ABSTRACT

Competitive surfing is a growing sport with evolving performance and safety demands. One particular challenge surfers face is the need to endure long breath-holds following bouts of surf paddling. The purpose of this study was to examine the association between aerobic fitness markers, such as VO₂peak and ventilatory thresholds, and post-paddling breath-hold capacity in competitive surfers. Eleven male collegiate level competitive surfers completed both a maximal graded exercise test and a simulated post-paddling breath-hold challenge on a modified paddling ergometer. Associations between markers of aerobic fitness and post-paddling breath-hold capacity were tested using linear regression modeling. The overall regression model indicated a positive linear association between the assessed markers of aerobic fitness and post-paddling breath-hold capacity ($r = .828$, $r^2 = 0.686$, $p = 0.035$). This association was explained by differences in VO₂peak ($\beta = 0.975$, $p = .034$). These findings suggest that VO₂peak may be an important training target for programs aimed at improving breath-hold capacity in surfers.

KEY WORDS: Surfing, aerobic capacity, ventilatory thresholds

INTRODUCTION

The sport of surfing has grown significantly in popularity since its development in the 15th century and will make its debut as an Olympic sport at the Tokyo games in 2020 (1). The heightened popularity and competitive stakes of surfing have naturally sparked an interest in characterizing the performance demands these athletes are undertaking. Farley et. al (6) observed a population of competitive surfers during two 20-minute surfing sessions in order to characterize the session’s physical components and physiological demands of surfing. The results suggest that on average during a competitive surfing session, each minute is composed of two 20-30-second intervals of moderate-vigorous paddling, a 15-second interval of wave riding, and a 15-second recovery interval. Given the intermittent aerobic nature of the sport, it’s possible that commonly assessed markers of aerobic fitness such as peak aerobic capacity (VO₂peak) and ventilatory thresholds, may be critical targets in a surfer’s training regimen.
As the popularity and competitive nature of surfing reaches new heights, the performance demands and associated risks these athletes are exposed to increases significantly. The most extreme risks are taken by “big wave surfers”, who routinely paddle or get towed into waves exceeding 20 ft in height. Regardless of wave size, there are many challenges that may force a surfer to endure an underwater breath-hold immediately following a bout of moderate-vigorous intensity aerobic exercise (6). The breath-hold challenge may be induced by a “hold down”, in which the surfer has an unsuccessful attempt to ride a wave and is pushed under water by the force of the breaking wave. Surfers are also challenged to hold their breath under water as they are paddling out to the “lineup” or area of the ocean where the waves begin to break. During this time, surfers must “duck dive” under oncoming waves so that they continually make progress towards the lineup rather than being washed backwards by the wave. In either scenario, the biggest physiological challenges to breath-hold capacity a surfer faces are increases in the production of carbon dioxide (VCO\(_2\)) as exercise intensity increases. CO\(_2\) crosses the blood-to-brain barrier, lowers the pH of interstitial fluids, and stimulates the drive to breathe in the respiratory control center (16). This should ultimately result in an acute reduction in breath-hold capacity following a bout of aerobic exercise such as those performed during a surfing session. This phenomenon has been observed consistently in other populations of aqueous athletes, such as competitive breath-hold divers and swimmers (3, 9). However, these relationships have not been studied specific to acute bouts of surf paddling.

The growing performance demands and potentially fatal risks of drowning while surfing highlight the need to identify easily assessable physiological training targets that may be associated with improved breath-hold capacity. Identifying training targets associated with improved drowning-related safety could inform the development of out-of-water strength and conditioning programs aimed at improving surfer’s post-paddling breath-hold capacity. Surfers face unique training challenges due to constantly changing oceanic conditions that limit the type and volume of in-water training they can perform, therefore having out-of-water training alternatives is paramount in maintaining surfing related fitness. Previous research in competitive breath-hold divers indicates that both specific breath-hold training exercises and aerobic exercise training can reduce oxidative stress and metabolic acidosis during breath-holding, ultimately resulting in enhanced breath-hold capacity (7, 18). However, surfers represent a unique population of athletes that may incur similar improvements in breath-hold capacity through supplemental breath-hold and aerobic exercise training. Research directed at examining the association between markers of aerobic fitness such as VO\(_2\)\(_{\text{peak}}\) and ventilatory thresholds with post-paddling breath-hold capacity will further our understanding of the potential role of aerobic exercise training in enhancing the in-water safety of these athletes. Previous studies have demonstrated that these markers are 1) positively associated with a surfer’s performance (8, 10, 14) and 2) inversely related to VCO\(_2\) during paddling exercise (7). However, no studies have examined the association between these parameters and surfer’s breath-hold capacity. Therefore, the purpose of this study was to determine if VO\(_2\)\(_{\text{peak}}\) and ventilatory thresholds are associated with post-paddling breath-hold capacity in collegiate level competitive surfers. We hypothesized that there would be a positive association between surfer’s post-paddling breath-hold capacity and these classically observed markers of aerobic fitness.
METHODS

