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Physiological Aspects of Surfboard Riding Performance

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Contents

Abstract

Surfboard riding (surfing) has experienced a 'boom' in participants and media attention over the last decade at both the recreational and the competitive level. However, despite its increasing global audience, little is known about physiological and other factors related to surfing performance. Time-motion analyses have demonstrated that surfing is an intermittent sport, with arm paddling and remaining stationary representing approximately 50% and 40% of the total time, respectively. Wave riding only accounts for 4–5% of the total time when surfing. It has been suggested that these percentages are influenced mainly by environmental factors. Competitive surfers display specific size attributes. Particularly, a mesomorphic somatotype and lower height and body mass compared with other matched-level aquatic athletes. Data available suggest that surfers possess a high level of aerobic fitness. Upper-body ergometry reveals that peak oxygen uptake ($\dot{V}O_{2peak}$) values obtained in surfers are consistently higher than values reported for untrained subjects and comparable with those reported for other upper-body endurance-based athletes. Heart rate (HR) measurements during surfing practice have shown an average intensity between 75% and 85% of the mean HR values measured during a laboratory incremental arm paddling $\dot{V}O_{2peak}$ test. Moreover, HR values, together with time-motion analysis, suggest that bouts of high-intensity exercise demanding both aerobic and anaerobic metabolism are intercalated with periods of moderate- and low-intensity activity soliciting aerobic metabolism. Minor injuries such as lacerations are the most common injuries in surfing. Overuse injuries in the shoulder, lower back and neck area are becoming more common and have been suggested to be associated with the repetitive arm stroke action during board paddling. Further research is needed in all areas of surfing performance in order to gain an understanding of the sport and eventually to bring surfing to the next level of performance.

Surfboard riding (surfing) is a popular sport enjoyed on the beaches of five continents at both the recreational and competitive level. The surfing action is to ride a surfcraft along the unbroken section or wall of a wave, as it inches closer toward the shore.[1] Modern surfing is performed using a foam and fibreglass board with the rider standing erect on his or her feet.

Surfing has experienced a meteoric growth over the last decade. The surfing industry has become a multi-million dollar worldwide business and surfing-related companies use elite surfers' images as an advertising call to their products. These companies offer higher level surfers good sponsorship contracts, normally based on their competitive performance. This attracts a large and increasing participation of young people, hoping to reach the highest competitive level. Moreover, surfing has become a common recreational sport, which is enjoyed by people of all standards.

Success at any level requires extremely high technical and skill abilities. However, to be competitive at the highest level, specific physiological attributes may also be important. Moreover, in a competitive plane, surfing has become a sport with year-round involvement. With the professionalisation of surfing, there has been an increased interest in the possible contribution of exercise science to overall surfboard riding performance. Despite the popularity of surfing, research about all aspects related to surfing performance is incredibly scarce. The aim of this article is to review physiological and physical characteristics of surfers, thereby presenting an overview of the sport, and to recommend future directions with regard to research into surfing physiology/performance.

1. Surfing Competition: Historical Development

Surfing is many centuries old, maybe millenniums. Historically, it was considered the sport of the Hawaiian kings, and only they could enjoy the pleasure of gliding over the waves. The birth of modern surfing is attributed to the Hawaiian Duke, Kahanamoku.[2] This exceptional aquatic sportsman, gold medal winner in the 100m free-style in the Olympic games of Stockholm 1912, devoted a lot of time to travelling all over Europe, Australia and the US performing surfing and swimming demonstrations. Since then, the popularity of surfing has been gradually growing.

The first surfing world championships took place in Australia in 1964.[2] Currently, many surfers participate in all levels of competition on the coasts of the five continents. Surfing governing bodies include the Association of Surfing Professionals (ASP), the International Surfing Association (ISA), each country's own surfing federation/association and surfing industry companies. However, recently, the ASP has made a great effort in assuming a leading role as the major professional surfing governing body, organising among other things a competitive calendar around the world. During 2003, >100 contests were held, featuring all disciplines of the sport: shortboard, longboard, juniors and masters.[3] The ASPs first World Championships for men was in 1976 and for women in 1977. In 1992, ASP introduced a two-tiered competition system.

The World Championship Tour (WCT) consists of the top 44 surfers competing throughout the season in the prime world surfing locations worldwide, while the World Qualifying Series (WQS) is the feeder system for the WCT. At the end of each competitive season, the last 16 surfers in the WCT automatically lose their place in the WCT, replaced for the next year by the top 16 WQS surfers. Surfers competing in the WCT are also allowed to compete in the WQS.

The individual ratings of the 2002–03 ASP listed 44 male surfers in the WCT and 600 in the WQS.[4] In 2003, the countries/regions with representation in the WCT were: Australia (24 surfers), Brazil (9), US (8) and Hawaii (4). The countries/regions represented in the WQS top 100 in 2002 were: Australia (37 surfers), Brazil (28), US (12), Hawaii (9), South Africa (5), Spain (3), France (3) and Portugal, New Zealand and Great Britain with one surfer each. The women's 2003 WCT lists 17 surfers representing seven countries:[4] Australia (9 surfers), US (2), Hawaii (2) and Brazil, South Africa, Peru and France with one surfer each. The 2002 WQS female circuit ranked 96 women. The countries with representation in the top 96 were: Australia (33 surfers), US (21), Hawaii (20), France (6), South Africa (4), Great Britain (3), Spain (2), Brazil (2) and Portugal, Japan, Costa Rica and Puerto Rico with one each. Although surfing is practised in a greater number of countries, according to these figures, competitive surfing appears to be particularly well developed in Australia, Brazil and the US (including Hawaii where surfers compete under Hawaiian identity).

