>Recreational – ex-competitive (men, n = 6; 21±3 yr)</td>
<td>Swim bench ergometry</td>
<td>54.2±10.2</td>
</tr>
<tr>
<td>Patterson, 2002</td>
<td>Competitive – elite (undefined) (not reported, n = 61; 34±6 yr)</td>
<td>Not reported</td>
<td>55.0±6.1</td>
</tr>
<tr>
<td>Mendez-Villanueva &amp; Bishop, 2005</td>
<td>Competitive – national (European) (men, n = 7; 26±3 yr)</td>
<td>Modified kayak ergometry</td>
<td>50.0±4.7</td>
</tr>
<tr>
<td></td>
<td>Competitive – regional (men, n = 6; 27±4 yr)</td>
<td></td>
<td>47.9±6.3</td>
</tr>
<tr>
<td>Present study</td>
<td>Competitive – junior national (Australian) (men, n = 8; 18±1 yr)</td>
<td>Swim-bench ergometry</td>
<td>39.5±3.1</td>
</tr>
<tr>
<td></td>
<td>Recreational (men, n = 8; 18±1 yr)</td>
<td></td>
<td>37.8±4.5</td>
</tr>
</tbody>
</table>
Previous research has shown highly-trained competitive swimmers to have a superior exercise economy when compared to low-level collegiate swimmers and triathletes (Fernandes et al., 2006). Fernandes et al. (2006) concluded that improved stroking mechanics is associated with less energy required to achieve the same absolute swimming velocity (i.e., increased economy). The same maybe true of surfboard paddling where improved paddling mechanics would result in less energy used to propel the surfer on his/her board through the water. Improved paddling economy may allow a surfer to conserve energy for wave riding and/or delay the onset of cardiovascular and/or muscular fatigue. The purpose of the present study was to measure and compare peak O\textsubscript{2} uptake and economy in recreational and competitive surfers during paddling ergometry.

3.2. Materials and Methods

Subjects

Eight recreational male surfers (Surfers\textsubscript{COMP}) and eight competitive male surfers (Surfers\textsubscript{REC}) volunteered to participate in the present study (age 16-20 yr). The Griffith University Human Research Ethics Committee approved this study. Written informed consent was obtained from all volunteers, as well as from their parental guardian if they were under 18 yr of age, before they were accepted as a subject. Surfers\textsubscript{COMP} were members of the Australian Junior National Team, had been competing nationally for a minimum of 4 yr in age-group events and surfing at least 7 session·wk\textsuperscript{-1}. Surfers\textsubscript{REC} had been surfing for a minimum of 4 yr and at least 2 session·wk\textsuperscript{-1}, but not participated in competitive surfing events, other than their local board-riding events (< 6 event·yr\textsuperscript{-1}). All participants had not been competing, training, or participating in any other organised sport more than 1 session·wk\textsuperscript{-1} within the last 12 mo. Each surfer was required to fill out a survey to determine their surfing history (years surfing; yr), number of hours spent surfing each week (surfing duration; h·wk\textsuperscript{-1}), and participation in dry-
land training (frequency of dry-land training; sessions wk\(^{-1}\)). Dry-land training consisted of any exercise training performed out of the water (e.g., running, strength training).

**Experimental design**

All subjects participated in 3 d of testing (Day 1, Day 2 and Day 3). Day 1 of testing involved familiarisation of the equipment and the measurement of stature, body mass, arm span, and sitting height using standard anthropometric methods (Australian Sports Commission, 2000). A 10-s sprint-paddling test was then performed on Day 2 to determine peak-paddling power output (W) in each surfer. The 10-s peak-paddling power output was used to calculate the predetermined power outputs for the four-stage, incremental-paddling test performed 48-72 h later on Day 3 of testing. Peak O\(_2\) uptake (L min\(^{-1}\)) and paddling economy (%) were subsequently determined from the incremental-paddling test performed on Day 3.

**Experimental equipment**

A *classic* Vasa Swim Ergometer (Vasa, Inc., Essex Junction, VT, USA) was used in the present study which is similar to the biokinetic swim bench previously described by Sharp *et al.* (1982). The Vasa Swim Ergometer was modified so that the bench did not slide (i.e., a stationary swim-bench ergometer). A biokinetic swim bench is not isotonic or isokinetic as the force and velocity of the arm pulling is not constant at a predetermined setting (Sharp *et al.*, 1982). A biokinetic swim bench has previously been described as a semi-accommodating resistance device which can be preset to a regulation speed that provides a constant amount of acceleration in proportion to the force applied by the user (Sharp *et al.*, 1982). The swim ergometer consisted of hand paddles attached to two pull-ropes that induce rotation of the isokinetic resistance device. The external power output of each separate arm pull is determined by two force transducers on each hand pulley that measure tensile force, distance and force duration.
When force is applied to the hand paddles, the pull-rope pays out a velocity which ranges up to maximum, termed the maximum pull velocity (MPV). The resistance unit on the swim-bench provided seven MPV settings. Power output is calculated with feedback provided continuously to the subject via a digital display unit. The paddling ergometer was calibrated prior to testing using methods previously described (Sharp et al., 1982). The optimum MPV setting was previously determined in our laboratory, as was the trial-to-trial reliability of peak power output determined during 10 s of maximal-intensity paddling in competitive male surfers (ICC = 0.995, p < 0.001; unpublished data).

**Incremental-paddling test and the determination of peak O$_2$ uptake**

Peak O$_2$ uptake for paddling was measured during an incremental-paddling test performed on the swim-bench ergometer. The protocol for the incremental-paddling test consisted of four, 3-min work stages followed by a 20 W·30 s$^{-1}$ increase until volitional exhaustion. The incremental-paddling test protocol was developed from similar methods used by Mendez-Villanueva et al. (2005b) on surfers using a modified-kayak ergometer (Mendez-Villanueva et al., 2005b). The power output of the four, 3-min work stages was 10%, 15%, 20%, and 25% of the peak-paddling power output achieved during the 10-s sprint-paddling test determined on Day 2 of testing. The incremental-paddling test protocol was designed to provide incremental work rates that were appropriate for each individual. Given the paucity of data demonstrating appropriate incremental-paddling test work rates for junior surfers, we used the peak power output achieved during the 10-s sprint-paddling test to provide an incremental-paddling test protocol that would be age, gender, body mass, and training status appropriate. All surfers in the present study completed the incremental-paddling test with a similar time to exhaustion and at similar exercise intensities relative to peak O$_2$ uptake (i.e., between 15-55% peak O$_2$ uptake; Table 3). Surfers were required to stay within ±5 W of the
predetermined power output with stroke rate spontaneously chosen by the surfer in order to maintain the required power output.

As the surfers paddled pulmonary gas exchange was measured breath-by-breath (Figure 3.1) using a metabolic measurement system (MedGraphics CardiO2, Cardiopulmonary Diagnostic Systems, St. Paul, MN). Subjects wore a nose clip and breathed through a low-resistance mouthpiece and volume sensor assembly (pneumotachograph). Gases were drawn continuously from the mouthpiece assembly through a capillary line and analyzed for O\(_2\) and carbon dioxide (CO\(_2\)) concentrations by fast-response analyzers. The O\(_2\) and CO\(_2\) analyzers and the pneumotachograph were calibrated before and after each test using gases of known concentration and a 3-L syringe, respectively. Breath-by-breath O\(_2\) uptake values were averaged over 30 s with peak O\(_2\) uptake taken as the highest 30-s O\(_2\) uptake value.

Figure 3.1 Measurement of the pulmonary gas exchange of a surfer whilst paddling on a swim-bench ergometer.
Heart rate (HR) and rhythm were monitored continuously using a modified CM5 electrode configuration and a Lohmeier electrocardiograph (M607, Munchen Germany) with the ECG signal transferred onto a computer for storage using custom designed software. HR values were averaged over 30-s intervals and the last 30-s interval of each work stage was reported as the HR for that work stage. Peak HR was taken as the highest instantaneous HR value achieved during the incremental-paddling test. Blood [La] was measured pre exercise, during the last 20 s of every work stage, as well as at 1-, and 3-min post exercise using a Lactate Pro blood analyser (Arkray Factory Inc, Japan).

**Determination of paddling economy**

O₂ uptake values corresponding to the four, 3-min work stages of the incremental-paddling test varied between 15 and 55% of peak O₂ uptake. Data collected from the four submaximal work stages, as well as the peak O₂ value, were used to establish the O₂ uptake-power output relationship for paddling (Figure 3.2). The linear regression of the O₂ uptake-power output relationship was used to calculate paddling economy (%) for each surfer by calculating the inverse of the slope of the line and converting O₂ uptake into kJ using the conversion factor of 20.92 kJ·L⁻¹ of O₂.
Figure 3.2 $O_2$ uptake-power output relationship in recreational (REC) and competitive (COMP) junior male surfers determined during paddling ergometry. Values presented are group means and were determined from four, 3-min submaximal constant load work stages and the peak exercise values (i.e., peak $O_2$ uptake and peak power output). The ‘slope of the line’ calculated from the $O_2$ uptake-power output relationship was used to calculate paddling economy (%).

Data analysis

All group data are reported as a mean and standard deviation (mean, s). Independent t-tests were used to test for group differences in surfing history, physical characteristics, peak power output achieved during the 10-s sprint-paddling test, peak exercise variables determined during the incremental-paddling test (power output, $O_2$ uptake, HR, and [La$^-\$]) and paddling economy. Submaximal exercise variables (power output, $O_2$ uptake, HR, [La$^-\$]) determined during the four work stages ($WS_1$, $WS_2$, $WS_3$, $WS_4$) of the incremental-paddling test were examined using a mixed-factor design ANOVA (between group factor = surfing status; within group factor = work stage). Pairwise comparisons were examined where a significant F value was observed. Correlations among surfing experience and number of hours spent surfing per week with peak $O_2$
uptake and paddling economy were investigated using Pearsons correlation coefficients. Statistical significance was accepted at $P < 0.05$.

3.3 RESULTS:

Table 3.2 Physical characteristics, surfing experience and participation patterns of recreational (Surfers$_{REC}$) and competitive (Surfers$_{COMP}$) junior male surfers.

<table>
<thead>
<tr>
<th></th>
<th>Surfers$_{REC}$ (n = 8)</th>
<th>Surfers$_{COMP}$ (n = 8)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (yr)</td>
<td>18±2</td>
<td>18±1</td>
</tr>
<tr>
<td>Body mass (kg)</td>
<td>66.8±13.0</td>
<td>68.0±11.7</td>
</tr>
<tr>
<td>Stature (cm)</td>
<td>175.1±10.3</td>
<td>172.9±9.6</td>
</tr>
<tr>
<td>Sitting height (cm)</td>
<td>89.9±5.2</td>
<td>87.0±5.6</td>
</tr>
<tr>
<td>Arm span (cm)</td>
<td>179.9±11.0</td>
<td>175.8±13.6</td>
</tr>
<tr>
<td>Surfing experience (yr)</td>
<td>6.6±4.4</td>
<td>12.3±2.8*</td>
</tr>
<tr>
<td>Total surfing duration (h·wk$^{-1}$)</td>
<td>7.5±3.9</td>
<td>18.1±5.3*</td>
</tr>
<tr>
<td>Surfing frequency (session·wk$^{-1}$)</td>
<td>5±1</td>
<td>13±3*</td>
</tr>
<tr>
<td>Total dry-land training duration (h·wk$^{-1}$)</td>
<td>1.5±2.7</td>
<td>0.5±0.6</td>
</tr>
<tr>
<td>Dry-land training frequency (session·wk$^{-1}$)</td>
<td>1±2</td>
<td>1±1</td>
</tr>
<tr>
<td>Participation in competitive events (event·yr$^{-1}$)</td>
<td>3±3</td>
<td>25±5*</td>
</tr>
</tbody>
</table>

Values presented are group mean±s. *Significantly different to recreational surfers, $p < 0.05$. 
Surfing history and physical characteristics

There were no differences (p > 0.05) in physical characteristics between Surfers\textsubscript{REC} and Surfers\textsubscript{COMP} (Table 3.2). Surfing experience (Table 3.2) was greater in Surfers\textsubscript{COMP} who had been surfing for an average of 6 yr longer than Surfers\textsubscript{REC} (t = -3.059, p = 0.008), 11 h more per week (t = -4.579, p < 0.001) and 8 sessions more often per week (t = -7.522, p < 0.001). However, there was no difference in the number of hours spent dry-land training between the two groups. The Surfers\textsubscript{COMP} competed in significantly (t = -11.417 p < 0.001) more surfing events per year compared to Surfers\textsubscript{REC}. Peak power output achieved during the 10-s sprint-paddling test was not significantly different (t = -0.062, p = 0.952) between Surfers\textsubscript{COMP} 389±79 W and Surfers\textsubscript{REC} 380 ± 110 W.

Incremental-paddling test results

Table 3.3 illustrates the power output (W), O\textsubscript{2} uptake (L\textperiodcentered min\textsuperscript{-1}) and HR (beat\textperiodcentered min\textsuperscript{-1}) for Surfers\textsubscript{REC} and Surfers\textsubscript{COMP} across the four, 3-min work stages of the incremental paddling test. The predetermined power outputs for the four work stages of the incremental-paddling test were not significantly different between the two groups (F < 0.002, p = 0.961). The O\textsubscript{2} uptake achieved during the four, 3-min work stages of the incremental-paddling test were also expressed relative (%) to peak O\textsubscript{2} uptake (Table 3). O\textsubscript{2} uptake measured during the four work rates was between about 15 and 55% of peak O\textsubscript{2} uptake for all subjects.
Table 3.3. Mean values determined during the four submaximal work stages of the incremental-paddling test in recreational (Surfers\textsubscript{REC}) and competitive (Surfers\textsubscript{COMP}) junior male surfers.

<table>
<thead>
<tr>
<th>Incremental-paddling variable</th>
<th>test</th>
<th>Surfers</th>
<th>Work stage</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>WS\textsubscript{1}</td>
</tr>
<tr>
<td>Power output (W)</td>
<td>Surfers\textsubscript{REC}</td>
<td>38±8</td>
<td>58±12</td>
</tr>
<tr>
<td></td>
<td>Surfers\textsubscript{COMP}</td>
<td>38±11</td>
<td>57±16</td>
</tr>
<tr>
<td>(O_2) uptake (L\textcdot min\textsuperscript{-1})</td>
<td>Surfers\textsubscript{REC}</td>
<td>0.48±0.10</td>
<td>0.96±0.20</td>
</tr>
<tr>
<td></td>
<td>Surfers\textsubscript{COMP}</td>
<td>0.43±0.10</td>
<td>0.86±0.17</td>
</tr>
<tr>
<td>(O_2) uptake (% peak (O_2) uptake)</td>
<td>Surfers\textsubscript{REC}</td>
<td>19.4±4.0</td>
<td>38.2±3.2</td>
</tr>
<tr>
<td></td>
<td>Surfers\textsubscript{COMP}</td>
<td>16.2±3.0</td>
<td>32.4±4.6</td>
</tr>
<tr>
<td>HR (beat\textcdot min\textsuperscript{-1})</td>
<td>Surfers\textsubscript{REC}</td>
<td>102±12</td>
<td>114±12</td>
</tr>
<tr>
<td></td>
<td>Surfers\textsubscript{COMP}</td>
<td>108±15</td>
<td>122±15</td>
</tr>
<tr>
<td>Blood [La\textsuperscript{-}] (mmol\textcdot L\textsuperscript{-1})</td>
<td>Surfers\textsubscript{REC}</td>
<td>1.2±0.3</td>
<td>1.6±0.0</td>
</tr>
<tr>
<td></td>
<td>Surfers\textsubscript{COMP}</td>
<td>1.0±0.2</td>
<td>1.1±0.2</td>
</tr>
</tbody>
</table>

Values presented are group mean±s. HR = heart rate, [La\textsuperscript{-}] = lactate concentration, \(WS\) = work stage. The power output of the four, 3-min work stages were 10\%, 15\%, 20\%, and 25\% of the peak-paddling power output achieved during a 10-s sprint-paddling test determined on Day 1 of testing. \*Significantly different to recreational surfers (p < 0.05).