Participants
A sample of eleven male collegiate level surfers were recruited and screened for participation. In order to be included in the study, participants had to meet the minimum criteria to compete on the “A” level team at the California Polytechnic State University, which is reserved for the team’s most skilled surfers. In order to compete on the “A” level team, surfers must exhibit the ability to perform multiple turns, carves, and air maneuvers on a single wave. The decision to include only male participants was made due to a small population of existing female surfers on the “A” team, none of which volunteered for the study. Participants were excluded from the study if they had any pre-existing cardiovascular, respiratory, metabolic, or orthopedic conditions that would limit their participation in moderate-to-vigorous physical activity. All study procedures as well as the risks and benefits of participating in the study were explained to each participant both in writing and verbally. Participants provided written informed consent prior to participating in any aspect of the study. All procedures were approved by the institutional review board at the California Polytechnic State University.

Protocol
Participants completed two testing sessions in the Human Performance Laboratory at the California Polytechnic State University. Each session was separated by a one-week washout period. Prior to each visit, participants were asked to avoid engaging in moderate-to-vigorous intensity exercise for at least 24 hours. The goal of the first testing session was to familiarize the participant with all study procedures, obtain informed consent, collect anthropometric measures (height and weight), and assess VO2peak and ventilatory thresholds. The goal of the second testing session was to test the participant’s breath-hold capacity following a simulated surf paddling bout.

Participants completed a maximal graded exercise test on a modified Vasa Swim Ergometer (Vasa Inc., Essex Junction, VT, USA). The ergometer was modified in a surfing specific fashion by affixing a surfboard to the ergometer and placing towels under the surfer’s chest to simulate the in-water angle of the surfboard using previously validated methods (5). A visual depiction of the modified ergometer set-up is provided in Figure 1 below. Once participants were familiarized with the ergometer and the procedures, they began a 2-minute warm-up period in which they were asked to maintain a power output of 20 watts. Following the warm-up, participants were asked to increase their power output by 10 watts each minute until volitional exhaustion. Minute ventilation (VE), VO2, and VCO2 were assessed via open circuit spirometry with a Parvo Medics True One 2400 metabolic cart (Parvo Medics, Sandy, UT, USA). Heart rate was continuously monitored via Polar H7 heart rate monitor (Polar Electro Inc, Bethpage, NY, USA).

All graded exercise testing data were examined by a blinded member of the research staff and validated by an unbiased trained expert. VO2peak was identified as the highest VO2 observed during the graded exercise test. Ventilatory thresholds were determined via visual inspection of the VE, ventilatory equivalents for oxygen (VE:VO2) and carbon dioxide (VE:VCO2), and
VCO₂:VO₂ curves over time (2). Generally, in response to incremental aerobic exercise, $V_E$ will increase linearly with two exponential inflexions in the rate of increase. The first ventilatory threshold (VT1), sometimes referred to as the anaerobic threshold, was identified as the VO₂ at which: 1) the first exponential inflexion in the $V_E$ curve occurred and 2) there was a concurrent increase in $V_E$:VO₂ with no increase in $V_E$:VCO₂. The second ventilatory threshold (VT2), sometimes referred to as the point of respiratory compensation, was identified as the VO₂ at which: 1) the second exponential inflexion in the $V_E$ curve occurred and 2) there was a concurrent inflexion in the VCO₂:VO₂ curve.

**Figure 1.** Participant is performing a maximal graded exercise test on a swim ergometer with surfing-specific modifications while ventilatory gases are collected.

**Statistical Analysis**

Shapiro-Wilke tests for normality were conducted in order to test for normal distributions in our primary independent and dependent variables. Descriptive statistics were calculated for all variables as Mean ± SD. Linear regression modeling was utilized in order to test the association between the dependent (post-paddling breath-hold capacity) and independent variables (VO₂peak, VT1, and VT2). Significance for all statistical tests were assessed using an α-level criterion of $p < 0.05$. All analyses were performed in SPSS (version 24, Chicago, IL)
RESULTS

Descriptive characteristics of the participants are summarized in Table 1 below. As expected in a population of collegiate level surfers, their levels of aerobic fitness were in between that of recreational and nationally ranked surfers examined in previous studies (10, 13). In relation to our hypothesis, the overall regression model indicated a positive linear association between the assessed markers of aerobic fitness and post-paddling breath-hold capacity \((r = .828, r^2 = 0.686, p = 0.035)\). Of the three aerobic fitness parameters examined, only \(\text{VO}_2\text{peak} \) \((\beta = 0.975, p = .034)\) and not \(\text{VT1} \) \((\beta = -0.308, p = .215)\) or \(\text{VT2} \) \((\beta = 0.305, p = .451)\) were associated with post-paddling breath-hold capacity. Specifically, a higher \(\text{VO}_2\text{peak} \) for surf paddling was associated with a longer post-paddling breath-hold duration. This relationship is depicted visually below in Figure 2.

