Electromyographic Analysis of the Surf Paddling Stroke Across Multiple Intensities

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Abstract

Nessler, JA, Ponce-Gonzalez, JG, Robles-Rodriguez, C, Furr, H, Warner, M, and Newcomer, SC. Electromyographic analysis of the surf paddling stroke across multiple intensities. *J Strength Cond Res* XX(X): 000–000, 2019—Surfers spend a majority of their time in the water paddling. The purpose of this study was to examine activity in 5 muscles that contribute to paddling at different velocities and to characterize oxygen use, paddling cadence, and surfboard motion at each velocity. Twelve recreational surfers completed an incremental paddling test on a shortsurfboard in a swim flume. Surface electromyography was recorded bilaterally from latissimus dorsi, upper and mid trapezius, and posterior and mid deltoid. Electromyographic activity increased as water velocity increased for all muscles, but the change in activation between endurance and sprint paddling was greatest for latissimus dorsi ($p < 0.001$). At higher water velocities, the middle deltoid was activated earlier in the paddling stroke ($p = 0.005$). Oxygen use, paddling cadence, and surfboard roll/yaw increased with increasing water velocity. These data may be useful for athletes, trainers, and equipment designers interested in increasing power and efficiency of the paddling stroke.

Key Words shoulder, upper extremity, surfing

Introduction

The sport of surfing has grown in popularity in recent decades. Current estimates for participation are as high as 20 million persons worldwide (19,35). In 2020, surfing will be incorporated into the summer Olympic Games for the first time in history (36). Like many sports, physical conditioning and skill are crucial to an athlete's success (10,13,15,21,33), and there is growing interest in strength, cardiovascular conditioning, and motor learning to improve performance (6,12). Although there are numerous professionals and facilities that market themselves as resources to support the training and preparation of surfing athletes, much remains unknown regarding the physical demands of the sport and the optimal ways to train. Furthermore, an improved understanding of human performance in the sport of surfing may lead to improvements in equipment design.

Paddling is an important component of surfing and an area in which physical training can impact performance. Several studies have reported that a surfer spends between 40 and 60% of their time in the water paddling (3,11,17,21,23,25), and data suggest that there are measurable differences in paddling ability that are associated with skill level (10,15,33). Surfers who lack stamina become fatigued and are unable to maneuver and position themselves in the proper place to catch waves (17). Surfers who are unable to paddle at higher maximal velocities often experience difficulty while standing up on more challenging waves (6,31–33). This occurs because a surfer who is unable to paddle at an adequate velocity will catch the wave late and will be forced to stand while the wave is breaking, often while their board is positioned on the more vertical aspect of the wave's surface. Improper paddling or lack of physical conditioning may also lead to injury. Epidemiological data suggest that the most common chronic injuries among surfers include the low back and shoulder, both of which are often reported to be aggravated during extended bouts of paddling (14,26,28).

To date, studies that have analyzed the surf paddling motion are limited in number and scope. Two specific shortcomings in previous literature were addressed here. First, detailed analyses of surfboard paddling in previous studies have focused on performance at a single paddling speed (8,27–29). These analyses are inadequate because surfers paddle at a wide range of intensities in the water (1,3,11,17,21,23,24). For example, surfers often engage in endurance paddling, which occurs when an athlete paddles out into the lineup or paddles to maneuver themselves in position to catch a wave. This low to moderate paddling intensity can be maintained for at least 3 minutes in experienced, recreational surfers (27) and at least 6 minutes in competitive surfers (12). Global positioning system and video

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data indicate that endurance paddling typically involves paddling at velocities between 0.8 and 1.1 $m \cdot s^{-1}$ (3,11,17). Furthermore, when competitive surfers were asked to paddle a distance of 400 m, the average time was approximately 360 seconds with a velocity of 1.1 $m \cdot s^{-1}$ (12). Surfers also engage in sprint paddling, which occurs while the athlete is attempting to catch a wave. This type of paddling is performed at maximal effort, often for very short durations (less than 10 seconds) (11,12). One group has reported that competitive surfers were able to achieve maximum paddling velocities of 1.6 (12), 1.7 (32), and 1.77 $m \cdot s^{-1}$ (31) on average while paddling a distance of 15 m in a pool. A second group reported that competitive surfers were able to paddle at a velocity of 1.89 $m \cdot s^{-1}$ during a 10-second trial in a 25-m pool (21).