Surfing contests are based on elimination heats. The normal contest format consists of 20- to 40-minute heats, in which two, three or four surfers are given scores by a group of judges. The role of judges in a surfing contest is to decide which surfer performs manoeuvres closest to the judging criteria in any heat. The surfing judging criteria has evolved over the years parallel to surfing technique and equipment development. The main judging criteria that surfers have to accomplish is: "the surfer must perform committed radical manoeuvres in the most critical sections of a wave with style, power and speed to maximise scoring potential. Innovative and progressive manoeuvres will be taken into account when rewarding surfers for committed surfing. The surfer who executes this criteria with the highest degree of difficulty and most control on the best wave shall be rewarded with the highest score".[5] The winners of each heat advance to the next round until reaching the final. The competitive calendar within the different circuits includes several trials over the season (see table I). Surfers get a numerical score based on their final position in each event. At the end of the tour, after adding up all the scores obtained in each event, the surfer with the highest score will be the eventual winner. There are also other different competition modalities, including the World Surfing Games, organised by the International Surfing Federation, each country's National Championship and a series of other 2- to 3-day specialty events.

Table I. Example of a possible competitive calendar of one World Championship Tour (WCT) surfer during the 2003 season

Date	Circuit/category	Location
Mar 4–16	WCT	Australia (East coast)
Apr 7–13	WQS	Australia (West coast)
Apr 15–26	WCT	Australia (South coast)
May 6–18	WCT	Tahiti
May 25–Jun 6	WCT	Fiji
Jun 9–15	WQS	Maldives
Jun 18–29	WCT	Japan
Jul 7–13	WQS	South Africa
Jul 15–25	WCT	South Africa
Jul 26–Aug 3	WQS	US (California)
Aug 4–10	WQS	France
Aug 11–17	WQS	France
Aug 18–24	WQS	France
Aug 25–31	WQS	Japan
Sep 4–13	WCT	US (California)
Sep 19–28	WCT	Portugal
Sep 30–Oct 11	WCT	France
Oct 12–24	WCT	Spain
Oct 27–Nov 4	WCT	Brazil
Nov 4–9	WQS	Brazil
Nov 11–23	WQS	Hawaii
Nov 24–Dec 7	WCT	Hawaii
Dec 8–20	WCT	Hawaii

WQS = World Qualifying Series.

2. Analysis of the Activity

Lowdon[6] has described the surfing process as follows: first of all, the surfboard is paddled out with the surfer in the prone position in order to reach the take-off area. Once there and when a suitable wave approaches, some powerful strokes are needed to give the board enough speed to be gathered up by the swell. When the wave has been caught, it is necessary to quickly stand up and to perform manoeuvres on the wave's wall until the wave breaks on the beach. At this point, the same process has to be repeated many times throughout the surfing session. Therefore, the physical demands imposed by surfing practice should be examined from the variety of specific situations that are essential in this sport.

Time-motion analysis provides useful information about the physical demands associated with a particular sport. Meir et al.[7] analysed surfing activity during 1 hour of recreational surfing practice. Surfers' movements were classified as: arm paddling (lying in a prone position), stationary, riding wave and miscellaneous (e.g. other activities such as ducking under white water and wading). The percentage of time spent in each activity was determined, with arm paddling being the most time-demanding activity, representing 44% of the total time, remaining stationary represented 35%, while wave riding and miscellaneous represented 5% and 16% of the total time, respectively. To extend the existing data on motion analysis during surfing, we recently investigated the movement patterns of competitive surfing during an international contest.[8] Forty-two male professional surfers were filmed during 42 elimination heats of 25 minutes duration. Videotape analysis revealed that surfers were, on average, paddling and stationary 51% (25–70%) and 42% (23–72%) of the total time, respectively. Wave riding accounted for 3.8% (2–7%) of the total time, whereas miscellaneous activity accounted for the remaining 2.5% (0.1–6%) of the total time. The small differences reported between recreational surfing[7] and competitive surfing[8] may simply reflect the specific demands imposed during either competitive or recreational surfing. It also possible that those percentages reflect variations due to the influence of the multiple environmental factors that can affect surfing temporal structure (e.g. swell size, inconsistent surf, currents, wave length or wave frequency). Moreover, during competition, tactical decisions due to different factors (e.g. heat opponent's scores or wave selection) might have also had an impact on surfers' activity patterns. Nonetheless, it appears that surfers spend between 45% and 50% of their time total paddling and between 35% and 40% of their total time remaining stationary. The rest of the time is shared among wave riding and various activities such as recovering the board after falling or duck diving under the broken waves.

3. Surfer Characteristics

Surfing is an activity characterised by intermittent exercise bouts of varying intensities and durations involving different body parts and numerous recovery periods. The duration of surfing practice typically ranges from 20 minutes in a competitive situation to over 4–5 hours during good wave-condition practice sessions. Moreover, surfing training and competition can be performed in a wide range of environmental conditions (e.g. different wave size, type of breaker, line-up situation). These variables are likely to impact on the underlying physiological demands of surfing practice. To cope with the ocean demands, surfers must respond to extensive periods of intermittent exercise, with clearly different upper-body (i.e. arm paddling) versus lower-body (i.e. wave riding) demands. Surfing practice also requires great mental and cognitive activity in a wide range of environmental conditions. Nevertheless, during training on-water, the majority of surfers are not conscious that they are training and most of them would consider this time as fun rather than as training.[9] Therefore, little attention has been devoted to the types of physiological adaptations that can be attributed to surfing practice. However, it should be understood that surfing is, above all, a sport requiring exceptional whole body physical skills, technique and mental aptitude, and that physical fitness itself can not compensate the full development of