There were no significant interactions between surfing status and work stage for \(O_2\) uptake (L\textcdot min\textsuperscript{-1}; \(F = 1.055, p = 0.378\)) or HR (bpm; \(F = 0.158, p = 0.924\)), and both \(O_2\) uptake (\(F = 157.785, p < 0.001\)) and HR (\(F = 154.699, p < 0.001\)) significantly increased systematically across the four work stages indicative of the increasing power outputs. In contrast, there was a significant interaction between surfing status and work
stage for [La\(^-\)] (F = 2.893, p = 0.046). Blood [La\(^-\)] significantly increased (p = 0.002) from a value of 1.2 ± 0.3 mmol·L\(^{-1}\) measured during WS\(_1\), to a value of 1.9 ± 0.9 mmol·L\(^{-1}\) measured during WS\(_3\) of the incremental paddling test in Surfers\(_{REC}\). Moreover, blood [La\(^-\)] continued to increase significantly from the previous work stage at WS\(_3\) (p = 0.002) and WS\(_4\) (2.4 mmol·L\(^{-1}\), s= 0.9) (p = 0.002) in Surfers\(_{REC}\) (Figure 3.2). Blood [La\(^-\)] did not significantly increase from a value of 1.0 ± 0.2 mmol·L\(^{-1}\) measured during WS\(_1\) until a blood [La\(^-\)] of 1.6 ± 0.5 mmol·L\(^{-1}\) was achieved during WS\(_4\) of the incremental paddling test in Surfers\(_{COMP}\) (p = 0.019). The significantly increasing blood [La\(^-\)] during the four stages of the incremental-paddling test observed in the Surfers\(_{REC}\), resulted in significantly different blood [La\(^-\)] measured at WS\(_4\) (p = 0.040) between the two groups.

![Figure 3.3. Change in blood lactate concentration ([La\(^-\)]) during an incremental paddling test in junior male recreational (REC) and competitive (COMP) surfers. Blood [La\(^-\)] was measured at the end of four, 3-min constant-load work stages and 3-min post a 20 W·min\(^{-1}\) increment to exhaustion. *Significantly different to competitive surfers.](image-url)
Table 3.4. Peak values determined during the incremental-paddling test in recreational (SurfersREC) and competitive (SurfersCOMP) junior male surfers.

<table>
<thead>
<tr>
<th></th>
<th>SurfersREC (n = 8)</th>
<th>SurfersCOMP (n = 8)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Incremental peak power</td>
<td>199±24</td>
<td>199±45</td>
</tr>
<tr>
<td>Peak O₂ uptake (L·min⁻¹)</td>
<td>2.52±0.50</td>
<td>2.66±0.35</td>
</tr>
<tr>
<td>HRpeak (beat·min⁻¹)</td>
<td>194±5</td>
<td>188±7</td>
</tr>
<tr>
<td>Peak blood [La⁻] (mmol·L⁻¹)</td>
<td>8.2±2.7</td>
<td>6.8±1.1</td>
</tr>
<tr>
<td>Peak RER</td>
<td>1.2±0.1</td>
<td>1.1±0.1*</td>
</tr>
</tbody>
</table>

Values presented are group mean±s. HRpeak = Peak heart rate, Peak blood lactate concentration ([La⁻]) = 3 min post-exercise blood [La⁻], RER = respiratory exchange ratio at peak exercise. *Significantly different to recreational surfers (p < 0.05).

Table 3.4 presents the peak values determined during the incremental-paddling test. Peak power output (t = 0.035, p = 0.973), peak O₂ uptake (t = -0.874, p = 0.397) and peak HR (t = 1.941, p = 0.073) achieved during the incremental-paddling test were not significantly different between SurfersREC and SurfersCOMP. Blood [La⁻] determined 3-min post exercise (i.e., peak [La⁻]) was not different in SurfersREC and SurfersCOMP (t = 1.369, p =0.203). There were significant differences (t = 2.417, p = 0.030) in RER values for recreational and competitive surfers at peak exercise.

The mean slope of the line for the O₂ uptake-power output relationship was not different between SurfersREC (0.012 L ± 0.002·min⁻¹·W⁻¹) and SurfersCOMP (0.014 ± 0.003 L·min⁻¹·W⁻¹) and (t = -1.818, p = 0.091). Subsequently, a paddling economy of 21.4 ± 4.0 % calculated for the SurfersCOMP was not different to the paddling economy of 24.7 ± 3.4 % calculated for the SurfersREC (t = 1.767, p = 0.099). The Pearsons correlation coefficient of the line of best fit was higher than 0.98 in all subjects and not different (t
= -0.914, p = 0.376) between Surfers\textsubscript{COMP} (r = 0.994 ± 0.004) and Surfers\textsubscript{REC} (r = 0.992 ± 0.006) suggesting that any small variations in the relative work rates performed during the incremental-paddling test did not affect paddling economy values. Furthermore, there were no significant relationships between surfing experience and the number of hours spent surfing per week with peak O\textsubscript{2} uptake, paddling economy and peak power output, with all correlation values less than 0.400 (p > 0.05).

### 3.4 DISCUSSION

The primary finding of the present study was that the peak O\textsubscript{2} uptake determined during an incremental-paddling test was not different between recreational surfers (Surfers\textsubscript{REC}) and competitive surfers (Surfers\textsubscript{COMP}). The similar peak aerobic power was accompanied by no differences in paddling economy between the two groups. Interestingly, Surfers\textsubscript{COMP} participated in significantly more hours of surfing per week and had been surfing for longer when compared to Surfers\textsubscript{REC}, yet no relationships between surfing experience and peak O\textsubscript{2} uptake and/or paddling economy were observed. These findings suggest that peak O\textsubscript{2} uptake and economy are not sensitive determinants of ability or experience in junior male surfers.

The number of hours spent surfing each week of the Surfers\textsubscript{COMP} in the present study are consistent with values reported for competitive surfers (Mendez-Villanueva & Bishop, 2005a). The surfers in the present study were participating in minimal dry-land training (range 0 - 2 session-wk\textsuperscript{-1}), despite the Surfers\textsubscript{COMP} being ranked in the top 20 surfers in Australia for their age group. However, dry-land training participation of less than 2 session-wk\textsuperscript{-1} is consistent with previous observations in competitive surfers (Lowdon et al., 1989) and suggests that the majority of a surfer’s training is undertaken in the water (Mendez-Villanueva & Bishop, 2005a). No recent study has reported the training experience and training volume of top competitive surfers, so it is unclear if the dry-
land training patterns of the junior surfers in the present study is similar to current open-age competitive male surfers.

It should be noted that our surfers were considered junior surfers who were competing nationally in 21 yr and under competition. In comparison, the top 40 open-age male surfers currently (2009 World Championship Tour team) range in age from 20-37 yr with a mean age of 27 ± 4 yr (Association of Surfing Professionals, 2009). Thus, any conclusions made about the peak aerobic power and paddling economy of the surfers in the present study represent professional junior surfers and can not be generalized to the current population of highly-competitive Australian open-age male surfers. Furthermore, it is likely that the surfers participating in the present study were a combination of pubescent and post-pubescent individuals (16-20 yr). The inclusion of prepubescent and post-pubescent individuals in studies comparing physiological measurements must be considered when making conclusions about group differences and differences among other studies. In particular, at any given age, during late adolescence, there is wide variation in size, physique, and body composition at which time the rate of growth and biologic maturation greatly influence exercise capacities such as strength, aerobic performance and anaerobic performance (Malina et al., 2004).

The subject characteristics described for SurfersCOMP in the present study (18 ± 1 yr.; 172.9 ± 9.6 cm; 68.0 ± 11.7 kg) were not notably different to the participant physiological characteristics reported in earlier studies by Lowdon (1980) (22 ± 3 yr.; 173.6 cm; 68.0 ± 7.2 kg), Meir et. al. (1991) (21 ± 3 yr; 175.8 ± 5.8 cm; 68.9 ± 5.7 kg) or Mendez-Villanueva et al. (2005b) (26 ± 3 yr; 172.1 ± 4.9 cm; 67.0 ± 4.3 kg) who all describe highly-competitive male surfers. Surfers in the present study may be shorter and lighter when compared to swimmers (179 ± 4 cm, 71.4 ± 6.8 kg; 23 ± 4 yr) (Swaine, 2000), surf lifesavers (176.1 ± 1.8 cm; 72 kg; 21 ± 1 yr) (Morton & Gastin, 1997) and water polo players (180.9 cm, 80.3 kg, 22 yr) (Pinnington et al., 1987). Furthermore, the stature and body mass of the surfers in the present study appear lower
than normative data presented for the general population (Jackson et al., 2002), consistent with previous suggestions that a lower centre of body mass is an important requirement for surfing performance (Lowdon, 1980). Although subjects in the present study suggest that surfers have a reduced body mass and stature when compared to other aquatic athletes and normative data, no differences were observed in the stature, body mass, sitting height, or arm span between Surfers\textsubscript{REC} and Surfers\textsubscript{COMP} in the present study. Therefore, while a shorter stature, lower body mass, and longer arm span is a common physical characteristic of surfboard riders, the results of the present study suggest that these characteristics are not a distinguishing factor of surfing ability in junior surfers.

This is the first study to measure peak O\textsubscript{2} uptake in recreational surfers and compare these values with competitive surfers. No difference was observed between the peak O\textsubscript{2} uptake of Surfers\textsubscript{REC} (37.8 ± 4.5 mL·kg\textsuperscript{-1}·min\textsuperscript{-1}) and Surfers\textsubscript{COMP} (39.5 ± 3.1 mL·kg\textsuperscript{-1}·min\textsuperscript{-1}). These findings are surprising considering that the Surfers\textsubscript{COMP} spent a significantly greater amount of time surfing per week (approximately 10 h) when compared to the Surfers\textsubscript{REC}. The peak O\textsubscript{2} uptake values of both Surfers\textsubscript{COMP} and Surfers\textsubscript{REC} are slightly less than values previously reported for competitive surfers during incremental paddling (Table 1). Differences in peak O\textsubscript{2} uptake values across studies may be due to differences in testing protocols and/or ergometers used (Lowdon et al., 1989; Meir et al., 1991; Mendez-Villanueva et al., 2005b). In the present study, the similar peak O\textsubscript{2} uptake values for Surfers\textsubscript{REC} and Surfers\textsubscript{COMP}, using the same testing protocols, suggest that peak O\textsubscript{2} uptake may not be a sensitive measure of surfing performance or participation levels and may not directly influence surfing performance for junior surfers. These results are similar to that of Mendez-Villanueva et al. (2005b) who found no differences in peak O\textsubscript{2} uptake in two groups of open age surfers of different surfing ability (Mendez-Villanueva et al., 2005b). Nevertheless, a longitudinal study measuring peak O\textsubscript{2} uptake in previously untrained surfers (recreational) maybe
needed to make accurate conclusions about the effect of surfing on peak aerobic power in competitive male surfers.

In the present study, there were no significant difference in the peak power output achieved during incremental-arm paddling on a swim-bench ergometer between SurfersREC (199 ± 24.1 W) and SurfersCOMP (199 ± 44.9 W). This is inconsistent with findings by Mendez-Villanueva et al. (2005b) who found European top-level competitive surfers to have a greater peak power output (154.71 ± 36.82 W) than regional level competitive surfers (117.7 ± 27.14 W) despite demonstrating no difference in peak aerobic power between the two groups (Mendez-Villanueva et al., 2005b). The differences in peak power output achieved during incremental paddling reported by Mendez-Villanueva were not explained. The differences in the findings of the present study when compared to the findings of the previous study by Mendez-Villanueva et al. (2005b) could simply be attributed to the disparity in the surfer’s age between the two studies. Malina, Bouchard & Bar-Or, (2004) demonstrate that peak power output can increase dramatically throughout puberty and it cannot be concluded that all surfers in the present study were post-pubescent. However, we found no significant correlation between the number of years surfing and time spent surfing per week with peak power output, suggesting that peak power output does not improve with surfing experience in junior surfers.

There were no differences in the slope of the line determined from the \( O_2 \) uptake-power output relationship between the two groups. Accordingly, we demonstrated that the paddling economy of recreational surfers is not different from the paddling economy of competitive surfers. Unfortunately, we are unable to comment as to whether surfing, *per se*, improves paddling economy as no previous research has determined paddling economy of untrained individuals. Other aquatic sports demonstrate improvements in economy with increased experience and competitive status (Fernandes et al., 2006), suggesting that exercise economy is improved with increased participation and possibly
an important physiological characteristic for performance. It is possible that paddling economy may change with age (junior to open age) and be an important physiological characteristic for open age surfers. Further research investigating paddling economy in recreational and competitive open age surfers is needed to confirm such suggestions. However, we found no significant correlation between number of years surfing and paddling economy in junior surfers, suggesting that paddling economy does not improve with surfing experience in junior surfers.

To the best of our knowledge, no study has previously reported the paddling economy of swim-bench ergometry; only during free or tethered swimming. The O₂ uptake-power output relationship slope values of SurfersCOMP (0.014 ± 0.003 W·L·min⁻¹) and SurfersREC (0.012±0.002 W·L·min⁻¹) are consistent to what is reported for leg cycling (0.011 ± 0.001 L·min⁻¹·W⁻¹) (Yasuda et al., 2008), (0.010 ± 0.000 L·min⁻¹·W⁻¹) (Weber & Schneider, 2001), but less than arm cranking (0.028 ± 0.001 L·min⁻¹·W⁻¹) (Yasuda et al., 2008). The slope of the O₂ uptake-power output relationship in the present study suggests that economy of paddling in a group of surfers is greater than the economy of arm cranking and equivalent to leg cycling. While it is commonly accepted that upper-body exercise (e.g., arm-cranking) is less efficient than lower-body exercise (e.g., leg cycling), improved economy during paddling in the present study could be attributed to:

1. The principle of specificity or, 2. The nature of paddling exercise in the prone position. Athletes (e.g., surfers) that train particular muscle groups (e.g., upper-body) with a repeated movement and contraction pattern (e.g., paddling) may experience specific histological and neuromuscular adaptations associated with the task. Therefore, it is reasonable to suggest that surfers who regularly train for paddling exercise will have improved economy values when compared to untrained individuals performing the unfamiliar task of arm cranking. Furthermore, arm cranking is performed in the sitting position that may involve the recruitment of more stabilising muscles (that do not contribute to power output) when compared to paddling in a prone position. However, it can not be discarded that differences observed between paddling
economy in the present study, and arm cranking and leg-cycling economy in previous studies, may be associated with differences in testing equipment.