A second shortcoming in the literature relates to a lack of muscle activation data in the upper extremity while paddling in water. Some information regarding muscle activation during the surf paddling stroke might be gleaned from analyses of the front crawl stroke in swimming and a previous study that analyzed paddling using a land-based ergometer (5,20,22,29,30,34). For example, earlier studies report that electromyographic (EMG) activity generally increases as swimming speed and intensity increase (2,5,20). However, none of these previous studies are adequate analogs for paddling a surfboard in water. Freestyle and front crawl swimming involve significant lower extremity muscle activation (22), and the athlete is submerged to a greater depth when compared with paddling a surfboard, which may alter upper extremity biomechanics. Land-based ergometers that can be modified to mimic surfboard paddling do not simulate the instability and motion of a board in water, and they lack the spatial reference of the surface of the water, tactile feedback of motion through fluid, and drag force distributed across the entire submerged portion of the arm (29). Additional data, specific to paddling a surfboard in water at various speeds, are needed to improve the overall understanding of muscle activity during the surf paddle stroke.

Therefore, the primary purpose of this study was to characterize upper extremity muscle activation generated by surfers while paddling across a range of relative velocities in water. Muscle recruitment patterns at different velocities were examined and compared for muscles with differing function (propulsion, return/placement of the arm, and scapular rotation) to provide insight into their relative contributions to endurance and sprint paddling. Based on the previous literature in front crawl swimming (5,20,22), it was hypothesized that muscle activation in the upper extremity would increase uniformly as relative velocity increased, and that the relative timing of muscle activation would remain consistent across paddling velocities. A secondary purpose of this study involved the analysis of $\dot{V}O_2$, paddling cadence, and surfboard motion while surfers paddled at each velocity. Based on the previous experiments in other sports, it was hypothesized that oxygen use ($\dot{V}O_2$) would increase as participants paddled at greater relative velocities. Finally, it was hypothesized that surfboard motion (roll angle and yaw acceleration) would increase, as athletes are required to paddle at a higher velocity, based on data from earlier experiments (8,27).

Methods

Experimental Approach to the Problem

This study characterized the activation of 5 muscles in the upper extremity while surfers paddled at different intensities. This was accomplished by asking surfers to complete a paddling test in a swim flume, as the water velocity was precisely controlled and progressively incremented from 0.6 $m \cdot s^{-1}$ up to each surfers' maximum paddling velocity. While paddling at each velocity, surface EMG was used to record and compare the magnitude and timing of activation of the latissimus dorsi, upper and mid trapezius, and posterior and mid deltoid of the right and left arms. This approach also allowed for the comparison of oxygen consumption ($\dot{V}O_2$), paddling cadence, and surfboard motion (roll and yaw) at different water velocities.

Subjects

Twelve recreational surfers (9 male and 3 female; age 29.75 ± 9.15 years, height 1.76 ± 0.09 m, and body mass 72.22 ± 17.96 kg, subject characteristics measured mean ± *SD*) were recruited from the local surfing population. Prospective surfers were included if they met age requirements (18–45 years), had a minimum of 5 years of surfing experience, and currently surf at least 3 days per week. Participants were excluded if they did not meet the inclusion criteria or exhibited any health risk or condition that would affect paddling performance. This study was primarily descriptive; therefore, the number of participants was selected to provide sufficient data for characterization of the paddling stroke and to be consistent with previous research of a similar nature (11,29,32,33). All participants completed a brief surf history questionnaire, a health history questionnaire (AHA/ACSM Health/Fitness Facility Participation Screening Questionnaire). All participants were informed of the benefits and risks associated with participation and provided their written informed consent on an institutionally approved document before any data collection. All procedures were approved by the institutional review board at California State University, San Marcos.

Procedures

Participants were asked to refrain from exercise for the 24 hours preceding data collection and to avoid eating a heavy meal or caffeine ingestion for 3 hours before data collection. All participants performed 2 incremental paddling tests on the same day as part of a separate study, each test separated by a 90-minute recovery period. One test was performed on a swimbench ergometer (Vasa Inc., Essex, VT), and the other was performed while paddling in a fresh water swim flume (Endless Pool Elite, Fitness Machines, LCC, Aston, PA). The test order was randomized across participants. Because data from the swim flume are most analogous to paddling in the ocean, only data from that test are presented here.