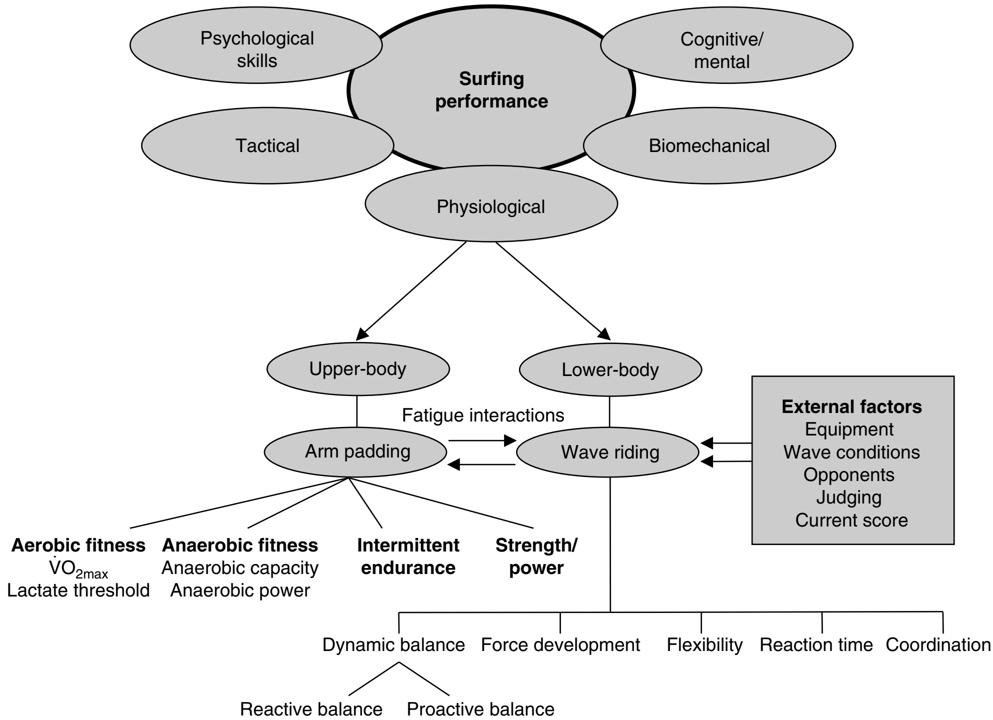

Fig. 1. Schematic diagram of the physiological aspects relevant to surfing performance. Competitive success would be dependent on the interrelationship between surfer's psychological, tactical, cognitive, technical/biomechanical and physiological capacity. $\dot{V}O_{2max}$ = maximal oxygen uptake.

these abilities. Figure 1 shows many of the variables that might influence surfing performance.

3.1 Physical Characteristics

3.1.1 Age

In March 2003, the average age of the WCT top 44 ASP-ranked men was 27.5 ± 3.6 (22.1–36.9) years,[4] which is higher than values obtained by Lowdon[10] in 1978 for international level surfers (n = 76) competing on the world professional surfing circuit (22.2 ± 3.2 years). The average age of the female competitors listed in the 2003 WCT top 17 was 26.7 ± 4.4 years (19.5–32.1 years). Lower figures for elite female surfers of 21.6 ± 3.4 years (Lowdon;[10] n = 14) and 23.3 ± 3.3 years (Felder et al.;[11] n = 10) have also previously been reported. It would appear, therefore, that current world-class professional surfers are consistently older than 25 years ago, probably reflecting the maturity of competitive surfing itself and/or the required years to refine mastery in surfing performance and competitive skills. Moreover, the increasing financial rewards might also delay the age of retirement for the modern competition surfer.

3.1.2 Body Type

Competitive surfers seem to be shorter and lighter than the average age-matched sporting population. The average height of the 2003 WCT top 44 ASP ranked male surfers was 174.7 ± 6.1cm (161–188cm).[4] This is consistent with a previous study reporting an average height of 173.6 ± 5.9cm for 76 male international surfers.[10] These values are less than the heights described for elite swimmers (183.8 ± 7.1cm; n = 231) and water polo players (186.5 ± 6.5cm; n = 190).[12] Females show similar trends. The average height of the 2003 WCT top 17 ASP ranked women surfers was 162.0 ± 4.9cm (152–172cm).[4] Previously, Lowdon[10] and Felder et al.[11] found slightly higher figures of 165.7 ± 4.9cm and 166.2 ± 6.7cm for 14 and ten elite female surfers, respectively. As with the males, female surfers are on average shorter than elite swimmers (171.5 ± 7.0cm; n = 170) or water polo players (171.3 ± 5.9cm; n = 109).[12] It has been previously reported that stability is inversely related to the height of the centre of gravity above the base of support.[13] A shorter stature may, therefore, be an advantage to surfing performance, as a lower centre of gravity would allow surfers to obtain better dynamic balance performance, which seems to be crucial for surfing.

With respect to body mass, Lowdon[10] reported an average value of 67.9 ± 7.2kg for 76 male international surfers. Again, notable differences exist between surfers and elite aquatic athletes. Mazza et al.[12] reported body mass values of 78.4 ± 7.1kg and 86.1 ± 8.4kg for swimmers (n = 231) and water polo players (n = 190), respectively. Regarding female surfers, Lowdon[10] and Felder et al.[11] reported body mass values of 59.3 ± 6.7kg and 57.9 ± 8.3kg, respectively. As with men, competitive female swimmers (63.1 ± 5.9kg; n = 170) and water polo players (64.8 ± 7.2kg; n = 109) are heavier than surfers. Together with the stature figures, values for body mass suggest that a relatively short and light body type may be advantageous for performing specific movements in surfing.

Anthropometric analyses of surfers have revealed that a surfer's body composition appears not to play a major role in surfing performance.[6,11,14] According to an anthropometric evaluation of both males and females,[11,14,15] surfers present a wide range of body fat values, suggesting no ideal body fat level related to surfing performance. Generally, estimated percentage body fat in surfers is higher than that reported in other level-matched endurance athletes, although lower than the average for college-age men.[6,14] Lowdon and Pateman[15] reported average figures of 10.5% for 76 world-class male surfers. The same authors[15] reported mean body fat values of 19.5% for 14 elite female surfers. Higher values of 22.0 ± 4.0% were reported by Felder et al.[11] for ten elite female surfers. As a surfer's mass is supported while paddling and riding, low adiposity appears not to represent a real advantage from a performance perspective.[6] Moreover, some authors[11,15] have theorised that moderate body fat levels may be an advantage and a physiological adaptation providing protection against the constantly wet and windy surfing environment.