A higher blood \([\text{La}^-]\) was observed in Surfers\(_{REC}\) when compared to Surfers\(_{COMP}\) during submaximal paddling in the present study. In agreement with this finding, Mendez-Villanueva et al. (2005b) demonstrated that the paddling intensity at which 4 mmol·L\(^{-1}\) of lactate occurs in the blood was less in surfers of lower competitive standard compared to surfers of greater competitive standard despite the two groups achieving the same peak \(O_2\) uptake. The results of the study by Mendez-Villanueva et al. (2005b) and the findings of the present study show that the blood lactate threshold might be a more sensitive determinant of surfing ability or the level of surfing experience. Indeed, anaerobic threshold has been demonstrated as a more sensitive measure of endurance performance in other endurance-trained athletes when compared to values of peak \(O_2\) uptake (Bassett & Howley, 2000). Furthermore, Mendez-Villanueva et al. (2005b) suggested that a higher blood lactate threshold during board paddling may delay fatigue-induced impairments in fine motor skills necessary for subsequent board riding. Nevertheless, the incremental-paddling protocol used in the present study was not designed to precisely determine the blood lactate threshold.

**Concluding Remarks**

We found no differences in peak \(O_2\) uptake and paddling economy between Surfers\(_{COMP}\) and Surfers\(_{REC}\). Furthermore, surfing frequency and surfing experience did not correlate with peak \(O_2\) uptake or paddling economy. This suggests that peak \(O_2\) uptake and paddling economy are not sensitive measures of surfing ability or experience in junior surfers. Interestingly, a greater blood \([\text{La}^-]\) was measured in Surfers\(_{REC}\) compared to Surfers\(_{COMP}\) during submaximal paddling suggesting differences in the blood lactate threshold between the two groups. The findings of the present study suggest that peak aerobic power and paddling economy cannot decipher surfing ability, while further
research is required to determine if the blood lactate threshold is a defining physiological characteristic of surfers of differing ability.
CHAPTER 4

MAXIMAL-PADDLING PERFORMANCE IN JUNIOR RECREATIONAL AND COMPETITIVE SURFERS
4.1 INTRODUCTION:

When an athlete dominates a sport across several events (e.g., Michael Phelps – swimming), or for a long period of time (e.g., Lance Armstrong – cycling, Kelly Slater – surfboard riding), it prompts questions about the unique physical characteristics that are required for successful performance in that sport. Nevertheless, in contrast to swimming and cycling, there is very little research examining the physiological characteristics of elite surfboard riders (surfers) (Mendez-Villanueva & Bishop, 2005a), despite the emerging profile of surfboard riding (surfing) as one of the world’s most popular and competitive professional sports (Booth, 2005).

A small number of research studies have reported peak aerobic power in competitive surfers during upper-body incremental exercise (Lowdon et al., 1989; Meir et al., 1991; Mendez-Villanueva et al., 2005b; Patterson, 2002). However, movement patterns determined during a competitive surfing event, demonstrate that ~90 % of all paddling bouts during a surfing session are for time intervals of between 3.8 and 131.0 s (Mendez-Villanueva et al., 2006). These movement patterns suggest that the non-oxidative energy systems may be important for successful performance in surfboard riding. No previous study has examined the maximal-paddling performance of surfers or measured and compared anaerobic energy production during short-term exercise between competitive and recreational surfers.

The 30-s Wingate Anaerobic Test (WAnT) is well accepted as a reliable and valid method (Bar-Or O, 1987) of measuring and comparing maximal leg-cycling performance among groups of untrained children (Dotan & Bar-Or, 1980), adults (Dotan & Bar-Or, 1983, Minahan et al., 2007), and athletes (Tanaka H et al., 1993, Zajac et al., 1999). In an effort to maintain sports specificity, researchers have modified the 30-s WAnT to examine maximal performance during arm cranking (Hawley et al., 1992) and swim-bench paddling (Swaine, 2000) in swimmers, or double-arm exercise in
rowers (Koutedakis & Sharp, 1986). Furthermore, in order to provide some insight into the group differences observed in the total work produced, researchers have evaluated both the aerobic and anaerobic energy contributions to short-duration maximal efforts (Medbo & Burgers, 1990; Serresse et al., 1988).

The accumulated O\textsubscript{2} (AO\textsubscript{2}) deficit has been previously used to estimate the anaerobic energy contribution to 30 s of maximal cycling (Medbo & Burgers, 1990). An increased AO\textsubscript{2} deficit determined during the 30-s WAnT would suggest a greater contribution from the anaerobic energy systems when compared to other individuals/groups and/or provide some evidence of anaerobic energy system augmentation (e.g., via training). Medbo and Burgers (1990) demonstrated significantly higher (30% higher) AO\textsubscript{2} deficit values for sprint-trained athletes when compared to untrained and endurance-trained individuals when measured during a 30-s maximal-cycling effort (Medbo & Burgers, 1990).

In the present study, we used a swim-bench ergometer to determine and compare short-duration power output between junior male recreational and competitive surfers. Furthermore, we estimated the aerobic and anaerobic energy contributions to a 30-s WAnT for paddling (WAnT\text{PADDLING}) in the two groups. The measurement of anaerobic power and the relative contribution of energy systems to maximal-paddling performance in surfers may provide exercise scientists and coaches with important information for the prescription of exercise training programs and the priorities placed on relevant energy systems.
4.2 MATERIALS AND METHODS:

Subjects

Eight competitive male surfers (Surfers_{COMP}) (18±1 yr) and eight recreational male surfers (Surfers_{REC}) (18±2 yr) volunteered as subjects to participate in the present study. Surfers_{COMP} were members of the Australian Junior National Team and had been representing their State while competing nationally for a minimum of 2 yr in age-group events. All Surfers_{REC} had been surfing at least 2 session/wk for a minimum of 4 yr, but had not participated in competitive surfing events, other than their local board-riding events (< 6 event/yr). All participants had not been competing, training, or participating in any other organised sport more than 1 session/wk within the last 12 mo. The Griffith University Human Research Ethics Committee approved this study. Written informed consent was obtained from all volunteers, as well as from their parental guardian if they were under 18 yr of age, before they were accepted as a subject.

Experimental design

Surfers_{COMP} and Surfers_{REC} participated in three separate days of testing (Day 1, Day 2, and Day 3). Familiarisation of the testing equipment and procedures was conducted on Day 1 of testing. Subjects also performed a 10-s maximal-paddling test on Day 1 to determine peak power for the subsequent prescription of the work rates used during the incremental-paddling test. It has previously been demonstrated that peak power determined during a 10-s maximal-paddling test on a swim-bench ergometer is reliable in junior male competitive surfboard riders (Chapter 2). On Day 2 of testing, surfers performed one, 30-s WAnTPADDLING on the swim-bench ergometer for the determination of peak, mean power and fatigue index (FI%) as well as for the contributions of the aerobic (AO_2 uptake) and anaerobic (AO_2 deficit) energy systems. At least 48 h later, on Day 3 of testing, surfers performed an incremental-paddling test to exhaustion on the
swim-bench ergometer to determine the O$_2$ uptake-power relationship and peak O$_2$ uptake for paddling.

**Equipment**

A *classic* Vasa Swim Ergometer (Vasa, Inc., Essex Junction, VT, USA) was used to perform: i. The 10-s maximal-paddling test, ii. 30-s WAnT$_{PADDLING}$, and iii. The incremental-paddling test to exhaustion. The swim-bench ergometer consisted of hand paddles attached to two pull ropes that induce rotation of the isokinetic resistance device. Two suitably mounted force transducers on each hand pulley measured tensile force, distance and force duration for the calculation of external power output of each separate arm pull. When force is applied to the hand paddles, the pull rope pays out at a velocity which ranges up to maximum, termed the maximum pull velocity (MPV). The resistance unit on the swim-bench provided seven MPV settings. Based on previous testing (Chapter 2), the highest MPV setting of 7 was used in all tests, for all surfers. Power output is calculated and continuously fed back to the subject via a digital display unit. The display unit on the ergometer used in the present study had no memory storage, so the duration of the paddling tests were recorded via digital video and played back to obtain 1-s power output values displayed during the trial. The swim-bench ergometer was calibrated prior to testing by vertically dropping known masses attached to the hand paddles over set distances. Power was calculated by dividing the work by the time of the pull. Each drop was filmed and video digitising was used to determine the time of each drop. The calibration procedures were based on those previously described by Sharp *et al.* (1982) for a similar swim-bench ergometer to that used in the present study.

Breath-by-breath pulmonary gas-exchange was measured during the 30-s WAnT$_{PADDLING}$ and the incremental-paddling test using a metabolic measurement system (MedGraphics CardiO$_2$, Cardiopulmonary Diagnostic Systems, St. Paul, MN).
Subjects wore a nose clip and breathed through a low-resistance mouthpiece and volume sensor assembly (pneumotachograph). Gases were drawn continuously from the mouthpiece assembly through a capillary line and analyzed for O$_2$ and carbon dioxide (CO$_2$) concentrations by fast-response analyzers. The O$_2$ and CO$_2$ analyzers and the pneumotachograph were calibrated before and after each test using gases of known concentration and a 3-L syringe, respectively. Breath-by-breath O$_2$ uptake values were averaged over 30 s for the incremental-paddling test and over 5 s for the 30-s WAnT$_{PADDLING}$. Peak O$_2$ uptake for the incremental-paddling test was determined as the highest 30-s average O$_2$ uptake value.

Heart rate (HR) and rhythm were monitored continuously using a modified CM5 electrode configuration and a Lohmeier electrocardiograph (M607, Munchen Germany) with the ECG signal transferred onto a computer for storage using custom designed software. HR values were measured beat-by-beat and then reported every s for the 30-s WAnT$_{PADDLING}$ and for every 30-s interval for the incremental-paddling test. Peak HR was taken for both the WAnT$_{PADDLING}$ and the incremental-paddling test as the highest 1-s HR value achieved during the duration of the test.

Blood lactate concentration ([La$^-$]) was analysed at the time of blood collection using an automated hand-held blood lactate analyser (Lactate Pro, Arkray, Japan). A small amount of Finalgon ointment (Boehringer Ingelheim, NSW, Australia) was applied to the subject’s earlobe prior to blood collection to induce hyperaemia. The earlobe was subsequently cleansed thoroughly using alcohol wipes (Tyco Healthcare Group LP, USA). The earlobe was punctured using a 2.3 mm disposable lancet (Safe-T-Pro Plus, Accu-Chek, Australia). Approximately 5 µL of blood was collected onto a test strip for the subsequent determination of blood [La$^-$] immediately before the commencement of the test (10 min following warm up), and at 3-min post the 30-s WAnT$_{PADDLING}$ test.
The 30-s Wingate Anaerobic Test for paddling (WAnTPADDLING)

The 30-s WAnTPADDLING test consisted of 30-s of all-out alternate arm paddling at a self-selected stroke rate. Prior to the test subjects participated in a 5-min warm up consisting of 3-min light-intensity continuous paddling followed by three, 5-s all-out paddling efforts; each 5-s effort was separated by a 30-s rest period. Subjects then rested off the swim-bench for 10 min before they were asked to resume their position on the swim-bench to commence the test. Each subject was reminded to paddle maximally until they were instructed to stop and advised that they would be given strong verbal encouragement. Subjects commenced the 30-s WAnTPADDLING with both arms stretched out in front of their body. The chief investigator then provided a 3-s countdown to ‘go!’ which triggered the start of the test. Surfers were not informed of the elapsed time and verbal encouragement went for 32 s before the surfers were told to stop in order to prevent them from slowing down too early. Subjects continued to paddle against an MPV setting of 3, at 50 rev/min for at least 5 min after the 30-s WAnTPADDLING.

Peak power, mean power, fatigue index (FI%) and delta blood lactate concentration (Δ[La-]), were determined as indices of anaerobic energy production (Green & Dawson, 1993; Minahan et al., 2007; Scott et al., 1991; Vandewalle & Pérès, 1987). Peak power was determined as the highest power output value produced for the duration of the test, whereas mean power was determined as the average power output for the duration of the test (i.e., 30 s). The FI% was calculated as the absolute difference between the highest and the lowest work rate expressed as a percent of the highest work rate. The Δ[La-] was measured as the change in [La-] from resting to 3-min post exercise.
Incremental-paddling test for the determination of the \( \text{O}_2 \) uptake-power relationship and peak \( \text{O}_2 \) uptake

Peak \( \text{O}_2 \) uptake for paddling was measured during an incremental-paddling test performed on the swim-bench ergometer, as previously discussed in chapter 3.2. The protocol for the incremental-paddling test consisted of four, 3-min work stages followed by a 20 W \( \cdot \) 30 s\(^{-1} \) increase until volitional exhaustion. The incremental-paddling test protocol was developed from similar methods used by Mendez-Villanueva \textit{et al.} (2005b) on surfers using a modified-kayak ergometer (Mendez-Villanueva \textit{et al.}, 2005b). The power output of the four, 3-min work stages was 10\%, 15\%, 20\%, and 25\% of the peak-paddling power output achieved during the 10-s sprint-paddling test determined on Day 2 of testing. The incremental-paddling test protocol was designed to provide incremental work rates that were appropriate for each individual. Given the paucity of data demonstrating appropriate incremental-paddling test work rates for junior surfers, we used the peak power output achieved during the 10-s sprint-paddling test to provide an incremental-paddling test protocol that would be age, gender, body mass, and training status appropriate. Surfers were required to stay within \( \pm 5 \) W of the predetermined power output with stroke rate spontaneously chosen by the surfer in order to maintain the required power output. The test was terminated when the surfer could no longer maintain the predetermined power output and had already been given two prior warnings to “pick up” the intensity. \( \text{O}_2 \) uptake, power output, and HR were all continuously monitored throughout the incremental paddling test using method

The \( \text{O}_2 \) uptake and corresponding power values achieved during the four, 3-min constant load work stages, as well as the peak \( \text{O}_2 \) uptake and peak power of the incremental-paddling test, were used to determine the \( \text{O}_2 \) uptake-power relationship for each subject (Figure 4.1). The \( \text{O}_2 \) uptake for each work stage was taken as the average value of the last 30 s of each work stage. The linear regression of the \( \text{O}_2 \) uptake-power
relationship was used to calculate the total energy demand (AO₂ demand) for the 30-s WAnT PADDLING.

![Graph showing oxygen uptake vs power output]

**Figure 4.1** The mean O₂ uptake-power relationship determined during an incremental-paddling test in recreational (REC) and competitive (COMP) junior male surfers. The group means for the slope of the line for the recreational surfers (0.017 ± 0.007) was not different to the slope of the line determined for the competitive surfers (0.014 ± 0.003).