All participants paddled the same short surfboard (5′10 × 18 × 2 1/4 in.) for their test in the swim flume to facilitate more direct comparison of performance across surfers. Surfboard size was not controlled in previous sprint paddling experiments, and it is possible that differences in maximum paddling velocity among participants in previous studies might be partially attributable to differences in board size, as most previous studies allowed surfers to use their personal boards (12,21,32). Participants wore either boardshorts (male) or standard 2 piece swimsuit (female) and did not wear a wetsuit. The outdoor swim flume consists of a custom-sized pool (2.75 m wide × 4.9 m long) and motorized turbine that generates a precisely controllable, constant flow of water against the paddling surfer. The incremental paddling test in the swim flume began at a speed of 0.6 $m \cdot s^{-1}$ and increased by 0.1 $m \cdot s^{-1}$ every minute until the surfer was no longer able to keep up with the flow of water. Water velocity was measured and verified at each stage in the test using a flow-watch flow meter (JDC Electronics, Yverdonles-Bains, Switzerland). Water temperature was maintained between 18 and 21° C for all trials.

Oxygen consumption ($\dot{V}O_2$, expressed in $mL \cdot kg^{-1} \cdot min^{-1}$) and respiratory exchange ratio were measured using a TrueOne 2400 metabolic measurement system (Parvo Medics, Sandy, UT). An oro-nasal mask (Hans Rudolph Inc., Shawnee, KS) and 5-m tube were used to capture gas exchange at 15-second intervals for the duration of the test. The extended tube length was accounted for in calculations of $\dot{V}O_2$ using a mathematical offset recommended by the manufacturer (Parvo Medics).

Muscle activation was measured at 1,926 Hz using Delsys Trigno wireless EMG electrodes, placed over the surface of the upper trapezius, mid trapezius, middle deltoid, posterior deltoid, and latissimus dorsi on the right and left hand side of the participant (10 EMG sensors total, Figure 1). Detailed description of EMG electrode placement has been provided previously (28,29). These muscles were selected to represent each of the 3 primary muscular actions performed during the paddling stroke: propulsion, arm return/placement, and scapular rotation/retraction. Limitations exist for measuring the activation of muscles on the ventral surface of the athlete (e.g., pectoralis major and serratus anterior) because these sensors are often submerged and physically interact with the surface of the surfboard, typically resulting in significant motion artifact (29). Sensors were then covered with a waterproof adhesive bandage (3M Nexcare Tegaderm) and remained in place until the participant had completed both paddling trials (ergometer and swim flume) on the same day. An additional Trigno sensor was placed on the top of the surfboard near the nose, and the integrated accelerometer function was used as a tilt sensor to measure pitch and roll angles, as well as yaw acceleration of the board (captured at 150 Hz). The tilt angle of the board was measured at rest in still water to be used to offset readings captured while participants were paddling. All EMG sensors were tested, and each signal was verified before data collection began.

Figure 1. Experimental setup: Instrumented participant paddling at 1 $m \cdot s^{-1}$ in a freshwater swim flume.

Statistical Analyses

Electromyography and accelerometer data were filtered (fourth-order Butterworth with 20- and 40-Hz cutoff, respectively) (7). Time series acceleration data from the middle deltoid sensors were used to determine the beginning and end of each stroke by identifying local minima in the filtered data. The average timing difference between the occurrence of the local minima of the acceleration and the beginning of the paddling stroke was determined from pilot analysis that compared video footage with accelerometer data. The beginning of each stroke in the current data was then determined by applying this correction factor to each local minimum. Average stroke duration and cadence were also calculated using accelerometer data for both the right and left arms. Electromyography data were full wave rectified, filtered (described above), and then averaged across all complete strokes captured during each stage of the test. The area under the curve was then calculated for the mean EMG-stroke profile for each muscle. Electromyography data were normalized by the dividing raw data (in mV per second) by the highest EMG area under the curve detected for each subject. Electromyography data were then expressed as a percentage of maximal activation achieved during the test. Data acquired for the left and right side were averaged together for each participant. The use of maximum voluntary isometric contractions (MVICs) is a common method for normalizing EMG activity; however, this approach was not used here due to challenges associated with obtaining valid maximal contractions in upper and middle trapezius (9) and reports that athletes often exceed their MVIC when performing dynamic movements such as swimming (20).