Somatotyping is one of several techniques to evaluate human body morphology. Lowdon[10] performed an anthropometric evaluation of 76 male and 14 female international competitive surfboard riders and reported that world class surfboard riders possessed a distinctive somatotype, showing the following mean values for men and women, respectively: endomorphy (fatness) 2.6, 3.9; mesomorphy (muscularity) 5.2, 4.1 and ectomorphy (linearity) 2.6, 2.6. These figures are close to those observed in other aquatic sports at an elite standard (see figure 2),

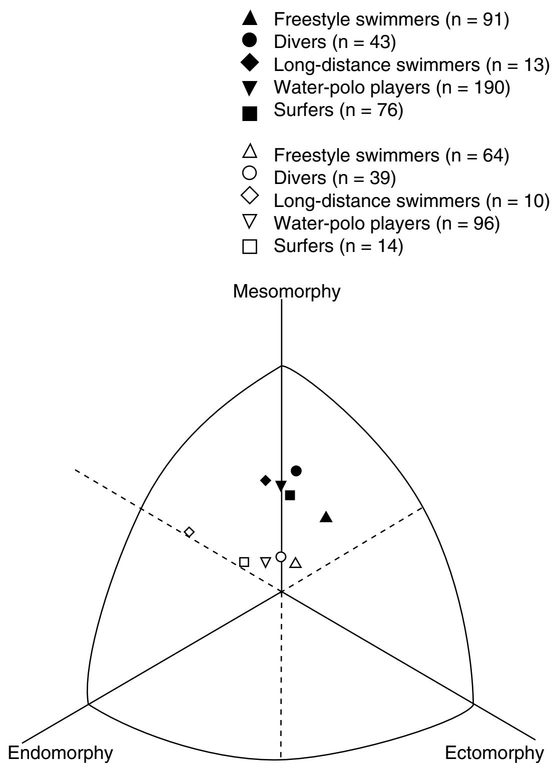

Fig. 2. Somatoplot of male (open symbols) and female (filled symbols) athletes for different aquatic sports at elite standards (reproduced from Lowdon,[10] with permission).

most notably male long-distance swimmers (n = 13) [2.5, 5.3, 2.3], male water polo players (n = 190) [2.5, 5.3, 2.4] and female water polo players (n = 96) [3.6, 3.9, 2.8].[16]

In summary, the limited data available suggest that specific size attributes, particularly lower height and body mass compared with other matched-level aquatic athletes and a mesomorphic somatotype, might be an advantage for success in top-international surfing. In particular, lower stature is likely to benefit dynamic balance, which seems to be an important requirement for surfing performance. Further research is required to evaluate the relationship between body type and surfing performance.

3.2 Physiological Characteristics

As mentioned in section 2, upper-body exercise (i.e. arm paddling) represents the most time demanding activity in surfing.[7,8] Taking into consideration that professional surfers can spend between 1 and 5 hours daily training in the water,[11] the total amount of time spent arm paddling can, therefore, be very high. In addition, Meir et al.[7] reported that during 1 hour of recreational surfing, the mean heart rates (HRs) during arm paddling represented 80% of the laboratory peak heart rate (HR_{peak}) attained by the surfers during a progressive swim bench ergometer peak oxygen uptake ($\dot{V}O_{2peak}$) test. This suggests that a good aerobic fitness level might be an important fitness factor to consider in this sport.

3.2.1 Peak Oxygen Uptake

Dynamic leg exercise (i.e. cycle ergometer or treadmill) is the most popular and conventional mode of exercise testing. However, research strongly supports the specificity of fitness and testing concept.[17] The physiological and metabolic differences between legs and arms during maximal and submaximal exercise have been previously identified.[18,19] For example, comparing exercise of the legs and arms, $\dot{V}O_{2peak}$ values during arm work are approximately 70% of the values obtained during leg exercise.[18] However, highly upper-body trained subjects can achieve arm-crank values approaching 90% of their cycle $\dot{V}O_{2peak}$.[18] Therefore, alternative methods involving arm exercise appear to be more appropriate to detect specific physiological adaptations in those individuals engaged in sports activities dominated by arm work,[17,18] such as surfers.

Very little published data are available describing the physiological responses during an upper-body exercise using specific testing protocols in surfers.[7,9,20] In an early study by Lowdon et al.,[9] 12 male competitive college surfers were selected to carry out three different laboratory tests (tethered board paddling, prone arm cranking and treadmill running). With respect to the two tests carried out with the upper body, the $\dot{V}O_{2peak}$ values were 2.87 ± 0.04 L/min (40.4 ± 2.9 mL/kg/min) and 2.95 ± 0.38 L/min (41.6 ± 4.0 mL/kg/min) for tethered board paddling and prone arm cranking, respectively. As similar maximum physiological values were obtained with prone arm cranking and tethered board paddling, this suggests that prone arm cranking is a valid and easy substitute (easily set up by modifying widely available cycle ergometers) for more complex laboratory requirements (i.e. tethered board paddling or swim bench) for assessing aerobic fitness in surfers.

Meir et al.,[7] after evaluating six Australian recreational surfers, reported higher $\dot{V}O_{2peak}$ values than Lowdon et al.;[9] 3.75 ± 0.83 L/min (54.20 ± 10.2 mL/kg/min) using a swim bench prone arm paddling protocol. Mendez-Villanueva et al.[20] reported values of 3.34 ± 0.31 L/min (50.00 ± 4.67 mL/kg/min) and 3.40 ± 0.37 L/min (47.93 ± 6.28 mL/kg/min) for a group of European level (n = 7) and regional level (n = 6) competitive surfers, respectively, during a prone arm paddling exercise on a modified kayak ergometer. The differences in $\dot{V}O_{2peak}$ values reported in these three studies[7,9,20] seem not to reflect the level of the surfers evaluated since the highest $\dot{V}O_{2peak}$ values were achieved for recreational surfers.[7] However, several factors such as differences in the testing protocols between the three studies and other aspects related to surfing practice and performance may explain these results.