**Calculation of the energy contributions to the 30-s WAnT PADDLING**

To determine the anaerobic contribution of the WAnT PADDLING, we measured the accumulated O₂ (AO₂) deficit using methods described previously by Medbo and colleagues (Medbo & Tabata, 1989, Medbo and Burgers, 1990). Briefly, the linear regression of the O₂ uptake-power relationship was extrapolated to estimate the energy demand (in O₂ equivalents) for every 5 s of the 30-s WAnT PADDLING. The six, 5-s segments were summed to get the total estimated O₂ demand (AO₂ demand; L) of the WAnT PADDLING. The aerobic contribution (AO₂ uptake: L) to the WAnT PADDLING was
determined by summing the values of $O_2$ uptake measured during the six, 5-s segments of the test using open-circuit spirometry. The AO$_2$ deficit (anaerobic contribution) was then calculated by subtracting the AO$_2$ uptake from the AO$_2$ demand.

**Data analysis**

All group data are reported as means±SD. Independent t-tests were used to test for group differences in physical characteristics, surfing experience, and participation patterns as well as for peak power, mean power, FI%, HR, $\Delta[La]$, and $O_2$ uptake values determined during the three experimental paddling tests (10-s maximal-paddling test, 30-s WAnTPADDLING, and the incremental-paddling test). Paired t-tests were used to examine differences between the peak power achieved during the 10-s maximal-paddling tests when compared to peak power achieved during the 30-s WAnTPADDLING. Correlations among several experimental variables (e.g., number of yr surfing, peak power, AO$_2$ deficit) were examined using the Pearson’s Correlation Coefficient ($r$). Statistical significance was accepted at $P < 0.05$. 
4.3 RESULTS:

Physical characteristics and surfing experience

The physical characteristics and surfing experience of the SurfersREC and SurfersCOMP are presented in Table 4.1 (both the t scores and p values are displayed in the table). There were no significant differences in body mass or height between SurfersREC and SurfersCOMP. Surfing experience was greater in SurfersCOMP with differences in group mean values of 7 yr longer, 9 session/wk more, and 12 h/wk more when compared to SurfersREC. Furthermore, SurfersCOMP group means for competitive events/yr was 21 more when compared to SurfersREC.

Table 4.1 Physical characteristics, surfing experience, and participation rates of recreational (SurfersREC) and competitive (SurfersCOMP) junior male surfers.

<table>
<thead>
<tr>
<th></th>
<th>SurfersREC n = 8</th>
<th>SurfersCOMP n = 8</th>
<th>t score, p value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Body mass (kg)</td>
<td>66.7±6.3</td>
<td>68.9±4.7</td>
<td>-0.798, 0.438</td>
</tr>
<tr>
<td>Height (cm)</td>
<td>169.1±10.1</td>
<td>170.0±4.8</td>
<td>-0.451, 0.659</td>
</tr>
<tr>
<td>Surfing experience (yr)</td>
<td>4.5±0.8</td>
<td>11.6±2.1</td>
<td>-6.378, &lt;0.001</td>
</tr>
<tr>
<td>Surfing frequency (session/wk)</td>
<td>3±1</td>
<td>13±2</td>
<td>-10.234, &lt;0.001</td>
</tr>
<tr>
<td>Surfing duration (h/wk)</td>
<td>4.8±3.4</td>
<td>17.1±6.0</td>
<td>-5.1, &lt;0.001</td>
</tr>
<tr>
<td>Participation in competition (events/yr)</td>
<td>2±3</td>
<td>23±3</td>
<td>-14.575, &lt;0.001</td>
</tr>
</tbody>
</table>

Values presented are means±SD. Significance is accepted at P < 0.05.
10-s maximal-paddling test

Peak power achieved during the 10-s maximal-paddling test was greater ($t = -2.709, p = 0.017$) in Surfers$_{COMP}$ (418 ± 79 W) compared to Surfers$_{REC}$ (304 ± 89 W). Subsequently, the pre-determined power outputs for the start of the incremental-paddling test and the four, 3-min constant load work stages were also greater in Surfers$_{COMP}$.

Incremental-paddling test for the determination of the O$_2$ uptake-power relationship and peak O$_2$ uptake.

Table 4.2 illustrates the performance variables achieved during the incremental-paddling test. Peak power (W), peak O$_2$ uptake (L·min$^{-1}$) and peak HR (bpm) for the incremental-paddling test were not different between Surfers$_{REC}$ and Surfers$_{COMP}$. Furthermore, the mean slope of the line for the O$_2$ uptake-power relationship was not different between Surfers$_{COMP}$ and Surfers$_{REC}$ presented in Table 4.2 suggesting that paddling economy was not different between the two groups.
Table 4.2 Mean values determined during an incremental-paddling test to
exhaustion in recreational (Surfers_{REC}) and competitive (Surfers_{COMP}) junior male
surfers.

<table>
<thead>
<tr>
<th></th>
<th>Surfers_{REC} n = 8</th>
<th>Surfers_{COMP} n = 8</th>
<th>t score, p value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak power (W)</td>
<td>163±48</td>
<td>199±38</td>
<td>-1.674, 0.116</td>
</tr>
<tr>
<td>Peak O₂ uptake (L·min⁻¹)</td>
<td>2.5±0.2</td>
<td>2.7±0.1</td>
<td>-1.686, 0.114</td>
</tr>
<tr>
<td>Peak HR (bpm)</td>
<td>193±6</td>
<td>192±7</td>
<td>0.260, 0.799</td>
</tr>
<tr>
<td>Slope of the line (L·min·W⁻¹)</td>
<td>0.017±0.007</td>
<td>0.014±0.003</td>
<td>0.433, 0.672</td>
</tr>
</tbody>
</table>

Values presented are means±SD. Significance is accepted at P < 0.05. HR = heart rate. Slope of the line was calculated from the O₂ uptake-power relationship determined from four, 3-min submaximal constant load work stages and the peak exercise values (i.e., peak O₂ uptake and peak power).

30-s Wingate Anaerobic Test for paddling (WAnT_{PADDLING})

Performance values obtained during the 30-s WAnT_{PADDLING} are presented in Table 4.3. There was no difference (t = 0.346, p = 0.739) between the peak power determined during the 10-s maximal-paddling test when compared to the 30-s WAnT_{PADDLING} in either the Surfers_{COMP} or the Surfers_{REC}. Peak power, mean power, and ∆[La⁻] values achieved during the 30-s WAnT_{PADDLING} were greater in Surfers_{COMP} compared to Surfers_{REC}. There were no significant differences in FI% or peak HR achieved during the 30-s WAnT_{PADDLING} between the two groups. The mean AO₂ demand, AO₂ uptake, and AO₂ deficit for Surfers_{REC} and Surfers_{COMP} are illustrated in Figure 4.2. The AO₂ demand for Surfers_{REC} (1.82 ± 0.33 L) was less than (t = -2.350, p = 0.034.) Surfers_{COMP} (2.26 ± 0.32 L). However, the AO₂ uptake was not significantly different (t = -0.808, p = 0.433) between the two groups (Surfers_{REC} = 0.68±0.15 L, Surfers_{COMP} = 0.66 ± 0.13
Consequently, the $A_O^2$ deficit determined for $\text{Surfers}_{\text{REC}}$ (1.14 ± 0.38 L) was less than ($t = -2.566, p = 0.022$) the $A_O^2$ deficit determined for $\text{Surfers}_{\text{COMP}}$ (1.60 ± 0.31 L).

Table 4.3 Values determined during a 30-s Wingate Anaerobic Test for paddling ($\text{WAnT}_{\text{PADDLING}}$) in recreational ($\text{Surfers}_{\text{REC}}$) and competitive ($\text{Surfers}_{\text{COMP}}$) junior male surfers.

<table>
<thead>
<tr>
<th></th>
<th>$\text{Surfers}_{\text{REC}}$ n = 8</th>
<th>$\text{Surfers}_{\text{COMP}}$ n = 8</th>
<th>t score; p value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak power (W)</td>
<td>292±56</td>
<td>404±98</td>
<td>-2.821, 0.014</td>
</tr>
<tr>
<td>Mean power (W)</td>
<td>236±59</td>
<td>335±74</td>
<td>-2.958, 0.010</td>
</tr>
<tr>
<td>Fatigue Index (%)</td>
<td>34±8</td>
<td>28±6</td>
<td>0.284, 0.116</td>
</tr>
<tr>
<td>Peak HR (bpm)</td>
<td>180±26</td>
<td>186±11</td>
<td>-0.660, 0.520</td>
</tr>
<tr>
<td>$\Delta [\text{La}^-]$ (mmol-L)</td>
<td>4.9±0.9</td>
<td>7.8±1.2</td>
<td>-5.317, 0.001</td>
</tr>
</tbody>
</table>

Values presented are mean±SD. $\Delta [\text{La}^-]$ = change in blood lactate concentration from 10-min post warm up to 3-min post exercise; HR = heart rate. Significance is accepted at $P < 0.05$. 
Figure 4.2 Metabolic variables measured during a 30-s Wingate Anaerobic Test for paddling (WAnT_PADDLING) in recreational (REC) and competitive (COMP) junior male surfers. Energy demand in $O_2$ equivalents. Values presented are means ± SD. * REC significantly different to COMP (P<0.05). $AO_2$ demand = sum of total estimated $O_2$ demand of six, 5-s segments of the WAnT_PADDLING. $AO_2$ uptake = the aerobic contribution determined by summing the values of $O_2$ uptake measured during the six, 5-s segments. $AO_2$ deficit = the anaerobic contribution, calculated by subtracting the $AO_2$ uptake from the $AO_2$ demand. *Significantly different to competitive surfers, $p < 0.05$. 

![Graph showing metabolic variables measured during a 30-s Wingate Anaerobic Test for paddling in recreational and competitive junior male surfers.](image-url)
Correlations between surfing experience and exercise variables

The results of the correlation analysis are presented in Table 4.4. Surfing experience (number of yr surfing and/or number of surfing sessions per wk) was significantly correlated with the peak power and the AO₂ deficit achieved during the 30-s WAnT\textsubscript{PADDLING}, whereas surfing experience was not significantly correlated with peak aerobic power (i.e., peak O₂ uptake) and the slope of the line achieved during the incremental-paddling test.

Table 4.4 Pearson’s correlation coefficients determined between surfing experience (number of yr surfing) and surfing frequency (sessions per wk) and values obtained during a 30-s Wingate Anaerobic Test for paddling (WAnT\textsubscript{PADDLING}) and an incremental-paddling test.

<table>
<thead>
<tr>
<th></th>
<th>30-s WAnT\textsubscript{PADDLING}</th>
<th>Incremental-paddling test</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Peak power (W)</td>
<td>AO₂ deficit (L)</td>
</tr>
<tr>
<td>Number of yr surfing</td>
<td>r = 0.571</td>
<td>0.581</td>
</tr>
<tr>
<td></td>
<td>p = 0.021*</td>
<td>0.018*</td>
</tr>
<tr>
<td>Surfing sessions per/wk</td>
<td>r = 0.704</td>
<td>0.594</td>
</tr>
<tr>
<td></td>
<td>p = 0.002*</td>
<td>0.015*</td>
</tr>
</tbody>
</table>

AO₂ deficit = Accumulated O₂ deficit or contribution (in O₂ equivalents) of the anaerobic energy systems to the total energy demand of the 30-s WAnT\textsubscript{PADDLING}.

*Significantly correlated, p < 0.05. Slope of the line was calculated from the O₂ uptake-power relationship determined from four, 3-min submaximal constant load work stages and the peak exercise values (i.e., peak O₂ uptake and peak power).


4.4 DISCUSSION

The primary finding of the present study was that peak and mean power determined during a 30-s Wingate Anaerobic Test for paddling (WAnT\textsubscript{PADDLING}) was significantly higher in Surfers\textsuperscript{COMP} when compared to Surfers\textsuperscript{REC}. In agreement with these findings, both the AO\textsubscript{2} deficit and \(\Delta[\text{La}^-]\) determined from the 30-s WAnT\textsubscript{PADDLING} were higher in Surfers\textsuperscript{COMP} compared to Surfers\textsuperscript{REC}. These results suggest augmentation of the non-oxidative energy systems in Surfers\textsuperscript{COMP} when compared to Surfers\textsuperscript{REC}. The significant correlations observed between surfing experience (yr surfing) and surfing frequency (sessions/wk) and measures of non-oxidative energy production (e.g., peak power, AO\textsubscript{2} deficit) support the notion that surfboard riding promotes the development of the anaerobic energy systems and that anaerobic power may be an important determinant of surfing status. Thus, peak power and capacity determined during 30-s of maximal paddling may be considered as a sensitive measure of surfing ability or surfing experience in junior male surfers.

Anaerobic power measured in surfers during paddling ergometry

Peak power achieved in the 10-s maximal-paddling test was similar to the peak power achieved during the 30-s WAnT\textsubscript{PADDLING}, suggesting that both recreational and competitive surfers were able to achieve peak power during both the 10-s, and 30-s, maximal-paddling tests. The peak power values achieved by the Surfers\textsuperscript{COMP} during the 10-s maximal-paddling test (418 ± 79 W) in the present study, are somewhat higher than the peak power values achieved by junior male competitive surfers reported in our two previous studies using identical testing methods (348 ± 23 W; chapter 2 and 380 ± 110 W; chapter 3). Furthermore, peak power achieved during the 10-s maximal-paddling test observed in Surfers\textsuperscript{REC} in the present study (304 ± 89 W) were lower than values previously observed for a different group of Surfers\textsuperscript{REC} in our laboratory (385 ± 79 W; Chapter 3). No clear conclusions can be made as to why there were differences in
the peak power achieved during the 10-s maximal-paddling test for junior male Surfers\(_{COMP}\) and Surfers\(_{REC}\) across our three studies. However, it is possible that: i. There was a large range in the competitive ranking in Surfers\(_{COMP}\) across the three studies, ii. There were large differences in surfing experience and participation frequency for both Surfers\(_{REC}\) and Surfers\(_{COMP}\) across the three studies, or iii. The physical maturation within each group of surfers may have varied greatly.

The competitive ranking of Surfers\(_{COMP}\) was not determined in the present study or in our previous studies (Chapter 2 and Chapter 3). Surfing experience and participation levels were significantly different between Surfers\(_{COMP}\) and Surfers\(_{REC}\) in this study and our previous studies (Chapter 3). There were no differences (\(p > 0.05\)) in surfing experience and frequency between Surfers\(_{COMP}\) in this study and one of our previous studies (Chapter 3). Surfing experience and surfing frequency was not determined in Chapter 2. However there was a difference (\(t = 2.464, p = 0.027\)) in surfing frequency between Surfers\(_{REC}\) (3 ± 1 sessions/wk) in this study when compared Surfers\(_{REC}\) (5 ± 1 session/wk) in our previous study (Chapter 3). Surfers\(_{REC}\) in the present study had been surfing for 2 yr less and 3 less hr per wk when compared to the recreational surfers in our past study (Chapter 3). The reduced surfing frequency of Surfers\(_{REC}\) in the present study compared to our previous study (Chapter 3) may be associated with the lower 10-s peak power observed in this group as surfing frequency is positive correlated with anaerobic power. Minimum surfing experience and participation requirements needed to be met to participate in the study (minimum of 4 yr experience, surfing ~2 times per wk), however there was no maximum limit which resulted in a spread across our three studies in surfing experience and participation patterns in recreational surfers.