Average surfboard roll range of motion and the average pitch angle were calculated from the filtered time series data

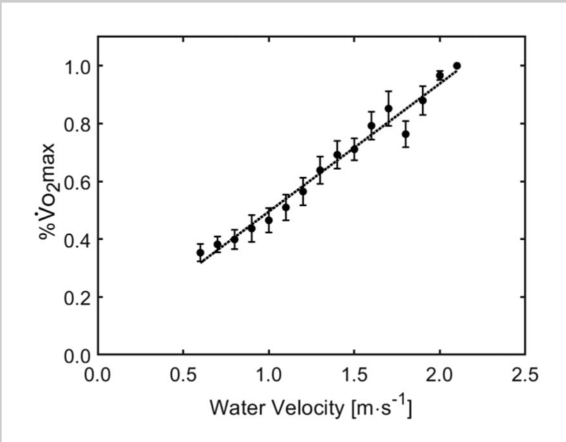

Figure 2. Oxygen consumption as a function of water velocity while paddling a short surfboard ($n = 12$) in a swim flume. Averages are taken from all participants who were able to paddle at each stage. $R^2 = 0.970$. Bars represent *SEM*.

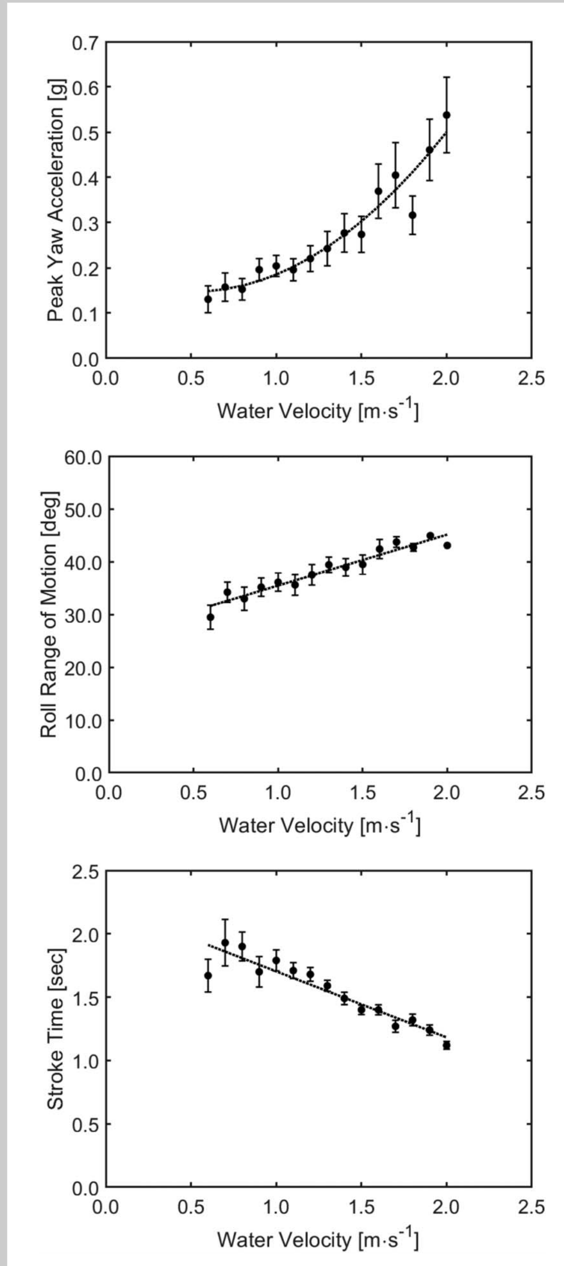

Figure 3. Surfboard and paddling mechanics as a function of water velocity. Averages are taken from participants who were able to paddle at each stage. $R^2 = 0.96$ for yaw acceleration (exponential fit), $R^2 = 0.93$ for roll range of motion, and $R^2 = 0.88$ for stroke time. Bars represent *SEM*.

acquired from the Trigno sensor placed on the nose of the board. Peak yaw acceleration was also recorded from the filtered accelerometer data by finding the largest value for acceleration for each stroke that occurred during each stage of the test, and then averaging these values across all strokes measured for each trial. All EMG data, $\dot{V}O_2$ data, stroke duration, and surfboard roll and yaw were averaged across participants and then plotted with respect to water velocity (ranging from 0.6 to 2.0 m·s^{-1}) and fit by either a linear (stroke time, board roll, and $\dot{V}O_2$) or exponential (board yaw acceleration, muscle activation) least squares-regression function. All plots and R^2 values were provided for comparison.