Differences in $\dot{V}O_{2peak}$ values might simply reflect a superior physical endowment of those surfers with the highest figures. However, the underlying physiological adaptations to surfing practice may also be related to the predominant local surfing conditions (e.g. type of waves or swell regularity). Lowdon et al.[9] stated that the local surfing venues frequented by the surfers used in their study were shorebreaks with a relatively short paddle out, generally requiring <2 minutes to return to the take-off area after riding each wave. In contrast, we have recorded arm paddling periods >4 minutes during competition heats,[8] while Lowdon[6] reported figures up to 10 minutes. These differences in arm paddling activity to return to the take-off area reflect the specific characteristics of each particular surfing spot. While these characteristics are likely to remain constant over time, it is possible that different physical attributes might be found when surfers from different surfing locations are compared. In addition, Lowdon et al.[9] reported that surf conditions were unusually small in the winter before the testing of the subjects. Thus, a less demanding training workload might partially explain the somewhat low $\dot{V}O_{2peak}$ values reported by Lowdon et al.[9] for competitive surfers compared with those found by Meir et al.[7] or Mendez-Villanueva et al.[20]

Although Meir et al.[7] pointed out that the six subjects examined in their study were recreational surfers, they had previously competed at state level. Moreover, in surfing, the difference between competitive or recreational surfers often does not reflect the amount of hours spent on the water for both groups. For example, Lowdon et al.[21] reported an average of 4 hours of surfing per day for almost 3 days per week in a sample of 346 surfers of varying age, experience and competence. Lowdon et al.[22] found that a group of 97 international-level surfers spent an average of 3.7 hours of surfing per day for >5 days a week (range 4–7 hours). Thus, the level of commitment to the sport, regardless of level, might assure similar global training stimuli and, therefore, the development of similar physiological adaptations between competitive and the most ardent recreational surfers.

Comparison of $\dot{V}O_{2peak}$ values obtained for surfers to values obtained in studies with other populations has to be done with caution due to the variety of testing protocols employed. In order to improve the specificity of fitness testing, surfers are typically assessed during prone arm paddling exercise, while the most common mode of upper-body ergometry for the general population is seated arm-cranking exercise.[18] Regardless of the expected differences in muscle recruitment between these two modes of exercise, body position adopted during exercise has been reported to alter the haemodynamic and performance parameters during exercise.[23,24] As a result, $\dot{V}O_{2peak}$ values during both arm and leg exercise have been found to be consistently lower in the horizontal posture (prone or supine) than in the erect (sitting or upright) posture.[24] However, despite adopting the prone position, absolute $\dot{V}O_{2peak}$ values achieved by surfers (3.26 L/min) are ~20% higher when compared with an active young male population tested with seated arm ergometry (2.57 L/min) [see tables II and III]. Similar differences (~20%) have been observed when mean values obtained for surfers are compared with average values

Table II. Upper-body peak oxygen uptake ($\dot{V}O_{2peak}$) values for untrained young males[a]

Study	No. of subjects	Age (y) [mean ± SD]	$\dot{V}O_{2peak}$ (L/min)	$\dot{V}O_{2peak}$ (mL/kg/min)
Sawka et al.[25]	13	24.0 ± 3.6	2.89	37.05
Aminoff et al.[26]	10	26.3 ± 2.3	2.19	26.80
Kang et al.[27]	8	21.0 ± 8.5	2.24	31.32
Schneider et al.[28]	6	28.0 ± 4.9	2.90	36.00
Rotstein and Meckel[29]	14	25.2 ± 2.9	2.60	34.60
Taylor and Batterham[30]	16	24.5 ± 4.5	2.91	37.94
Schneider et al.[31]	10	21.6 ± 5.1	2.08	25.77
Koppo et al.[32]	10	21.3 ± 2.5	2.74	37.10
Mean			*2.57*	*33.32*

a All studies utilised arm cranking in the sitting position as the testing mode.

Table III. Peak oxygen uptake ($\dot{V}O_{2peak}$) values for upper-body trained athletic young males and surfers (males) during prone position arm ergometry

Study	No. of subjects	Age (y) [mean ± SD]	Sample	Testing mode (body position)	$\dot{V}O_{2max}$ (L/min)	$\dot{V}O_{2peak}$ (mL/kg/min)
Upper-body trained athletes						
Bernard et al.[33]	14	21.0 ± 4.0	Swimmers	Arm traction bench (prone)	2.69	38.00
Swaine[34]	12	19.8 ± 3.1	College swimmers	Swim bench (prone)	3.22	43.69
Morton and Gastin[35]	7	21.0 ± 1.0	Surf lifesavers	Swim bench (prone)	2.94	40.38
Swaine and Winter[36]	12	22.0 ± 2.4	College swimmers	Swim bench (prone)	2.90	39.19
Swaine and Winter[36]	12	22.0 ± 2.4	College swimmers	Arm cranking (prone)	2.40	32.43
Konstantaki and Swaine[37]	9	21.0 ± 4.0	College swimmers	Swim bench (prone)	3.10	38.27
Mean					*2.87*	*38.66*
Surfers						
Lowdon et al.[9]	12	20.7 ± 1.2	College surfers	Tethered board paddling (prone)	2.87	40.4
Lowdon et al.[9]	12	20.7 ± 1.2	College surfers	Arm cranking (prone)	2.95	41.6
Meir et al.[7]	6	21.2 ± 2.8	Recreational surfers	Swim bench (prone)	3.75	54.2
Mendez-Villanueva et al.[20]	7	25.6 ± 3.4	Competitive surfers (European level)	Arm paddling (prone)	3.34	50.0
Mendez-Villanueva et al.[20]	6	26.5 ± 3.6	Competitive surfers (regional level)	Arm paddling (prone)	3.40	47.93
Mean					*3.26*	*46.83*

(2.56 L/min) obtained from 18 studies conducted with untrained and trained subjects.[18] Differences are even larger (~30%) when average relative $\dot{V}O_{2peak}$ values are compared between surfers (46.83 mL/kg/min) and the untrained population (33.32 mL/kg/min) [see table II]. Values for surfers are, however, more similar to specifically trained upper-body athletes, mainly swimmers, tested under similar conditions (i.e. prone arm paddling exercise) [see table III]. Once again, differences in $\dot{V}O_{2peak}$ between surfers and upper-body specific trained athletes are greater when relative values are considered (46.83 mL/kg/min and 38.66 mL/kg/min, respectively). The results suggest that surfing practice induces a high level of aerobic fitness, since $\dot{V}O_{2peak}$ values are close to those reported for other upper-body endurance-based athletes (i.e. swimmers) and consistently higher than values reported for an age-matched untrained population. However, longitudinal studies are needed to evaluate aerobic fitness adaptations due to surfing training.