The junior surfers recruited in the present study were aged between 16 and 20 yr old. Therefore, it is likely that some participants were pubescent, whilst others post-pubescent; the number in each group remains unknown. It is well known that growth and maturation throughout puberty result in significant increases in strength and
measures of exercise capacity (aerobic and anaerobic power) (Malina et al., 2004). These changes are not associated with chronological age, but the rate of biological maturation of the individual. Such factors need to be considered when making comparisons between groups within the same study or other studies. For example, the physique and physical dimensions (i.e., percent body fat and lean muscle mass), as well as the strength, power, and exercise capacity of a late-maturing 17 yr old, will be much less than when compared to a post-pubescent 17 yr old. Growth and maturation differences across groups were reduced by matching the age, height, sitting height, arm span and body mass across all groups. Consequently the group means for such physical dimensions for Surfers\text{COMP} and Surfers\text{REC} across all of our three studies were no different. However, the rate of biological maturation and associated changes in exercise capacity must be considered when making comparisons with other studies using adults.

Both the peak power achieved during the 10-s, and the 30-s maximal-paddling tests were greater in Surfers\text{COMP} compared to Surfers\text{REC} in the present study. Greater peak power in Surfers\text{COMP} suggests that junior male competitive male surfers have a greater anaerobic power than junior male recreational surfers. Surfers are required to paddle maximally from a stationary position to catch waves. Therefore, the anaerobic power of a surfer may be related to their ability to catch bigger or faster waves, waves that are hard to paddle onto (waves breaking slowly, strong winds, or waves with less energy) or catching a wave before another surfer. It is unclear if anaerobic power is related to surfing ability and at this stage we can only hypothesize. It is possible that anaerobic power may only be a result of greater surfing experience and participation patterns.

The peak power values for Surfers\text{COMP} (404 \pm 98 W; 5.86 \pm 1.42 W\cdot kg^{-1}) were larger than values achieved by competitive swimmers (304 \pm 22 W, 3.9\pm0.28 W\cdot kg^{-1}) (Swaine, 2000) and surf lifesavers (326 \pm 29 W; 4.49 \pm 0.40 W\cdot kg^{-1}) (Morton & Gastin, 1997), measured during front-crawl paddling or knee-boarding paddling on a stationary swim-bench ergometer. Furthermore, the peak power values of Surfers\text{REC} in the present study
(292 ± 56 W, 4.37 ± 0.84 W·kg⁻¹) were similar to that of the competitive swimmers and surf lifesavers. It is reasonable to assume that the upper-body peak power of competitive swimmers and surf life savers would be superior when compared to that of other sportsman, given the nature and energy demands of their sports. The higher anaerobic power in SurfersCOMP, and similar anaerobic power in SurfersREC when compared to other aquatic competitive athletes may be associated with differences in ergometers used across studies, but suggests that surfing results in significant improvements in anaerobic power.

**Contribution of the aerobic and anaerobic energy systems to 30-s Wingate Anaerobic Test for paddling**

A larger AO₂ deficit in SurfersCOMP compared to SurfersREC in the present study suggests that SurfersCOMP had a larger contribution of anaerobic metabolism to the WAnT PADDLING test when compared to SurfersREC. Furthermore, the higher mean power achieved and therefore total work performed by SurfersCOMP compared to SurfersREC was most likely attributed to the larger contribution of anaerobic metabolism. A greater anaerobic contribution to the WAnT PADDLING in SurfersCOMP compared to SurfersREC is also supported by the higher Δ[La⁻] values observed in SurfersCOMP during the exercise bout. The ability for SurfersCOMP to produce more work anaerobically during maximal paddling suggests that SurfersCOMP may have a greater ability to produce energy anaerobically. An improved ability to produce work anaerobically may be associated with SurfersCOMP undertaking more periods of high-intensity paddling when compared to SurfersREC, either during a surfing session, or overall on a weekly basis. Approximately 60% of all paddling in a competitive surfing session consists of bouts lasting between 1 and 20 s (Mendez-Villanueva et al., 2006), suggesting that competitive surfers are required to undertake regular bouts of short-duration paddling during competition.
The \( \text{AO}_2 \) deficit values reported relative to body mass for Surfers\textsubscript{COMP} (32.80 ± 4.64 mL·kg\(^{-1}\)) and Surfers\textsubscript{REC} (27.28 mL·kg\(^{-1}\)) in the present study, are both significantly less than \( \text{AO}_2 \) deficit values for a 30-s WAnT cycling test in endurance-trained (50-60 mL·kg\(^{-1}\)) and sprint-trained (65-75 mL·kg\(^{-1}\)) track cyclists (Calbet \textit{et al.}, 2003). The higher \( \text{AO}_2 \) deficit values in the sprint-trained cyclists when compared to endurance-trained cyclists suggests the \( \text{AO}_2 \) deficit is a sensitive measure to identify differences in anaerobic performance and sprinting ability in athletes. Therefore, that the \( \text{AO}_2 \) deficit measures observed in Surfers\textsubscript{COMP} and Surfers\textsubscript{REC} in the present study appears to be a sensitive measure of a surfers sprinting or maximal-paddling ability and anaerobic power. The differences in the \( \text{AO}_2 \) deficit for a 30-s WAnT\textsubscript{PADDLING} compared to 30-s WAnT for leg cycling may be associated with the larger amount of work performed and active muscle mass involved in cycling when compared to arm cranking. To the best of our knowledge, the \( \text{AO}_2 \) deficit of a 30-s maximal paddling or arm-cranking has not been previously determined.

It is estimated that anaerobic metabolism provides 70-90% of energy utilisation throughout the a WAnT for leg cycling in male adults (Calbet \textit{et al.}, 1997; Parolin \textit{et al.}, 1999; Withers \textit{et al.}, 1991). Also, it is well known that the \( \text{AO}_2 \) deficit calculated during a 30-s WAnT does not reflect anaerobic capacity, as an individual’s maximal anaerobic capacity cannot be reached in 30 s of maximal exercise (Calbet \textit{et al.}, 1997; Medbo \textit{et al.}, 1988; Medbo & Tabata, 1989). However, during all-out leg cycling of at least 1 min in duration, the \( \text{AO}_2 \) deficit measured is related to an individual’s anaerobic capacity (Calbet \textit{et al.}, 1997; Medbo & Tabata, 1989). It is unclear what percentage of an individual’s anaerobic capacity for maximal paddling is used during a 30-s WAnT\textsubscript{PADDLING}, as to the best of our knowledge, the maximal \( \text{AO}_2 \) deficit for paddling has not previously been determined. Further research investigating the maximal \( \text{AO}_2 \) deficit of paddling in competitive and recreational surfers is needed to determine the anaerobic capacity in the two groups of surfers.
A higher anaerobic power, AO\textsubscript{2} deficit and ∆[La\textsuperscript{-}] in Surfers\textsubscript{COMP} compared to Surfers\textsubscript{REC} suggests that the anaerobic characteristics of a surfer may be a sensitive measure of surfing ability, or an important physiological characteristic for a competitive surfer. However, such conclusions cannot be drawn from this study alone as the inconsistency in peak power determined during maximal paddling observed in the present chapter and the previous chapters suggest that anaerobic power is also related to surfing experience and frequency. Significant correlations were found between \text{WAnT\textsubscript{PADDLING}} peak power and AO\textsubscript{2} deficit with surfing experience (yr surfing) and surfing participation frequency (surfing hr/wk). Further research investigating peak power for paddling, the AO\textsubscript{2} deficit, and anaerobic capacity in two groups of surfers of different surfing ability but similar surfing experience and frequency (i.e. competitive surfers of different competition standard or ranking) will help determine whether measures of anaerobic performance are a sensitive indicator of surfing ability.

**Concluding remarks**

The present study found that Surfers\textsubscript{COMP} have a greater anaerobic power during a 30-s \text{WAnT} for paddling on a stationary swim-bench ergometer compared to Surfers\textsubscript{REC}. A greater AO\textsubscript{2} deficit and ∆[La\textsuperscript{-}] in Surfers\textsubscript{COMP} compared to Surfers\textsubscript{REC} in the absence of any differences in aerobic power suggests that the proportion of extra work produced by Surfers\textsubscript{COMP} was due to a greater anaerobic contribution. Further peak power and AO\textsubscript{2} deficit were both correlated with surfing experience and frequency. Collectively these findings suggest that measures of anaerobic performance may be sensitive measure of surfing ability. However, as surfing experience and frequency was greater in Surfers\textsubscript{COMP} compared to Surfers\textsubscript{REC} it is unclear whether anaerobic power and the AO\textsubscript{2} deficit are characteristics necessary for high performance surfing or whether they are only a result of the increased surfing experience and frequency.
CHAPTER 5

SURFBOARD RIDING POPUP MANOEUVRE AND LEG POWER IN RECREATIONAL AND COMPETITIVE JUNIOR SURFERS
5.1 INTRODUCTION:

Surfboard riding (surfing) can be divided into three main tasks: i. Lying prone on the surfboard and paddling (paddling), ii. The motion of pushing up from a prone to standing position (popup), and iii. Standing on the surfboard and riding a wave (wave riding). Competitive surfing is judged on wave-riding performance only, and is associated with the manoeuvres performed by the surfer on their board along the face of the wave. Coaching practices in the sport of surfing typically focus on balance, and the fundamental movement patterns of the core manoeuvres necessary to successfully ride a wave and score well in competition. To date, there is a paucity of scientific research examining board paddling, and the popup (Mendez -Villanueva, 2005a).

The speed and/or technique of the popup manoeuvre may influence a surfer’s ability to initiate the correct surfing posture on the board, or to move to the best location on the wave to successfully perform the first manoeuvre. Yet, it is unclear whether the timing or techniques of a popup manoeuvre varies amongst surfboard riders (surfers) of different level of ability. Studies of the biomechanical behaviours of the lower extremity during take-offs and landings for different jumps focus on impact forces (Zhang, *et al.*, 2000) comparisons of landing techniques (Decita & Skellt, 1992) and optimum take-off techniques (Seyfarth *et al.*, 2003). The on-land measurement of the timing and ground reaction forces (GRF) of the popup for surfing may help to characterise the manoeuvre and identify if there are any differences between recreational and competitive surfers. In the present study we used an in-ground force plate to examine the repeatability of the popup in surfers and to determine any differences in the timing and magnitude of the GRF produced between junior male recreational and competitive surfers.

The judging criteria for competitive surfing states that to maximize scoring potential a surfer is to perform controlled manoeuvres, with speed and power (Association of Surfing Professionals, 2008). In a qualitative assessment of surfing manoeuvres,
Everline (2007) hypothesised that a surfer requires leg strength to keep the surfboard in the appropriate position during wave riding and to navigate the accelerating surfboard as it gathers velocity down the wave. However, leg strength or leg power has not been characterised during wave riding or investigated in surfers of any level of ability. It is reasonable to assume that leg power may be important to perform controlled manoeuvres, with speed and power. Maximal vertical jump height is accepted as a reliable and valid indicator of leg power (Thomas et al., 1996). In the present study we used an in-ground force plate to measure maximal vertical jump height under conditions replicating a surfing stance in male competitive junior male recreational and competitive surfers.

A series of surfing physiology studies by Mendez-Villanueva and colleagues (Mendez-Villanueva & Bishop, 2005a; Mendez-Villanueva et al., 2005b; Mendez-Villanueva et al., 2006) led to the hypothesis that board paddling may result in fatigue-induced impairments in motor skills necessary for subsequent wave riding. Indeed, the performance of a previously inactive muscle group can be changed due to metabolic disturbances from a previously active muscle group (Bogdanis et al., 1994; Bohnert et al., 1998; Karlsson et al., 1998; Yates et al., 1983). Therefore, upper-body board paddling performed immediately before the surfing popup manoeuvre might induce peripheral and/or central fatigue that could lead to perturbations in the upper- and lower-body and subsequently changes in motor performance during the popup and/or a reduction in leg power. In the present study we measured the performance of a surf popup and maximal leg power before and after a bout of intermittent paddling to gain a further understanding about the influence of paddling on other aspects of surfboard riding.

The first aim of the present study was to investigate the trial-to-trial and day-to-day reliability of the measurement of the timing and magnitude of the vertical GRF produced during a popup manoeuvre. The second aim was to measure and compare the
popup performance variables and maximal vertical jump height in a group of junior male recreational and competitive surfers. The third aim was to determine if 25 min of intermittent surfboard paddling, similar to that performed in a competitive heat, influences the popup manoeuvre and maximal vertical jump height in junior male recreational surfers.

5.2 MATERIALS AND METHODS

Subjects

Twenty junior male recreational surfers and ten junior male competitive surfers volunteered to participate in the present study. Each participant had been surfing at least 2 d per wk and for at least 4 yr. The competitive surfers were competing at a state or national level for at least two years. The study was approved by the Griffith University Human Research Ethics Committee and written informed consent was obtained from each subject, as well as from their parental guardian if they were under 18 yr of age, before they were accepted as a subject. Body mass, standing height, sitting height, and arm span were all measured using methods and equipment previously described (Fredriks et al., 2005; Golshan et al., 2007). Briefly, body mass was measured before testing commenced, subjects were wearing shorts and no shirt with shoes off. Standing height was measured using a wall mounted stadiometer with subjects standing against the wall with no shoes on. Sitting height was also measured using a wall mounted stadiometer with subjects sitting against the wall on a 50-cm wooden box; 50 cm was taken from the total measured height. Arm span was measured from tip-to-tip of the middle fingers with hands maximally outstretches and palms facing out, while standing against a wall with no shoes on. All measurements were recorded to the nearest millimetre. Sitting height:height ratios and arm span:height ratios were calculated for all subjects. Each surfer was required to fill out a survey to determine their surfing experience (i.e., number of years surfing and number of sessions and hours surfing per
week), participation in dry-land training (i.e., frequency and duration of endurance and/or strength training) and participation in competitive surfing events (event/yr).

**Experimental design**

The twenty male recreational junior surfers and ten male competitive junior surfers were assigned into three groups of ten. Ten recreational surfers (Surfers_{REL}) were asked to perform two days of reliability testing for the assessment of the timing and magnitude of the vertical GRF’s produced during a popup manoeuvre and vertical jump (VJ) height on a force plate. Following reliability testing ten competitive surfers (Surfers_{COMP}) participated in one day of testing to measure the popup manoeuvre and VJ height. Ten recreational surfers (Surfers_{REC}) participated in three testing days to measure the popup and VJ height and determine if 25 min of intermittent surfboard paddling influences the popup and VJ height. (See Figure 5.1 for a schematic of the experimental design).
Figure 5.1 Schematic of the experimental design. SurfersREL = recreational surfers assigned to reliability testing; SurfersCOMP = competitive surfers; SurfersREC = recreational surfers.

Warm Up

Each day of testing commenced with a pre-test warm up consisting of 5 min of light-intensity paddling and three, 5-s paddling sprints performed on the swim-bench ergometer. The warm-up paddle was followed by 4-6 practice bouts of the popup and VJ, each practice was separated by at least 1-min rest. The pre-test warm up was also used as familiarisation of the popup and maximal VJ. Following the warm up, the surfers sat quietly for 20 min to ensure that they were fully recovered before testing commenced. All testing was performed at, or as near as possible, to the same time of day, with each of the three days of testing for SurfersREC separated by 48 to 72 h.