To compare muscle recruitment during endurance vs. sprint paddling across the 5 muscles examined here, a value for muscle activation during each paddling condition was acquired as follows. Raw EMG data for each muscle captured at 1.0 m·s^{-1} were recorded as an index of muscle recruitment that occurred during endurance paddling. Similarly, raw EMG data acquired at 1.6 m·s^{-1} were recorded as an index of muscle recruitment that occurred during sprint paddling. Velocities for endurance and sprint paddling were selected based on data from the previous experiments that indicate that most of the endurance paddling occurs at a velocity between 0.8 and 1.1 m·s^{-1} and sprint paddling at velocities up to 1.7 m·s^{-1} in competitive athletes (6,8,12,28). In the current data, 10 participants were able to paddle at velocities up to 1.6 m·s^{-1}, but 2 participants were unable to paddle at velocities greater than 1.4 m·s^{-1}. Therefore, the "sprint" paddling index for these 2 participants used muscle activation data for the final stage of their test (1.4 m·s^{-1}) from the left and right side. For all participants, the endurance index was subtracted from the sprint index to obtain a difference in muscle activation and divided by the sprint index to express the increase in EMG activation as a percent change. The percent change in EMG was then compared across the 5 muscles examined here, using repeated-measures analysis of variance (ANOVA). Post hoc analysis was performed using paired *t*-tests that compared differences between individual muscles.