Although, based on time motion analyses (see section 2), dynamic leg exercise (i.e. wave riding) represents only a small portion of the actual surfing time, two studies have assessed $\dot{V}O_{2peak}$ during lower extremity exercise in surfers. Lowdon and Pateman[15] reported values of 4.73 ± 0.81 L/min (70.2 ± 10.7 mL/kg/min) and 3.72 ± 0.59 L/min (62.2 ± 8.2 mL/kg/min) for 76 and 12 international level men and women, respectively. These values are close to those of endurance athletes.[38] However, cardiovascular fitness was assessed by prediction of $\dot{V}O_{2peak}$ from submaximal data using the Astrand-Ryhming nomogram, which has been reported to have a great variability.[39] Therefore, the poor accuracy of such predictions might result in an overestimation of the true aerobic power. Moreover, Lowdon et al.[9] found lower $\dot{V}O_{2peak}$ values of 4.02 ± 0.44 L/min (56.3 ± 3.9 mL/kg/min) for 12 competitive male surfers during a treadmill running exercise to exhaustion. Although these last values are greater than mean values for untrained subjects, they are far below those obtained for endurance-trained athletes (e.g. runners, cyclists or cross-country skiers). Further studies are needed to determinate the limb-specific adaptations underlying surfing practice.

3.2.2 Lactate Threshold

Another important determinant of endurance performance is the lactate threshold (LT). Despite the controversies around the different methods used to interpret the changes in lactate levels during athletic performance, LT remains an informative measurement and it has been shown to be a good index of endurance performance[40,41] and intermittent exercise performance.[42] Unfortunately, LT has not been extensively investigated in upper-body exercise.[18] In a recent study conducted in our laboratory,[20] we obtained upper-body LT values for a group of 13 high-level competitive surfers. Subjects were divided into two groups based on their competitive performance level. We found significantly higher values (~7%; $p = 0.01$) for greater competitive ability surfers than for lesser competitive ability surfers. Moreover, LT was correlated ($r = -0.58$, $p = 0.03$) with surfing performance (final ranking obtained during the competitive season).[20]

Although surfing is not an endurance race event, our findings suggest that a high upper-body LT may be associated with surfing performance. Riding a wave, standing on a surfboard, performing radical and controlled manoeuvres with the most speed, power and highest degree of difficulty seems to demand a superior level of postural control and whole body fine motor skills. Moreover, uncontrolled wave ride finish (loss of balance and falling down) has a negative influence on judges' score.[43] Upright wave riding is always preceded by a period of arm paddling exercise of different duration and intensity. The neuromuscular responses of one previously nonexercised muscle group after intense exercise leading to fatigue performed with another muscle group have been investigated.[44-47] Although none of these studies assessed any aspects of postural control after an exercise carried out with the upper body, these researchers all showed negative interference effects on muscular performance when a previous inactive muscle group was exercised. Therefore, it is possible that metabolic disruptions induced at a site remote from the legs (i.e. during arm paddling) might be associated with some negative effects on postural control and performance during wave riding. Although further research is needed, a greater arm LT may allow surfers to sustain intense periods of arm exercise with reduced metabolic disruptions and, therefore, reduced negative interferences with leg exercise performance during subsequent wave riding.

3.2.3 Summary

In summary, data available seem to provide evidence that surfers have a relatively high aerobic fitness. In particular, $\dot{V}O_{2peak}$ values obtained during arm exercise in surfers are higher than values reported for untrained subjects and comparable to those reported for other upper-body endurance sports. Additional research should also examine the existence of an upper-body aerobic fitness threshold below which a surfer is unlikely to perform successfully at the competitive level. In addition to more cross-sectional studies, further research is required to examine longitudinal changes in aerobic fitness with surfing practice. Finally, given that environmental conditions can greatly impact upon surfing practice, future research should evaluate whether 'cross-training' can be used to maintain 'surfing fitness' when quality waves are not available.

3.3 Neuromuscular Aspects

The neuromuscular system's ability to produce power at the highest exercise intensity, often referred as a 'muscular power' is an important determinant of athletic performance.[48] Although neuromuscular skills, such as agility, balance, muscular power, flexibility or reaction time are considered important in surfing, controlled studies on these variables are lacking. Comparing successful surfers with less successful surfers, Mendez-Villanueva et al.[20] showed that peak aerobic power (W) obtained during an incremental arm paddling exercise test to exhaustion may be an important general fitness index to assess in surfers. Higher level surfers obtained values greater (~25%; $p = 0.04$) than lower level surfers. This is similar to endurance-based sports that have reported peak aerobic power to be an important determinant of performance.[49,50]

Reaction time, or the speed at which a person moves in response to a stimulus, is also a critical element in most sports. Surfing is performed in a highly unstable and changing environment. Therefore, the ability to deal with cognitively challenging situations during surfing practice appears to be critical. The best surfers might respond quickly to all those external challenges and a high psychomotor performance could be an important determinant of competitive success. Lowdon and Pateman,[15] after studying the physiological attributes of a group of 76 male international professional surfers, have suggested that rapid movement responses to an external stimulus is an important determinant of surfing skill, due to the significant correlation ($p < 0.05$) found between placement in a professional contest and movement time response. Agility scores and balance have also been reported to be excellent in surfers, compared with athletes in other water sports.[51] Unfortunately, this information remains anecdotal since these authors did not provide any details about the testing procedures. Future research should be directed to identifying neuromuscular attributes relevant to surfing performance.