Table 1. Descriptive Characteristics

| Variable                                | Mean ± SD |
|-----------------------------------------|-----------|
| Age (years)                             | 22.1 ± 2.4|
| Weight (kg)                             | 73.3 ± 6.6|
| \(\text{VO}_2\text{peak} \) (L/min)     | 2.8 ± 0.5 |
| \(\text{VO}_2\) @ VT1 (L/min)           | 1.3 ± 0.2 |
| \(\text{VO}_2\) @ VT2 (L/min)           | 2.0 ± 0.4 |
| Peak aerobic power (watts)              | 140.0 ± 33.1|
| Peak sprint power (watts)               | 215.5 ± 38.1|
| Post-paddling breath-hold capacity (sec)| 27.8 ± 13.3|
| % change in breath-hold capacity from rest | -79.2 ± 7.5|

Figure 2. There was a strong linear association between \(\text{VO}_2\text{peak} \) for surf paddling and post-paddling breath-hold capacity in this population of surfers.

\begin{equation}
y = 20.885x - 30.334 \\
r^2 = 0.5202
\end{equation}
DISCUSSION

The purpose of this study was to determine if VO$_{2\text{peak}}$ and ventilatory thresholds are associated with post-paddling breath-hold capacity in collegiate level competitive surfers. We hypothesized that there would be a positive association between surfer’s post-paddling breath-hold capacity and these classically observed markers of aerobic fitness. The results suggest that in this population of surfers, VO$_{2\text{peak}}$ was positively associated with post-paddling breath-hold capacity. There was no association between ventilatory thresholds and post-paddling breath-hold capacity in this population.

Our findings suggest that enhancing VO$_{2\text{peak}}$ for surf paddling may be an ideal target for experimental training programs aiming to improve surfer’s drowning-related safety. While ventilatory thresholds were not related to post paddling breath-hold capacity, they appear to be important training targets related to surfing performance. Multiple studies have found that anaerobic thresholds, and not VO$_{2\text{peak}}$, are related to surfing performance in both recreational and competitive surfers (5, 10, 14). The collective findings of this body of research suggest that enhancing VO$_{2\text{peak}}$ and ventilatory thresholds may both be important training targets for surfers, albeit for different reasons. More specifically, VO$_{2\text{peak}}$ may be an important safety related training marker, while ventilatory thresholds may be more useful as performance markers. Similar findings have been reported regarding aerobic fitness and the “diving response”, or blunting of heart rate during exercise that occurs when athletes are immersed in water. Specifically, Bove et. al (4) found that breath-hold divers with higher levels of aerobic fitness exhibited higher degrees of bradycardia during aqueous exercise compared with lesser fit divers. This is likely due to classically observed increases in stroke volume following aerobic exercise training, which help improve metabolic efficiency at any absolute intensity of exercise (17). Ultimately, this enhanced efficiency will reduce VCO$_2$ and result in a decreased drive to breathe. Indeed, enhanced aerobic fitness has been previously related to a decreased VCO$_2$ during paddling exercise (7).

In this population of surfers, a 30-second bout of surf paddling decreased breath-hold capacity by an average of 79.2%. The observed decrease highlights the significant ventilatory disadvantage surfers are exposed to during a “hold-down” or a “duck-dive” following bouts of paddling. Given this knowledge, surfers should be engaging in sport specific training practices aimed at improving their breath-hold capacity. Specifically, breath-hold training programs involving alternating intervals of 20-seconds of breath-holding and 40-seconds of moderate intensity aerobic exercise have been shown to reduce oxidative stress and blood acidosis in highly-trained breath-hold divers (7). While it is likely that this response to training would be observed in surfers, no such studies have been conducted in this population. Our findings provide a physiological rationale for testing the efficacy of a similar breath-hold training program in surfers.

This was the first study to examine the association between markers of aerobic fitness and post-paddling breath-hold capacity in surfers. Another strength of this study was the use of surfing specific exercise testing equipment and procedures. Additionally, the anthropometric and
physiological characteristics of our surfers were in line with the expected values for a population of collegiate level competitive surfers (5, 10, 11, 14, 15).

While this study had several strengths, it is not without limitation. First, a sample size of 11 surfers may limit our ability to detect differences in ventilatory thresholds. Second, given the use of a homogenously male and well-trained population, these findings may not be generalizable to female or recreational surfers. Future studies should examine the relationship between aerobic fitness markers and breath-hold capacity in more diverse populations of surfers. Finally, while the use of surf paddling ergometry provides a highly controllable sport-specific testing medium, it does not replicate oceanic environmental conditions. Researchers should work to create testing methods and post-paddling breath-hold protocols that can be utilized in an oceanic environment to confirm the legitimacy of these findings.

In conclusion, our findings suggest that enhancing VO$_2$peak may aid in improving surfer’s post-paddling breath-hold capacity. Given that aerobic paddling makes up the majority of surf training and competition (6), it is likely that surfers could benefit from participating in a breath-hold training program employing alternating bouts of aerobic paddling and breath-holding. The use of surf paddling ergometers such as the one used in this study may be a convenient way for surfers to train in this fashion, especially when oceanic conditions limit in-water training opportunities. Randomized controlled training studies are needed determine the effects of supplemental aerobic surf paddling programs on post-paddling breath-hold capacity in this unique population of athletes.

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