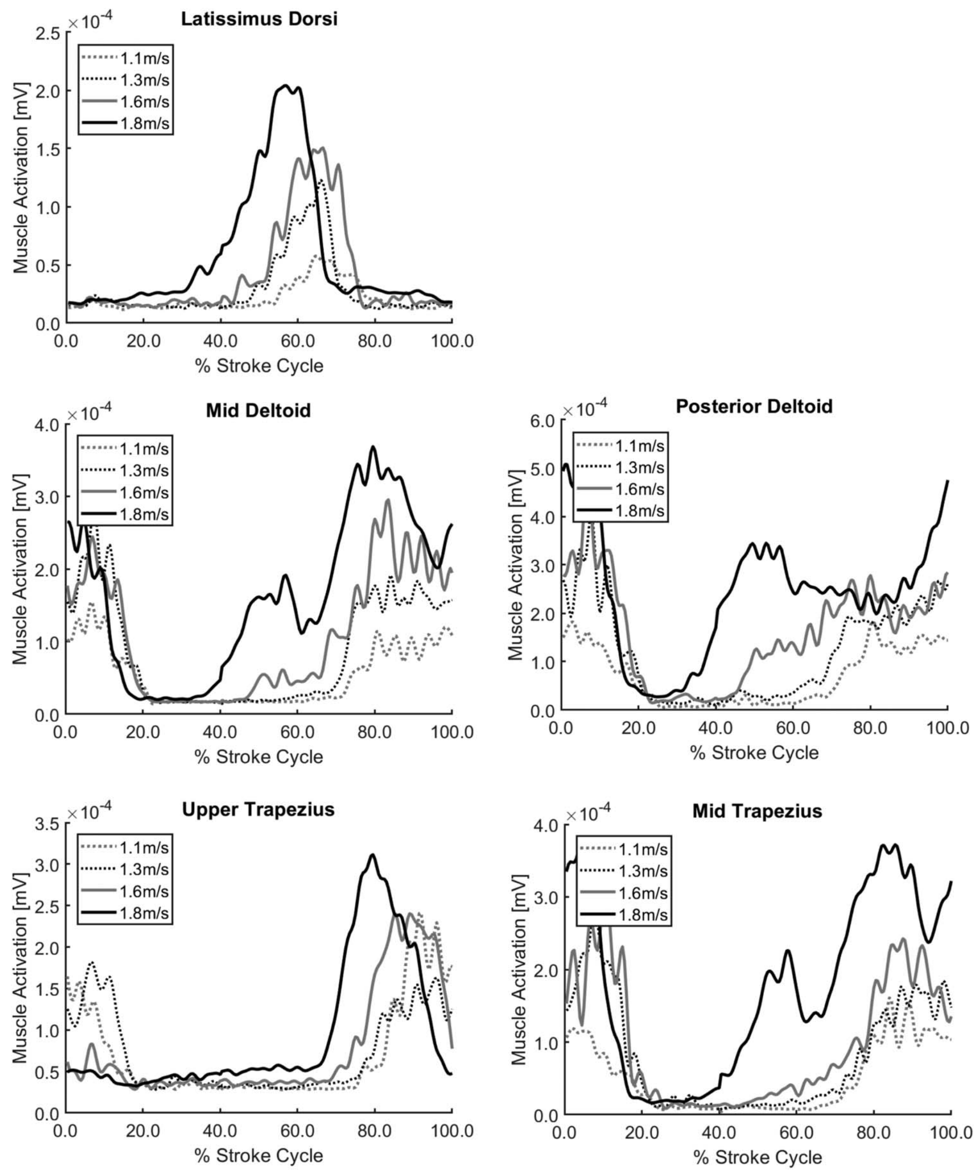

Figure 4. Muscle activation profiles, averaged across strokes for the right side only, for a representative participant paddling at 4 different water velocities. Data are rectified and low pass filtered (fourth-order Butterworth, cutoff 20 Hz) and are expressed with respect to the stroke cycle (0% = hand at most anterior or cranial position).

A similar approach was used to compare the duration of muscle activation between endurance and sprint paddling conditions. Using the mean EMG profiles for each subject, the percentage of the stroke in which each muscle was activated was determined for the 1.0 $m \cdot s^{-1}$ trial (endurance condition) and the 1.6 $m \cdot s^{-1}$ trial (sprint condition). For the 2 participants who were unable to paddle at velocities greater than 1.4 $m \cdot s^{-1}$, the data from their highest stage were used for their sprint condition. The change in percent activation between paddling conditions was then calculated by subtracting the endurance data from the sprint data, and compared across muscles using repeated-measures ANOVA. Post hoc analysis was performed using paired *t*-tests that compared differences between individual muscles. A family-wise significance level of 0.05 was used to determine significance for all statistical tests, and the Bonferroni correction was used to adjust for multiple comparisons for both sets of post hoc tests.

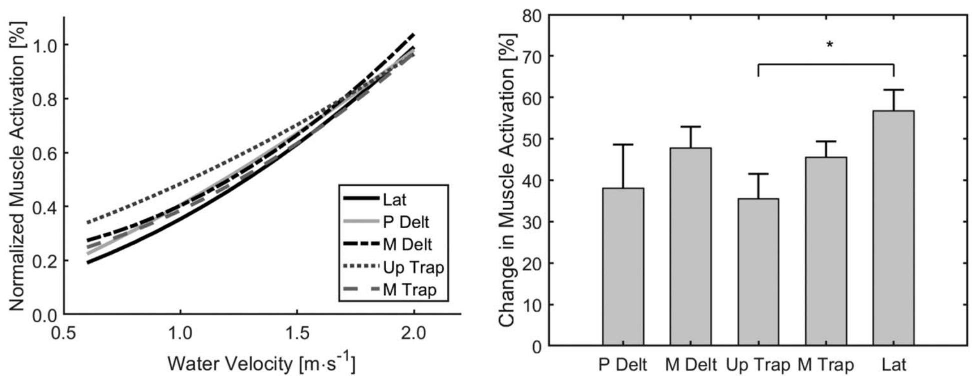

Figure 5. Changes in muscle activation across water velocity ($n = 12$). Left: muscle activation expressed as a percentage of the maximum activation level measured for each subject. Changes in muscle activity were best fit with a second-degree polynomial. Right: percent change in muscle activation between endurance paddling condition (1 m·s^{-1}) and sprint paddling (1.6 m·s^{-1}). A significant difference in percent change was detected between upper trapezius and latissimus dorsi (denoted by *). Bars represent *SEM*.

Results

All participants were able to complete at least 9 stages of the incremental test, achieving a paddling velocity of at least 1.4 m·s^{-1}. Ten of the 12 participants were able to achieve a paddling velocity of 1.7 m·s^{-1}, and 3 participants were able to complete stages at velocities of 2.0 m·s^{-1} or greater.

Oxygen consumption increased linearly as participants paddled at greater water velocities ($R^2 = 0.97$, Figure 1). The average peak $\dot{V}O_2$ attained was 31.38 ± 6.03 ml·kg^{-1}·min^{-1} (95% confidence interval [CI]: 27.97–34.79 ml·kg^{-1}·min^{-1}). Average stroke time decreased linearly as water velocity increased ($R^2 = 0.88$, Figure 2), yielding cadences between 35.94 ± 9.65 (95% CI: 30.48–41.4) and 53.61 ± 5.07 (95% CI: 50.74–56.48) strokes/min per arm at 0.6 and 2.0 m·s^{-1} respectively. Peak yaw acceleration also increased with increasing water velocity, but this relationship was best fit by an exponential curve ($R^2 = 0.96$, Figure 2). Surfboard pitch angle was 12.33 ± 2.26° (95% CI: 11.05–13.61°) on average, and was relatively unaffected by water velocity. Conversely, the amount of roll that occurred during each stroke (i.e., range of motion) increased with greater water velocities from approximately 26.91 ± 7.88° (95% CI: 22.45–31.37°) to 44.93 ± 0.57° (95% CI: 44.61–45.25°) at 0.6 and 1.9 m·s^{-1}, respectively ($R^2 = 0.88$, Figure 2).