4. Physiological Responses 'On-Water'

The HR response to exercise has been used as a measure of exercise intensity in a variety of sports and activities.[52] To date, however, only one study has reported data regarding physiological variables measured during surfing. Meir et al.[7] monitored HR responses in six recreational surfers during 1 hour of recreational surfing. To allow exercise intensity assessment, surfers previously carried out a maximal arm-paddling test on a swim-bench ergometer. The mean HR_{peak} value attained while surfing was 171 ± 7 beats/min, representing 95% (±3.6%) of the peak value attained during a swim-bench test (180 ± 6 beats/min). The mean HR value for the total time surfing (1 hour) was 135 ± 6 beats/min, which represented 75% (±4.2%) of the mean HR_{peak} measured during the laboratory progressive arm paddling $\dot{V}O_{2peak}$ test. Mean HR values for paddling and stationary were 143 ± 10 and 127 ± 7 beats/min, which represented 80% (±4.8) and 71% (±5.5), respectively, of the laboratory HR_{peak}. These results show that, as a recreational activity, the average HR obtained by Meir et al.[7] met the American College of Sports Medicine training intensity criteria (55/65% to 90% of the maximum HR) for developing and maintaining cardiorespiratory fitness in healthy adults.[53]

Due to the different types of muscular work (i.e. upper- vs lower-body, isometric vs dynamic contractions), the intermittent nature of surfing activity and the many external factors that might influence physiological responses to surfing, average HR values are not likely to represent all patterns of physical activity in surfing. Identification of high physical demand periods could provide more relevant data to understand the specific requirements of surfing. Therefore, HR were recorded continuously at 5-second intervals during a simulated 20-minute surfing competition heat in five male competitive surfers (Mendez-Villanueva et al., unpublished observations). Prior to the simulated surfing heat, subjects performed a laboratory maximal arm paddling test on a modified kayak ergometer to determinate $\dot{V}O_{2peak}$ and HR_{peak}. HR was classified based on percentage time spent in six zones:

1. <75% HR_{peak}
2. 75% < HR < 80% HR_{peak}
3. 80% < HR < 85% HR_{peak}
4. 85% < HR < 90% HR_{peak}
5. 90% < HR < 95% HR_{peak}
6. >95% HR_{peak}.

The group's mean (± standard deviation) $\dot{V}O_{2peak}$ and HR_{peak} values for the arm paddling test were 3.52 ± 0.38 L/min and 174 ± 9 beats/min, respectively. Mean HR for the simulated surfing heat was 146 ± 20 beats/min, representing 84% of the laboratory HR_{peak}. Surfers spent ~25% of the total time above 90% of their previously obtained laboratory HR_{peak} (see figure 3). In combination with the relatively high $\dot{V}O_{2peak}$ values for surfers previously reported and the time-motion analysis indicating relatively long recovery periods, such HR values suggest that periods of moderate intensity soliciting mainly the aerobic system are intercalated with bouts of high-intensity exercise demanding both aerobic and anaerobic metabolism. Furthermore, these results suggest that the high aerobic fitness values reported in surfers may be the out-

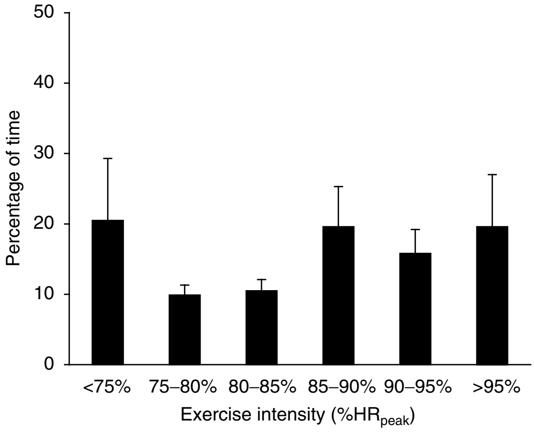

Fig. 3. Percentage of time spent in the heart rate (HR) categories of <75% HR_{peak}; 75% < HR < 80% HR_{peak}; 80% < HR < 85% HR_{peak}; 85% < HR < 90% HR_{peak}; 90% < HR < 95% HR_{peak}; and >95% HR_{peak} during a simulated competition heat (20 min) in a beach breaker. Data are for five competitive surfers. Values are means ± standard error. $\mathbf{HR_{peak}}$ = peak heart rate.

come of a training effect resulting from surfing practice. However, certain characteristics of surfing (e.g. isometric contractions during wave riding, high levels of concentration or great emotional stress) may induce an elevation of HR and, therefore, an overestimation of the actual physical demands during surfing.[52,54] Studies combining HR, blood lactate, respiratory gas measures and time-motion analysis are needed to determine the actual physiological load imposed during surfing.

5. Training Guidelines

Technical proficiency of specific surfing skills is the most important factor influencing surfing performance and will benefit the most from on-water training. Repetition of specific movement skills on waves with different characteristics is critical to automate and refine fundamentals and to build a repertoire of effective manoeuvres. Even though surfing sessions can last several hours, the practice of upright specific surfing skills is time limited (see section 2). As surfing technique is highly specific and off-water simulation is virtually impossible, a great amount of time must be spent in the water in order to refine all the technical abilities relevant to surfing performance. However, enhancement of relevant fitness areas proposed to be associated with physical performance in surfing (see figure 1) can be addressed through supplemental or non-specific sport training. In addition, alternative physical training might help surfers maintain or improve optimum fitness levels during periods of impeded surfing due to injury, poor surf conditions, etc. Individual physiological weakness might also be addressed through the implementation of specific off-water workouts. It should be noted that due to the difficulty in controlling the physical training load associated with surfing practice, additional training must be carefully monitored in order to avoid excessive fatigue and eventually overtraining.

Upper-body aerobic fitness appears to be important for surfers (see section 3.2). Fitness training to improve arm paddling performance should consist of a combination of upper-body endurance and strength training. Workouts might include prone board paddling, freestyle swimming or swimming bench interval training using data from the time-motion analysis (see section 2) to define the workout load. However, rather than simply replicating the time-motion analysis data, the overload principle should be applied in order to obtain appropriate training adaptations. Therefore, the number of bouts, the work/rest duration and exercise intensity should be carefully manipulated in order to obtain the desired training adaptations.

An optimal level of upper-body strength and power is believed to be an important component for successful performance in surfing. The inclusion of off-water resistance training should be designed to get the athletes stronger and more powerful. Higher levels of upper-body strength and power would assist surfers to generate rapid and explosive arm strokes needed to catch the waves or to avoid a set of broken waves. Moreover, strength and power training has been reported to improve endurance performance.[55] Due to the considerable amount of upper-body surfing training, specific muscular endurance in key muscles (e.g. shoulders, upper-back), that are essential to board propulsion, need not to be a part of a strength and conditioning programme for surfers.[56] Rather, this would be achieved by the great volume of in-water arm paddling during actual surfing. However, inclusion of such training workouts may be important during periods of impeded surfing.