Experimental equipment

The biokinetic swim bench previously used and described in the previous three studies was used. A biokinetic swim bench is not isotonic or isokinetic as the force and velocity of the arm pulling is not constant at a predetermined setting (Sharp et al., 1982). A
biokinetic swim bench has previously been described as a semi-accommodating resistance device which can be preset to a regulation speed that provides a constant amount of acceleration in proportion to the force applied by the user (Sharp et al., 1982). The swim-bench ergometer consisted of hand paddles attached to two pull-ropes that induce rotation of the isokintec resistance device. The external power output of each separate arm pull is determined by two force transducers on each hand pulley that measure tensile force, distance and force duration. When force is applied to the hand paddles, the pull-rope pays out a velocity which ranges up to maximum, termed the maximum pull velocity (MPV). The resistance unit on the swim-bench provided seven MPV settings. Power output is calculated and continuously feedback to the subject via a digital display unit. The paddling ergometer was calibrated prior to testing using methods previously described (Sharp et al., 1982). The ideal MPV setting for testing and the reliability of the swim ergometer has previously been tested in our laboratory (Chapter 2).

**Testing Day 1: Popup manoeuvre and maximal vertical jump**

Testing Day 1 was identical for SurfersREL, SurfersREC and SurfersCOMP, consisting of the measurement of the popup maneuver and maximal VJ height. The popup manoeuvre consisted of the surfer lying prone on an inground force plate (Kistler, Model 9287, Wintethur, Switzerland, 1000 hz) and moving quickly to a crouched surfing stance (Figure 5.2). When lying supine the surfers had the lower half of their legs off the force plate (Figure 5.2a). The initial GRF (when lying supine) was determined for each test to ensure that the surfers were lying on the force plate in a similar position, with the same mass on the force plate each trial. The VJ was performed 2-3 s immediately after the popup within the same test. The popup and VJ were performed in the same test to mimic the movements performed during surfing where the surfer moves from a board paddling position to a standing position, which is then followed by a powerful turn using the legs. The maximal VJ height was used as a measure of leg power. The VJ was
performed from the surfing stance (in a crouched position, figure 5.2b) immediately after the popup without the surfers repositioning their feet and with a preparatory bounce (counter movement). Surfers were instructed to jump maximally and to keep their trunk straight and not flex at the knees after the take-off (Figure 5.2c) and land back on the force plate in a stable crouched position. The surfers were instructed to perform the task as close as possible to that performed in the surf, with maximal intensity and effort. The surfers undertook 8-10 min of rest between each of the trials. Day 2 of testing for SurfersREL were procedures identical to Day 1. SurfersCOMP participated in no further testing after the Day 1 procedures.

Figure 5.2 Example of a recreational surfer performing popup test on the force plate, followed ~3 s later by a maximal vertical jump. a. prone position, b. surfing stance, c. vertical jump

The vertical GRF was measured during the popup and VJ. Five main variables investigated in the popup manoeuvre include: i. Initial GRF: the average GRF of surfers lying supine on the force plate, measured over 50 milliseconds, ii. Push-up peak force: the peak GRF during upper-body push up phase of the popup, iii. Push up rate of force development: the difference
between push-up peak force and initial GRF, over the difference between the time of the start of the manoeuvre to the time at which push-up peak force occurred i.e. (push-up peak force – initial GRF)/(start time – time of push-up peak force), iv. Landing peak force: peak GRF during the landing phase of the popup, and v. Total time: the time from the start of the manoeuvre to the end of the manoeuvre. Figure 5.3 provides an illustration of each of these variables.

Figure 5.3 Vertical ground reaction force (GRF) over time in milliseconds during a surf popup manoeuvre followed by a maximal vertical jump performed on an inground force plate. Values presented are an example of one competitive surfer. i. Initial GRF ii. Push up peak force, iii. Push up rate of force development iv. Landing peak force and v. Total time, and vi. Time in the air of the vertical jump.
The vertical GRF data was entered into custom designed software (using Visual Basic 6.3) to determine the five pop variables (i. Initial GRF, ii. Push up peak force, iii. Push up rate of force development, iv. Landing peak force, and v. Total time). The start and finish point of the popup were determined individually and identified visually; the start of the popup was taken as the point at which the GRF visually moved away from a steady value and the end taken as the point at which GRF moved back to a steady value. The five popup variables were then calculated by the custom design software which determined maximum values (single value) and the times at which the maximum occurred. All popup force variables were presented relative to body weight (BW) where body weight = mass (kg) × gravity (9.81 m/s²). The flight time ($T_{\text{air}}$) from the VJ was determined as the period over which GRF was zero. Vertical takeoff velocity ($V_v$) of the centre of gravity was calculated ($V_v = \frac{1}{2} \times T_{\text{air}} \times g$), where $g$ is the acceleration of gravity (9.81 m/s²) and jump height ($H_t$) computed as $H_t = V_v^2 \times (2g)^{-1}$ (Komi and Bosco, 1978). The data analysis was performed in a random order for all trials, as research has shown that the visual determination of start or finish points on a specific graph can be reliably determined with no bias if a random order of trials is used (Hodges et al., 2000).

**Testing Day 2 (SurfersREC): 10-s maximal paddling test to determine peak power for paddling**

Day 2 of testing for SurfersREC consisted of a 10-s maximal-paddling test to determine peak power of paddling. Peak power of paddling was used to calculate the power outputs for the work stages of the 25-min paddling protocol performed on day 3 of testing (Figure 5.4). The determination of peak power during a 10-s maximal-paddling test on the swim-bench ergometer is a reliable (day-to-day ICC r =0.995; Typical error <6% of mean values) method of assessing the short-term peak power for paddling in junior male surfers (Chapter 2). Subsequently, the warm up and methods used in the present study to determine the 10-s peak power of paddling were identical to those previously found in our laboratory (Chapter 2). Briefly a 5-min warm up was performed, consisting of 3-min light-intensity continuous
paddling, followed by a 30-s rest and three, 5-s sprints replicating the test start. The warm up
was followed by a 10-min rest. The test commenced with the surfer having both hands in the
paddles and their arms outstretched in front of them. The chief investigator then gave a 3-s
count down to ‘go’ at which time the surfer began alternate arm paddling at maximal effort.
The surfer was instructed to paddle maximally for the full 10 s and informed that they would
receive verbal encouragement throughout the test. Verbal encouragement went for 12 s
before the surfer was told to stop, to ensure that the surfer did not stop too early.

**Testing Day 3 (SurfersREC): The 25-min paddling protocol performed on the swim-
bench ergometer**

Day three of testing for SurfersREC consisted of 25 min of intermittent paddling on the swim-
bench ergometer (replicating a surf heat) followed immediately by one popup and VJ on the
force plate. The protocol for the 25 min of intermittent board paddling is presented in figure
5.4 and was based on the movement patterns reported for a competitive surfing session where
the total surfing time consisted of 44-51% board paddling, 35-42% stationary, 5% wave
riding and 2-16% miscellaneous activity (Mendez-Villanueva *et al.*, 2006). No wave riding or
miscellaneous activity was undertaken in the 25-min paddling protocol in the present study.
No previous study has reported the paddling intensity typically performed in a surfing heat or
recreational surfing session, only the maximal and mean heart rates (Meir *et al.*, 1991).
Therefore the relative percentages of 10-s peak power used for the paddling protocol (25% and
50%) were determined by pilot testing surfers paddling at random percentages of their 10-s
peak power whilst measuring their heart rate values. Paddling intensities of 25% and 50% of
10-s peak power produced heart rates similar or slightly higher than values reported for a
recreational surfing session (Meir *et al.*, 1991). Paddling intensities greater than 65% of 10-s
peak power were not used as many surfers found this too intense to complete the 25 min of
paddling.
Figure 5.4 The 25-min paddling protocol representing a competitive surfing heat previously reported to consists of 51% paddling and 42% sitting (Mendez-Villanueva et al., 2006).

Heart rate (HR) was continuously monitored during the 25-min paddling protocol by wireless portable electrode chest straps and watch monitors (Polar S410 Electro Oy, Finland). Second by second HR data was down-loaded onto a personal computer and peak HR and average HR taken as the maximum and mean HR values recorded during the 25 min of paddling. The peak and mean HR were measured to make comparisons with HR values observed during a recreational surfing session (Meir et al., 1991). Blood lactate concentrations ([La−]) were measured immediately prior to the start of the 25 min paddle and at 1-min post exercise from a drop of blood taken at the ear and using a Lactate Pro blood analyser (Arkray Factory Inc, Japan). The change in blood lactate concentration (Δ[La−]) from resting to 1-min post the popup and vertical jump following paddling was reported.
Statistics

Trial-to-trial reliability of the popup test was determined by calculating the intraclass correlation coefficient (ICC) between Trial 1 and Trial 2 on Day 1 of testing (i.e., between Day 1 Trial 1 and Day 1 Trial 2) for the five popup variables and VJ height in SurfersREL. Day-to-day reliability was determined by calculating the ICC values between Trial 1 performed on Day 1 of testing (Day 1 Trial 1) and Trial 1 of the popup and VJ performed on Day 2 testing (Day 2 Trial 1) for the five popup variables and VJ height. ICC’s are highly sensitive to heterogeneity of the sample of subjects (Hopkins, 2000), therefore the change in mean, typical error of measurement were also determined to closely investigate the reliability of the two testing methods (Hopkins, 2000). All group data are reported as means±SD. The reliability of the three trials of the popup and VJ for SurfersCOMP and SurfersREC were also confirmed by significant ICC values across all three trials for the five popup variables and VJ. Once reliability was confirmed, the three trials of each popup variable and VJ height were averaged and comparisons made between SurfersCOMP and SurfersREC using independent t-tests. Independent t-tests were also used to test for differences in surfing experience (yr surfing), surfing frequency (hr surfing per/wk and sessions surfing per/wk) and physical characteristics between SurfersREC and SurfersCOMP. For SurfersREC paired samples t-tests were used to make comparisons between Day 1 non-paddle values for all five popup variables and VJ height (no paddling) and the post-paddle variables (paddling) from Day 3 of testing. A paired sample t-test was used to determine changes in HR and blood [La–] from resting compared to 1-min post exercise. Statistical significance for all tests was accepted at P < 0.05.
5.3 RESULTS:

Reliability Testing

Significant ICC values were observed for the trial-to-trial and day-to-day comparisons of each of the five popup variables and VJ height (Table 5.1). The group mean for all change in mean values (% of the mean) was 0.3 % (range - 7.1 to 4.9 % of the mean) and the group mean for all typical error scores (% of the mean) was 5.2 % (range 1.2 % to 15.5 % of the mean) for both trial-to-trial and day-to-day comparisons.

Table 5.1 Intraclass correlation coefficients (ICC) for five variables of eight trials of a popup manoeuvre and vertical jump performed on a force plate.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Trail-to-trial (Day 1 Trial 1 – Day 1 Trial 2)</th>
<th>P Value</th>
<th>Day-to-day (Day Trial 1 – Day 2 Trial 1)</th>
<th>P value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial GRF</td>
<td>0.782</td>
<td>0.042</td>
<td>0.878</td>
<td>0.005</td>
</tr>
<tr>
<td>Push Up Peak GRF</td>
<td>0.956</td>
<td>&lt;0.001</td>
<td>0.849</td>
<td>0.005</td>
</tr>
<tr>
<td>Push Up RFD</td>
<td>0.971</td>
<td>&lt;0.001</td>
<td>0.982</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Landing Peak GRF</td>
<td>0.965</td>
<td>&lt;0.001</td>
<td>0.945</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Total Time</td>
<td>0.914</td>
<td>0.001</td>
<td>0.914</td>
<td>0.002</td>
</tr>
<tr>
<td>VJ Height</td>
<td>0.936</td>
<td>&lt;0.001</td>
<td>0.921</td>
<td>0.001</td>
</tr>
</tbody>
</table>

Eight trials were performed over two separate days. Trial-to-trial reliability (Day 1 Trial 1 vs. Day 1 Trial 2) and day-to-day reliability (Day 1 Trial 1 vs. Day 2 Trial 1) are both presented. Values presented are the average measures from comparisons between trials. ICC: Intraclass correlation coefficient; GRF: ground reaction force; RFD: rate of force development; VJ = vertical jump. All values are significantly correlated (P<0.05).
Physical characteristics and surfing history

There were no significant differences in the mean age of Surfers\textsubscript{REL} (19 ± 2 yr), Surfers\textsubscript{REC} (17 ± 1 yr) and Surfers\textsubscript{COMP} (17 ± 1 yr). Surfers\textsubscript{REC} were significantly taller when compared to Surfers\textsubscript{COMP}, but there were no other significant differences between the two groups for all other physical characteristics (body mass, sitting height and arm span) as presented in table 5.2. The age (19 ± 1 yr) and physical characteristics (178.3 cm, 72.1 kg) of Surfers\textsubscript{REL} were not significantly different to Surfers\textsubscript{REC}. Arm span, sitting height and surfing experience and surfing frequency were not measured in Surfers\textsubscript{REL}. Surfing experience was greater in Surfers\textsubscript{COMP} who had been surfing three yr longer, 12 hr more per week, seven more surfing sessions per wk when compared to Surfers\textsubscript{REC}. Surfers\textsubscript{COMP} competed in more (t = -9.000, P < 0.001) surfing events per year when compared to Surfers\textsubscript{REC} (20 ± 6 per/year; 3 ± 6 per/year, respectively).
Table 5.2 Physical characteristics, surfing experience, surfing frequency and participation patterns of recreational (Surfers\textsubscript{REC}) and competitive (Surfers\textsubscript{COMP}) male surfers.