Muscle activation increased at greater water velocities for all muscles examined. A representative sample of EMG activation profiles across 4 paddling velocities is provided in Figure 3. In each case, the relationship between normalized muscle activation and water velocity was best fit by an exponential curve, suggesting that an increase in water velocity of 0.1 m·s^{-1} at slower velocities (i.e., endurance paddling) resulted in a smaller increase in muscle activation when compared with the same change in water velocity occurring at greater velocities (i.e., sprint paddling, Figure 4). Although all muscles exhibited this relationship, latissimus dorsi demonstrated a more extreme rate of muscle recruitment at greater water velocities when compared with the recruitment curves for the other muscles (Figure 4). This observation was supported by statistical analysis, where repeated-measures ANOVA revealed a significant difference in percent increase in muscle activation between endurance and sprint paddling across muscles ($F_{4,10} = 2.692$, $p = 0.045$). Post hoc analysis revealed a significant difference in percent EMG increase

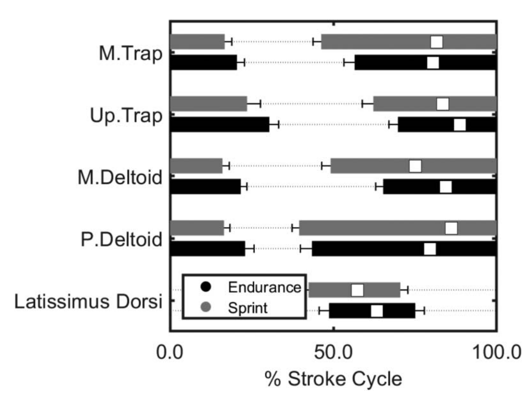

Figure 6. Periods of muscle activation for 5 muscles studied here ($n = 12$) as a function of stroke cycle (0% = hand at most anterior or cranial position). Dark bars indicate periods of the stroke where muscles are active; small white boxes indicate the average point where peak muscle activation was recorded. Data for the right and left limb were averaged together. Endurance refers to paddling at 1 m·s^{-1} water velocity, and sprint refers to paddling at 1.6 m·s^{-1}. A significant difference was noted in the timing of middle deltoid activation between paddling intensities. Bars represent *SEM*.

between the upper trapezius and the latissimus dorsi ($p < 0.001$, Figure 4). Data for 1 subject were removed from statistical analysis because of poor signal obtained from latissimus dorsi.

Increasing water velocity resulted in a significant increase in the duration of activation across the 5 muscles examined here (repeated-measures ANOVA, $F_{4,10} = 3.652$, $p = 0.016$, Figure 5). Post hoc analysis revealed a significant difference in duration between the middle deltoid and both posterior deltoid ($p < 0.001$) and upper trapezius ($p = 0.005$). This increase was generated by activating the middle deltoid earlier in the stroke, toward the end of the propulsive phase, while sprint paddling. During the endurance paddling trial, middle deltoid was not activated until later in the stroke, on average. The remaining 4 muscles examined here exhibited timing patterns that were relatively stable as water velocity increased (Figure 6).

Discussion

The primary purpose of this study was to characterize muscle activation across a range of water velocities while paddling in a freshwater swim flume. The data support the hypothesis that muscle activation would increase in all muscles studied here as water velocity increased. However, this increase in activity was not uniform across muscles. A detailed comparison of endurance vs. sprint paddling revealed that latissimus dorsi (propulsion) experienced a greater increase in activation relative to the *deltoid* (arm placement/return) and trapezius (scapular rotation) muscles. In addition, middle deltoid activation onset occurred earlier during sprint paddling, resulting in a significant increase in duration of activation for this muscle. A secondary purpose of this study was to analyze oxygen use, paddling cadence, surfboard motion at each paddling velocity. The data support the hypothesis that oxygen use, paddling cadence, and surfboard motion would all increase as water velocity increased. In particular, direct, linear relationships were observed between paddling cadence, surfboard roll range of motion, and $\dot{V}O_2$ with water velocity. Peak yaw acceleration of the surfboard exhibited an exponential relationship with water velocity. Additional results included the observation that 3 recreational surfers were able to paddle at a relative velocity of $2.0\ m \cdot s^{-1}$ or greater, and that surfboard pitch angle was relatively unaffected by water velocity.