A crucial aspect of surfing performance is the ability to exert muscular force with the right timing and coordination to perform upright manoeuvres across the wave's wall as powerfully as possible. Twisting with power means that surfers must optimise the actions between the whole body while still maintaining good control over the board. Excellent body control (proprioception) and balance is required to combine both power and control in the most stepping sections of the wave's wall. To refine these extremely difficult and specific skills, some modes of cross-training with exercises that imitate the movement patterns of surfing might be used. Skating, snowboarding or different Swiss ball exercises are all activities with skill components similar to surfing, especially dynamic balance and, therefore, might have a positive carryover effect and benefit surfing performance. Lower-body resistance exercises such as squat or plyometric jump training and explosive twisting trunk movements might help surfers to develop greater power and move the surfboard more radically over the wave's wall. Flexibility in the torso, hips, knees and ankles may allow more extreme and radical positions during surfing manoeuvres, making the tricks more powerful and visually attractive and, therefore, improve the chances to obtain better judges' scores.

Designing a fitness programme for a sport such as surfing is complicated by the specific skills required, the impossibility to plan workouts due to the unpredictable nature of surfing practice, the difficulty in controlling the training stress imposed by surfing and the prolonged competitive season. Training programmes that enhance each of skill-related components of physical fitness are likely to increase the probability of success. However, for the moment, most of the recommendations for improving surfing performance remain anecdotal due to the lack of specific information about many aspects of surfing performance.

6. Musculoskeletal Adaptations and Injury Risk

In addition to cardiovascular demands, the musculoskeletal system is also subjected to considerable demands during surfing. Surfing practice places the athletes at a high risk of overuse injury as a result of the physiological loads on the musculoskeletal system that occur with intense and repetitive surfing participation. Early research on surfing-injury epidemiology only included injuries requiring hospital or first-aid station treatment.[57-59] However, as in many other sports, surfers are likely to continue practice despite the presence of less serious injury.

Using survey techniques, Lowdon et al.[21,22] and more recently Nathanson et al.[60] investigated injury patterns in surfers. Lowdon et al.[21] studied the incidence of injuries in a sample of 346 surfers of various levels of competence. All injuries experienced over the previous years were requested. 337 injuries were reported and there was 3.5 injuries per 1000 surfing days. The most common injuries were lacerations (41%) followed by soft-tissue injuries (35%). Overuse injuries of the lower back, the neck and the shoulder represented 16% of all surfing injuries. In another study carried out with world class competitive surfers (n = 86), the same authors[22] reported similar findings. A total of 187 injuries were reported, representing 4.0 injuries per 1000 surfing days. Lacerations were the single most frequent injury and accounted for 45% of the total injuries. Sprain and strains were the next most frequent injury (37%). The lower back, shoulder, neck and knee represented 25%, 16%, 10% and 28%, respectively, of the total of sprains and strains reported.

More recently, Nathanson et al.,[60] using an Internet-based survey, obtained data from 1348 individuals reporting 1237 acute injuries and 477 chronic injuries. Lacerations were again the most common type of injury (42%). Chronic injuries represented 37% of all injuries reported. Most common were overuse injuries to the upper extremity and paraspinous muscles. Shoulder (18%), back (16%), neck (9%) and knee (9%) were the most frequently cited places. Preventative measures such as minor alterations in board design and use of protective equipment,[60] may decrease the number and severity of acute surfing injuries. Further research is needed to provide more detailed information allowing the development of practical preventive programmes to reduce the incidence of surfing injuries.

Overuse injuries appear to be becoming more common as surfers surf more frequently and for longer periods, due to technical advances in wetsuit design (allowing better body insulation in cold water) and the current level of professionalisation. The high frequency of shoulder, back and neck overuse injuries has been suggested to be associated with the repetitive arm stroke action and the body posture during adopted board paddling. The triggering causes of the aforementioned injuries are believed to be cervical and lumbar spine hyperextension (related to a continuous isometric contraction of the neck and scapular area muscles) as well as the internal rotation that accompanies all of the shoulder joint movements during the arm-paddling action, especially in low flotation surfboards.[22] Moreover, surfing practice does not seem to promote a balanced muscular development. In a physiological analysis of 18 surfers carried out by Gillam et al. (in Renneker[14]), it was observed that the surfers had powerful shoulder flexion and extension (more than other athletes) but they had less abdominal strength than the majority of athletes. Plag et al.[61] also reported below average abdominal strength values when surfers were compared with an age-matched sporting population reached. A limited flexibility in shoulders, back and hamstrings has also been reported.[14] Since muscle strength and flexibility imbalances in a concrete joint have been suggested to be a risk factor predisposing to injury,[62] controlled studies identifying these strength and flexibility deficits are needed. Results obtained in these studies should help surf coaches and exercise scientists in the development of specific conditioning programmes and other preventive measures that might help to reduce or lessen the severity of common overuse surfing injuries.

7. Conclusions

The results presented here show that very little is known about the physiological requirements of surfing. With such a paucity of data, it seems important to commence new research paths in all areas of surfing performance. Surfing popularity is growing and surfing is reaching an increasing global audience. Recommendations for future research include:

- additional time-motion analyses and investigation of physiological responses during surfing training and competition in different environmental conditions to provide further insights into the specific physiological nature of the sport;
- longitudinal studies to determine the physiological responses and adaptations to surfing training and detraining;
- more detailed physiological and neuromuscular assessment of surfers of various levels;
- investigations into the effects of travel on surfing performance;
- further studies establishing the incidence of both acute and overuse injuries, and the effects of training and technique modifications on injury incidence.

The final outcome of many surfing contests is often decided by only a few tenths of point. Therefore, even very small changes can impact a surfer's ability to succeed or fail. Future findings will help to gain a better understanding of the sport and eventually to bring surfing to the next level of performance. Moreover, individual athletes might benefit from better and more consistent performance, fewer injuries, and, as a result, enjoy longer careers.

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