<table>
<thead>
<tr>
<th></th>
<th>Surfers\textsubscript{REC} (n = 8)</th>
<th>Surfers\textsubscript{COMP} (n = 8)</th>
<th>t score; p value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Body Mass (kg)</td>
<td>68.2±6.2</td>
<td>62.9±9.9</td>
<td>1.880, 0.076</td>
</tr>
<tr>
<td>Height (cm)</td>
<td>178.9±4.6</td>
<td>172.1±8.2</td>
<td>2.986, 0.008</td>
</tr>
<tr>
<td>Sitting height (cm)</td>
<td>91.4±3.4</td>
<td>90.1±4.4</td>
<td>1.405, 0.177</td>
</tr>
<tr>
<td>Arm span relative to height (%)</td>
<td>103.0±1.8</td>
<td>103.0±3.2</td>
<td>-0.193, 0.849</td>
</tr>
<tr>
<td>Surfing experience (yr)</td>
<td>6.3±2.3</td>
<td>8.7±2.5</td>
<td>-2.407, 0.027</td>
</tr>
<tr>
<td>Total surfing duration (h/wk)</td>
<td>7.7±1.6</td>
<td>19.5±4.9</td>
<td>-7.328, &lt;0.001</td>
</tr>
<tr>
<td>Surfing frequency (session/wk)</td>
<td>5.4±1.7</td>
<td>11.6±2.6</td>
<td>-6.547, &lt;0.001</td>
</tr>
<tr>
<td>Total dry-land training duration (h/wk)</td>
<td>1.7±1.4</td>
<td>2.6±1.4</td>
<td>-7.328, &lt;0.001</td>
</tr>
<tr>
<td>Dry-land training frequency (session/wk)</td>
<td>1.6±0.8</td>
<td>2.7±1.6</td>
<td>-1.588; 0.130</td>
</tr>
</tbody>
</table>

All values are mean±SD. Surfing experience = number of years surfing on average, Surfing frequency = number of sessions surfing per week on average. *Significantly different at p < 0.05.
Popup and maximal vertical jump (VJ) height

There were no differences in the five popup variables as presented in table 5.4 and VJ height (figure 5.5) between Surfers\textsubscript{REC} and Surfers\textsubscript{COMP}. Further, there was no change in the five popup variables following the 25-min paddle, when compared to testing with no pre paddle. However, VJ height decreased significantly ($t = 4.553$, $p = 0.001$) following the 25-min paddle in Surfers\textsubscript{REC} when compared to VJ height with no pre-paddle (figure 5.5). There was a significant increase in HR ($t = -18.279$, $p = <0.001$) during the 25-min paddle from a resting HR of $73 \pm 15$ bpm to a peak HR of $175 \pm 14$ bpm. Mean HR for the 25-min paddle was $135 \pm 15$ bpm. Blood [La⁻] also increased significantly ($t = -8.333$, $P < 0.001$) from resting ($1.3 \pm 0.3$ mmol/L) to 1 min post exercise ($6.6 \pm 1.7$ mmol/L) with a $\Delta$[La⁻] of $5.0 \pm 2.6$ mmol/min.

Table 5.3 Five variables of a popup manoeuvre performed on a force plate in junior male recreational (Surfers\textsubscript{REC}) and competitive (Surfers\textsubscript{COMP}) surfers without prior paddling (no paddling), and in the same group of recreational surfers following 25 min of board paddling (paddling).

<table>
<thead>
<tr>
<th></th>
<th>Surfers\textsubscript{COMP}</th>
<th>Surfers\textsubscript{REC} No paddling</th>
<th>Surfers\textsubscript{REC} Paddling</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial GRF (BW)</td>
<td>0.76±0.04</td>
<td>0.75±0.83</td>
<td>0.73±0.07</td>
</tr>
<tr>
<td>Push up peak GRF (BW)</td>
<td>1.18±0.11</td>
<td>1.13±0.11</td>
<td>1.16±0.11</td>
</tr>
<tr>
<td>Push up RFD (BW/ms)</td>
<td>0.003±0.002</td>
<td>0.002±0.001</td>
<td>0.002±0.002</td>
</tr>
<tr>
<td>Landing peak GRF (BW)</td>
<td>1.56±0.16</td>
<td>1.66±0.31</td>
<td>1.57±0.34</td>
</tr>
<tr>
<td>Total Time (ms)</td>
<td>1.44±0.64</td>
<td>1.37±0.95</td>
<td>1.45±0.23</td>
</tr>
</tbody>
</table>

Values are the group means±SD of the average of three trials, except for Surfers\textsubscript{REC} Paddling which consisted of only one trial. GRF; vertical ground reaction forces normalised to body weight (BW).
Figure 5.5 Maximal vertical jump height in recreational surfers (Surfers\textsubscript{REC}) and competitive surfers (Surfers\textsubscript{COMP}). Paddle\textsubscript{REC} = maximal vertical jump height in the same group of recreational surfers following 25 min of board paddling. Values are the group means±SD of the average of three trials, except for Paddle\textsubscript{REC} which consisted of only one trial. * Significantly different to other two measures (t=4.553, p=0.001).
5.4 DISCUSSION

The present study found that the measurement of the timing and magnitude of the vertical GRF’s of a popup manoeuvre and maximal VJ height on a force plate were reliable from trial-to-trial and day-to-day in surfboard riders. Furthermore, we found that there were no differences in the timing and magnitude of the vertical GRF of the popup or maximal VJ height between junior male recreational and competitive surfers. Vertical jump height however, was reduced following 25 min of intermittent surfboard paddling in recreational surfers. There was no change in the popup variables following 25 min of paddling. These findings suggest that in recreational surfers board paddling may influence lower body performance in the wave riding component of surfing.

Characterisation of surf popup manoeuvre

The peak vertical GRF produced during the push up phase of the popup manoeuvre by Surfers\textsubscript{COMP} (1.18 ± 0.11 BW) and Surfers\textsubscript{REC} (1.13 ± 0.11 BW) are less than vertical GRF’s produced during other sports movements. For example, the initial push up phase of the popup is much less than peak vertical GRF’s produced by gymnasts (2.38 ± 0.26 BW) during the round-off phase of the Yurchenko vault (Seely & Bressel, 2005). The GRF of the push up phase of the popup may be less than values reported for other sports movements because the total body mass of the surfers was not on the force plate. More accurate comparisons can be made between other sports for the landing phase of the popup where the total mass of the surfer was on the force plate. The peak GRF of the landing phase of the popup for Surfers\textsubscript{COMP} (1.56 ± 0.16 BW) and Surfers\textsubscript{REC} (1.66 ± 0.31 BW) are less than that for sports specific landings in gymnastics (3.0 to 5.0 BW) (McNitt-Gray \textit{et al.}, 1994) and volleyball (1.7 ± 0.5 BW) (Cronin \textit{et al.}, 2008). The push off peak GRF and landing peak GRF closely match the vertical GRF forces produced during walking at 1.0 to 3.0 m.s\textsuperscript{-1} (1.0 to 1.5 BW) (Nilsson & Thorstensson, 1989) suggesting that the vertical GRF of the landing of a popup is relatively small.
Maximal vertical jump (VJ) to determine leg power

There were no significant differences in the VJ height between SurfersREC and SurfersCOMP. However, VJ height of both SurfersCOMP (40.0 ± 9.2 cm) and SurfersREC (38.2 ± 4.7 cm) is larger than values reported for physically active men (30 ± 5 cm, 24.5 ± 4.3 yr) (Urinowitsch et al., 2007) and similar to that of power athletes well trained in track and field jumping and sprint events (40 ± 5cm, 24.5 ± 4.3 yr) (Urinowitsch et al., 2007), using similar testing methods. Further, the VJ height of both SurfersREC and SurfersCOMP are similar to age and gender matched international volleyball players (42.8 ± 2.5 cm) (Stanganelli et al., 2008) and international basketball players (40.1 ± 3.7 cm) (Apostolidis et al., 2004) who also measured VJ height from flight time in the air. It is reasonable to suggest that the leg power of track and field power athletes, elite volleyball players and basketball players would be among the highest of any sportsman given the nature of their sports. The similar mean VJ height observed in the present study for SurfersCOMP as well as SurfersREC when compared to elite track and field athletes, volleyball players and basketball players suggest that both recreational and competitive surfing requires a substantially high level of leg power, presumably for wave riding and turning manoeuvres. These findings suggest that leg power may be an important physical characteristic for all levels of surfing (e.g., beginner, recreational and competitive). Also, a simple VJ test may be a useful test to monitor changes in leg power with surf specific training or when recovering from injury.

Influence of the 25-min paddling bout on the popup GRF’s and VJ height

The 25 min of paddling did not influence the popup manouvre variables in SurfersREC. However, there was a significant decrease in SurfersREC VJ height (pre-paddling = 38.2 ± 4.7 cm, post-paddling 34.0 ± 5.1 cm) following the 25 min of paddling, indicating that the prior paddling had a negative influence on leg power. It is unclear what mechanisms are associated with a decrease in performance of a previously inactive muscle group following a period of
exercise in another muscle group. Changes in metabolic properties such as elevated blood [La\(^{-}\)] (Bogdanis \textit{et al.}, 1994; Yates \textit{et al.}, 1983) and/or neuromuscular components associated with muscle contractile properties (Bohnert \textit{et al.}, 1998) have previously been suggested to have a dominant effect on changes in performance of a previously inactive muscle group. A significant increase in blood [La\(^{-}\)] and HR were observed during the 25-min of paddling. The group mean values for maximal and average HR during the 25-min paddle were similar to HR values reported for ex-competitive surfers during a one hr recreational surfing session (max = 171 ± 8 bmp, mean = 135 ± 7 bpm) (Meir \textit{et al.}, 1991). However, the paddling intensity performed and HR’s achieved during a competitive surfing heat are unknown, so it is unclear if the paddling intensities of the 25-min paddle in the present study resulted in similar physiological responses to a 25-min competitive heat.

The VJ performed in the present study included a countermovement immediately preceding the popup, which involved a rapid semi-squat movement prior to jumping vertically; (Asmussen & Bond-Petersen, 1974). Muscle activation-contraction coupling and body-segment coordination are important characteristics of the countermovement and ensure that stored elastic energy is converted into positive energy for the VJ (Voigt \textit{et al.}, 1995). Both muscle activation-contraction coupling (Rozzi \textit{et al.}, 1999) and VJ segment coordination (Rodacki \textit{et al.}, 2002) are impaired following a period of moderate to high-intensity lower-body exercise. It is possible that a reduction in VJ height following upper-body exercise (i.e., paddling) in the present study may be associated with impairments in muscle activation-contraction coupling or the body segment coordination in the lower-body necessary for a successful VJ. The measurement of muscle activation-contraction coupling or segment coordination during a VJ following a period of paddling is necessary to make any scientific conclusions.

It is important to note that the popup on the force plate is a closed skill unlike a popup performed in the surf which is influenced by many outside variables, many of which are highly variable e.g., surfboard and wave movement. However, the laboratory-based protocol
and methods used in the present study were designed to gain further understanding about the timing and magnitude of vertical GRF produced during the popup to help develop concepts for future research. Further, SurfersCOMP in the present study did not undertake the 25-min paddling testing. It is necessary to consider that SurfersREC may not be familiar with the movement patterns and intensities of paddling in a competitive heat. Future research investigating leg power in competitive surfers after 25 min of paddling would provide further knowledge about the influence of board paddling on leg power in competitive surfers.

Concluding Remarks

There were no significant differences in the popup GRF variables or maximal VJ height between SurfersREC and SurfersCOMP. Further research is needed looking at horizontal as well as vertical GRF during the popup in a larger group of surfers to draw any conclusions about non-significant trends in the data. Both SurfersREC and SurfersCOMP had relatively high leg power, suggesting that leg power is an important characteristic for both recreational and competitive surfing. Therefore, maximal VJ height may be a simple measure to assess lower body power for surfing or monitor changes during surf specific training. The primary finding of the present study was a decrease in VJ height in SurfersREC following 25 min of intermittent surfboard paddling. These findings suggest that a period of paddling may influence the performance of the previously inactive lower body and possibly influence subsequent wave-riding performance in SurfersREC. The mechanisms associated with a decrease in leg power following board paddling are unclear, possibly associated with impairments in muscle activation-contraction coupling or the body segment coordination due to fatigue.
CHAPTER 6

DISCUSSION AND CONCLUSIONS
6.1 SUMMARY OF THE FINDINGS

Time motion analysis and HR assessment during recreational and competitive surfing sessions suggest that both the oxidative and non-oxidative energy systems are important for surfing (Mendez-Villanueva et al., 2006; Meir et al., 1991). The assessment of endurance performance for paddling (Chapter 3) and short-duration high-intensity paddling (Chapter 4) in recreational and competitive surfers provides a greater understanding of the importance of the oxidative and non-oxidative energy systems to surfing performance. Previous studies have established an exercise protocol for the assessment of endurance performance (i.e., peak aerobic power) for paddling (Lowdon et al., 1989; Mendez-Villanueva et al., 2005b). However, Chapter 2 in the present thesis was the first study to assess the reliability of a short-duration high-intensity paddling test for the subsequent determination of maximal-paddling performance.

Knowledge of peak aerobic power for paddling and paddling efficiency as well as the maximal-paddling power of recreational and competitive surfers provides a greater understanding of the energy systems in relation to surfing experience and participation patterns. Nevertheless the relationship between paddling performance and wave-riding ability has not been previously examined. Chapter 5 in the present thesis begins to examine the relationship between paddling ability and wave-riding by determining the effect of paddling on the “popup manoeuvre”. The research findings are valuable for surf coaches, sports scientists and health professionals, to help design surf-specific fitness training programs and monitor changes in paddling performance with training or following injury.

Study 1 of the present thesis aimed to develop “Two reliable protocols for assessing maximal-paddling performance in surfboard riders” (Chapter 2). Peak power achieved during a 10-s maximal-paddling test performed in the laboratory on a swim-bench
ergometer was found to be reliable in surfers. For a field-based test, peak velocities measured during a 10-s maximal-paddling test in a swimming pool, performed on the surfers own surfboard was a reliable method to measure of maximal-paddling performance in the water whilst kicking and paddling or paddling only. The development of a reliable lab-, and field-based test for the assessment of short-term power output for paddling in surfboard riders has provided new tools and methods to undertake further research in this area.

**Study 2** ‘Peak aerobic power and paddling economy in recreational and competitive junior surfers’ (Chapter 3) measured aerobic performance during an incremental paddling test to exhaustion. There were no differences observed between SurfersREC and SurfersCOMP for peak O\textsubscript{2} uptake and paddling economy and no significant correlations between surfing experience (yr surfing) and surfing frequency (sessions surfing per/wk) with peak O\textsubscript{2} uptake and paddling economy. The findings suggests that peak O\textsubscript{2} uptake and paddling economy are not sensitive measures of surfing ability, experience and participation frequency in junior surfers. A higher blood ∆[La\textsuperscript{-}] in SurfersREC when compared to SurfersCOMP was observed during submaximal constant load paddling suggesting it is possible that the blood lactate threshold may be a more sensitive determinant of surfing ability than measures of peak O\textsubscript{2} uptake.

The ‘Maximal-paddling performance in recreational and competitive junior surfers’ was investigated in **Study 3** (Chapter 4). Peak power, mean power and ∆[La\textsuperscript{-}] measured during a 30-s Wingate anaerobic test for paddling (WAnT\textsubscript{PADDLING}) were all significantly higher in SurfersCOMP compared to SurfersREC. The anaerobic contribution to the WAnT\textsubscript{PADDLING}, measured as the accumulated O\textsubscript{2} deficit (AO\textsubscript{2} deficit) was also greater in SurfersCOMP than SurfersREC. Anaerobic power and AO\textsubscript{2} deficit were both highly correlated to surfing experience and frequency. Peak O\textsubscript{2} uptake during incremental paddling to exhaustion and paddling economy were also determined and values were consistent with Study 2 (Chapter 3). There were also no differences
between Surfers\textsubscript{REC} and Surfers\textsubscript{COMP} and peak O\textsubscript{2} uptake and paddling economy were not related to surfing experience and frequency.

While peak aerobic power and paddling economy might not be sensitive determinant of surfing ability, we hypothesised that prolonged paddling performed before wave-riding might generate fatigue and influence wave-riding performance. More specifically, board paddling may result in fatigue-induced impairments in motor skills necessary for the popup and subsequent wave riding. \textbf{Study 4} (Chapter 5) set out to investigate the ‘\textit{Surfboard riding popup manoeuvre and leg power in recreational and competitive surfers}’, and the influence of board paddling.

The timing and magnitude of the vertical ground reaction forces of the surf popup in Surfers\textsubscript{REC} was not different following 25 min of paddling. However, a significant decrease in maximal vertical jump height was observed following the 25 min of paddling, suggesting that leg power is reduced by a bout of surf paddling. A reduction in leg power may also influence wave-riding performance as it is likely that leg power is necessary to perform successful surfing manoeuvres on the board along the face of the wave. Further research is needed to draw any scientific conclusions about the relationships between paddling and the popup manoeuvre and leg power and wave-riding performance.

The four experimental chapters in this thesis began by developing new testing methods and protocols to test physiological characteristics never before investigated in recreational and competitive surfers. The results from the first three studies suggest that maximal-paddling performance and anaerobic power may be more sensitive measures of surfing ability than features of aerobic performance (economy and peak O\textsubscript{2} uptake). However, from the findings alone, it cannot be concluded that anaerobic characteristics are more important for surfing performance than aerobic characteristics. Specifically, it appears that both recreational and competitive surfers have a higher than normal peak
O$_2$ uptake when compared to untrained populations and other upper-body trained athletes, suggesting that aerobic power is an important physiological consideration for surfing of any level.

The fourth and final study investigated possible relationships between surf-paddling and wave-riding. No previous scientific research has investigated wave-riding performance in surfers; as such there are no known scientific methods of measuring wave-riding performance in surfers. The fourth study set out to develop methods of assessing the pop-up phase of wave-riding and determine if a bout of 25-min paddling influenced pop-up performance or maximal vertical jump height. Although no significant differences were observed in the timing and ground reaction forces of the pop-up following paddling, maximal vertical jump height decreased significantly. A decrease in maximal vertical jump height following a bout of paddling indicates that surf-paddling can indeed influence subsequent lower body performance during wave-riding. The relationship between maximal vertical jump height (leg power) and wave-riding are unclear so no concrete scientific conclusions can be made. The development of methods of assessing lower body performance during surfing and further research in this field is necessary to gain further understanding about the scientific relationships between paddling and wave-riding.

6.2 FURTHER CONSIDERATIONS AND FUTURE RESEARCH

This thesis has provided scope for further avenues of surfing research to be explored. The main limitations, recommendations and future research opportunities of each of the 4 studies have been specifically addressed in the discussion of each study chapter in the thesis. The following section will reiterate such considerations and discuss recommendations and future research questions that have come into view following the completion of this thesis.
Sensitive measures of surfing ability

Unlike other individual competitive sports (e.g., swimming, surf lifesaving) that have standard measures of performance (e.g., time), there are no reported reliable or valid scientific measures of surfing ability. Movement patterns, heart rates, metabolic responses and blood variables during surfing or surf-related movements can all give an indication of the physiological demands of surfing with the results used as an indication of performance. Ultimately, the identification of a simple, reliable and valid test that is related to surfing ability would be a highly valuable piece of information for surf coaches and sports scientists for talent identification and monitoring performance.

The development of reliable protocols for assessing paddling performance in Study 1 revealed limitations that are associated with field-testing. The dimensions and volume of the surfboard and the height and weight of the surfer greatly influence the velocity of the board and the surfer paddling through the water. This variable was not controlled for in Study 1 and so no accurate comparisons between surfers or between the field-testing results and laboratory-testing results could be made. For future field-tests that wish to make comparisons between surfers or validate peak power achieved on the swim-bench ergometer, it is recommended that the dimensions and volume of the board relative to the size and mass of the surfer paddling is controlled.

The popup maneuver that was tested within the laboratory was a closed skill task, unlike the maneuver performed in the surf which is influenced by many uncontrolled variables. When a popup is performed on a surfboard in the surf (figure 1.2a and 1.2b, Chapter 1), the board is sitting on the water moving at various velocities and slopes down the face of the wave. Testing on an in-ground force plate does not take into consideration the motion of the board into the water as the surfer exerts force on it to popup. Further, it is important to consider that in laboratory testing a portion of the surfers legs were on the ground, unlike surfing where they would be in the water, and that in the laboratory a
portion of the surfer’s legs were off the force plate when in a prone position. Having a portion of their legs off the force plate could influence the push-up ground reaction force of the popup if the surfers used their feet. The surfers were not instructed how to popup (i.e. not use feet) but instead to do what felt most natural and to repeat this each time. Such factors must be taken into consideration when designing future testing characterising the popup maneuver.

Future research on the forces exerted during a popup maneuver could be investigated by using force plates built into the deck of a surfboard to be used whilst surfing. Such equipment would provide a greater understanding about the upper- and lower-body forces exerted whilst wave riding and performing various maneuvers in different types of surf (e.g. size, speed, break type) or on different boards (e.g. short wide board vs. medium narrow board).

**Ranking a surfers ability**

Previous studies and the studies of this thesis have made comparisons between surfers according to competitive status or level of competition and season ranking (Mendez-Villanueva, 2005b). However, it is unclear whether a surfer’s level of surfing ability is represented by their competitive level or season ranking. Many recreational surfers may have the same level of surfing ability as a competitive surfer, but choose not to compete. Alternatively, there may be competitive surfers who choose not to compete at a higher level or who have low season ranking because they do not perform well during competition. These factors must be considered when making comparisons between competitive surfers of different levels of surfing ability or with recreational surfers. These factors were considered in the present study by recruiting only nationally competitive junior surfers.

**Surfing experience and frequency**
The findings of this thesis revealed that there is great variability of surfing experience and frequency within the recreational surfing population of junior male surfers. There is no literature available reporting the surfing participation patterns of recreational surfers so it is unclear whether the recreational surfers in the present study reflect a ‘typical’ recreational group of surfers. The recreational surfers recruited for this thesis had a minimum of 4 yr experience and minimum participation frequency of 2 d/wk. The inclusion of a maximum amount of surfing experience and maximum surfing frequency may have reduced the large spread in surfing experience and frequency observed in the recreational surfers recruited in this thesis.

It is unclear if the improved maximal-paddling performance in SurfersCOMP compared to SurfersREC in Study 3 were related to surfing ability or due to differences in surfing experience and surfing frequency. A study using SurfersREC and SurfersCOMP who have the same surfing experience and frequency may help to identify whether differences observed in paddling performance are mostly associated with surfing ability or surfing experience and frequency. Further, the measurement of paddling performance in various groups of recreational surfers with different levels of surfing experience and surfing frequency would provide an understanding of the influence of recreational surfing on the aerobic and anaerobic energy systems.

**Junior surfers**

The four studies of this thesis involved male surfers between 16 and 20 yr of age, which may have included both pubescent and post-pubescent males. Growth and maturation during puberty results in increased body size, changes in physical dimensions (height, percent body fat and lean muscle mss) and subsequently increases in strength, power and exercise capacity (Malina, *et al*., 2004). It is well accepted that chronological aging does not reflect biological aging or differences observed in rate of growth and maturation amongst individuals of the same age. Therefore to permit meaningful
comparisons between groups of adolescents, the age, gender and physical dimensions of each participant must be considered (Blimkie et al., 1998; Welsman et al., 1996; Weber et al., 2006). Therefore, to reduce the influence of different rates of growth and maturation of the junior surfers in the present study the age, height, sitting height, arm span and body mass were matched across the groups of recreational and competitive surfers. It is recommended that future research investigating surfers use post-pubescent individuals to make accurate comparisons with past surfing studies who used open aged surfers.

**Recruiting surfers**

The recruitment of competitive surfers is difficult due to their busy travel schedule of events and/or trips away to locate the best surf. In Study 4 there was an inability to recruit enough competitive surfers to travel to the research laboratory where the in-ground force plate was, for three separate days of testing. Subsequently the popup and leg power following 25 min of intermittent paddling was only tested in recreational surfers. Therefore, future research measuring the popup and leg power following 25 min of paddling in competitive surfers may help to identify if reductions in leg power following paddling are associated with surfing ability and/or surfing experience and surfing frequency. The development of simple testing equipment and methods that can be transported easily or performed near the beach is recommended when testing competitive surfers.

**Future research**

Possible future research associated with each of the four thesis studies was discussed in the discussion of each chapter and throughout this discussion. Other possible future research that the author has identified in the process of this thesis is briefly summarised in the following section.
Study 1: i. Comparisons of maximal-paddling performance in surfers of different age groups, genders, experience, participation frequency or board type typically surfed (e.g., short and wide board vs. short and narrow board), ii. Investigation of the influence of different paddling techniques on maximal-paddling performance, iii. Measurements of changes in maximal-paddling performance associated with injuries or during recovery from injuries, and iv. The monitoring of changes in maximal-paddling performance following different training interventions.

Study 2 and Study 3: i. The assessment of aerobic power, paddling economy, and short-term power output in junior male surfers of different age groups (14-16 yr, 16-18 yr and 18-20 yr) to determine possible changes in performance throughout puberty, ii. Measurement of aerobic and anaerobic power in recreational adult surfers to make accurate comparisons with open age competitive surfers in past studies, iii. Measurement of aerobic power and anaerobic power in recreational and competitive junior girls or adult women to determine any differences associated with gender, and iv. Measurement of aerobic power and anaerobic power for paddling in a non-surfing population to gain further understanding about the influence that surfing has on upper-body aerobic power and economy.

Study 4: i. Characterising the horizontal ground reaction forces during the popup on the force plate may be more sensitive than vertical ground reaction forces to determine differences between SurfersREC and SurfersCOMP, ii Synchronized video analysis of the popup maneuver to help characterise differences in SurfersREC and SurfersCOMP, iii. The design of equipment to measure upper- and lower-body forces produced whilst surfing, iv. measurements of other physiological performance measures (e.g. maximal-paddling performance, core-muscle strength) following periods of paddling, to help identify the influence of paddling on wave-riding performance, v. The assessment of the popup and leg power in various groups of surfers (e.g. age, gender, type of board surfed), and vi.
The assessment of the popup in beginner surfers to help identify better instructing techniques.

There is no scientific research investigating the psychology of surfing and the influence that cognitive processing and decision making has on surfing performance. Therefore, it is unclear how much a surfer’s ability to maintain focus and make accurate decisions in the surf influences their performance. It is reasonable to assume that a surfer’s ability to make quick and accurate decisions is important in competition, big wave surfing and also in long surfing sessions where fatigue may influence cognitive processes. Research exploring relationships between physiological characteristics, cognitive performance and surfing performance may be beneficial.

6.3 CONCLUSIONS

This PhD thesis has investigated paddling performance in junior male recreational and competitive surfers. A recent review of the surfing literature by Mendez-Villanueva & Bishop (2005a) revealed that it is unclear whether aerobic power is related to surfing ability in competitive surfers and that no previous research had measured aerobic power in recreational surfers. The author of this thesis recognised that in the review by Mendez-Villanueva & Bishop (2005a) and throughout the surfing literature there was no discussion about the anaerobic contribution to a recreational or competitive surfing session. Indeed, there had been no investigation of any anaerobic characteristics of surfers of any level of ability. This was surprising considering that ~60 of all paddling bouts in a competitive heat are between 1 and 20 s in duration. The first study in this thesis developed reliable surf-specific laboratory and field tests to measure maximal-paddling performance in surfers, and thus provides new methods to progress sports science research in this field.
The present research revealed that there were no significant differences in peak aerobic power and paddling economy between recreational and competitive junior surfers. There were also no significant relationships in aerobic power and paddling economy between surfing experience and participation frequency. To elucidate what the difference may be in determining performance beyond aerobic measures, anaerobic-paddling performance measures were investigated in Study 3. It was demonstrated that anaerobic power, change in blood lactate concentrations and the accumulated O$_2$ deficit of a 30-s maximal paddling test are greater in competitive surfers compared to recreational surfers. Collectively, these findings reveal that the measures of anaerobic performance are more closely related to surfing ability, surfing experience and participation frequency than measures of aerobic performance.

The characterisation of the popup manoeuvre and leg power in recreational and competitive surfers in study 4 revealed no significant differences in the timing and magnitude of ground reaction forces produced during a popup manoeuvre between Surfers$\text{REC}$ and Surfers$\text{COMP}$, or in Surfers$\text{REC}$ following 25 min of paddling. The primary finding was a decrease in maximal vertical jump height in Surfers$\text{REC}$ following 25 min of intermittent surfboard paddling, which suggests that a period of paddling may influence the performance of the previously inactive lower body and possibly influence subsequent wave-riding performance. The mechanisms associated with a decrease in leg power following board paddling are unclear, possibly associated with impairments in muscle activation-contraction coupling or the body segment coordination due to fatigue.

The main research outcomes of this thesis were: i. The development of two reliable protocols for assessing maximal-paddling performance, ii. The discovery that anaerobic-performance measures are most closely associated with surfing ability, surfing experience and surfing frequency than aerobic-performance measures, and iii. The discovery that 25 min of intermittent paddling can reduce leg power. The new protocols developed in this thesis and the greater knowledge provided about aerobic-
and anaerobic-paddling performance in recreational and competitive surfers has helped identify the long term physiological responses to recreational and competitive surfing, subsequently assisting surf coaches and sports scientists in the development of surf-specific training techniques.

**Perspectives**

The scientific findings from this thesis indicate that maximal-paddling ability is an important physiological characteristic for both recreational and competitive surfers. Study 2 and Study 3 in this thesis suggest that both recreational and competitive surfing of at least two to three sessions per wk results in a moderate to high level of aerobic power. However, it appears that additional surfing sessions per wk do not continue to improve aerobic power. It is reasonable to suggest that additional increases in aerobic power exceeding what is previously developed from regular surfing, may not result in further improvements in performance. On the contrary, Study 3 found that anaerobic power is higher in surfers of a competitive standard when compared to recreational surfers and that positive correlations exist between surfing sessions per wk and anaerobic power and other measures of anaerobic performance (accumulated O₂ deficit). Study 4 indicated that leg power is an important physiological characteristic for both recreational and competitive surfers and can be reduced following a period of paddling. Therefore, within the limitations of this PhD research it can be recommended that a substantial proportion of surf fitness training, for an intermediate to advanced surfer who is surfing regularly, includes exercises to improve maximal-paddling performance and leg power.
REFERENCES


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L·min⁻¹  liters per minute
LT  lactate threshold
m  meters
min  minutes
mL·kg⁻¹  millilitres per kilogram
mL·kg·min⁻¹  millilitres per kilogram per minute
mmol·kg⁻¹  millimoles per kilogram
mo  months
ms  milliseconds
m·s⁻¹  meters per second
O₂  oxygen
PCr  phosphocreatine
PPSurfPADDLING  peak power of surf paddling
s  seconds
SPL  sway path length
SurfersCOMP  competitive junior surf board riders
SurfersREC  recreational junior surf board riders
T_air  flight time
VO₂  oxygen uptake
VO₂peak  peak oxygen uptake
V_v  vertical take off velocity
VJ  vertical jump
W  watts
WAnT  wingate anaerobic test
WAnTPADDLING  surf paddling wingate anaerobic test
W·min⁻¹  watts per minute
yr  years