Electromyography analyses of the front crawl stroke in swimming suggest that upper extremity muscles can be broadly categorized as contributing to propulsion, scapular rotation, and return/placement of the arm (22,30,34). During the front crawl, the primary muscles that contribute to propulsion include the pectoralis major, triceps brachii, and latissimus dorsi, with pectoralis major active during the earlier "pull" interval of the propulsive phase and latissimus dorsi active later during the "push" interval (22,30). The primary muscles that contribute to scapular rotation include the upper and lower trapezius, rotator cuff muscles, and serratus anterior (22,30). In general, the scapular rotators seem to be active throughout the paddling stroke but are most active during the entry and exit phases of the stroke and are least active during the propulsive phase (30). Finally, the muscles that contribute to return/placement of the arm include the deltoid (3 heads) and, to a lesser extent, supraspinatus (22,30). Deltoid activation patterns are similar to those of the scapular rotators, although posterior deltoid has also been reported to contribute to propulsion in some cases (30). In a previous analysis performed while surfers paddled a modified, land-based ergometer, muscle activation patterns were relatively consistent with those reported for the front crawl in swimming (29).

The EMG-stroke profiles recorded here during endurance paddling trials (0.8–$1.1\ m \cdot s^{-1}$) are similar to those observed during the front crawl and when paddling a land-based ergometer (29). However, as velocity increased, both the timing and magnitude of activation were altered in the current data. In particular, as water velocity increased, the middle and posterior deltoid seemed to contribute more to propulsion. Evidence for this can be seen in Figure 3 where peaks in EMG activity appear for both middle and posterior *deltoid* at $1.8\ m \cdot s^{-1}$ that correspond roughly with the timing of peak EMG activity for latissimus dorsi during the propulsion phase. In addition, duration of middle deltoid activation was significantly increased during the sprint paddling phase, and this was caused by an increase in activity during the propulsive phase (Figure 5). This suggests that practice to increase sprint paddling capacity should be performed at higher intensities, where proper patterns of muscle recruitment are more likely to occur, rather than assuming that practice at lower intensities will elicit a similar pattern of muscle activation. In addition, these data suggest that the *deltoid* should be considered a propulsive muscle when analyzing the surfboard paddling stroke at higher intensities.

In addition to changes in the duration of EMG activity, there seemed to be a general shift in the timing of muscle activation between endurance and sprint paddling. For example, latissimus dorsi onset and peak activation occurred earlier in the stroke as surfers paddled faster (Figures 3 and 5). This may be the result of increased paddling cadence, which may preclude the completion of a full stroke, thus requiring surfers to focus their propulsive efforts earlier in the stroke to facilitate a faster turnover. This idea is consistent with the previous studies in front crawl swimming that reported changes in muscle activation across cadences while swimming at the same velocity, suggesting that a lower cadence allows an athlete to complete a longer, full stroke (2,4,5). These data suggest that surfers might benefit from a focus on lower cadence with longer and more complete paddling strokes, as swimmers were previously reported to improve their efficiency with a lower cadence.

The magnitude of muscle activation also increased as water velocity increased in all muscles studied here. This result is consistent with a few early studies in front crawl swimming (5,20), but the current data are the first to be reported in surfers while paddling in water at different relative velocities. In addition, latissimus dorsi exhibited the greatest percent increase in activation between endurance and sprint paddling, which is a result that has not been reported to date. This result, combined with the early onset of deltoid activation also observed here, suggests that paddling at higher relative velocities requires greater increases in muscle activity associated with propulsion compared with muscle activity related to arm placement and scapular rotation. Surfers interested in improving sprint paddling velocity should therefore focus on strength of muscles primarily involved in propulsion: pectoralis major, latissimus dorsi, triceps brachii, and deltoid.

Yaw acceleration was previously shown to be related to oxygen use (27), and the current data provide further evidence that it might be used as a proxy for measuring paddling intensity. Oxygen use, as measured by $\dot{V}O_2$, also exhibited a linear relationship with water velocity when normalized. The average peak $\dot{V}O_2$ measured here (31.38 ± 6.03 $ml \cdot kg^{-1} \cdot min^{-1}$) was consistent with data reported for recreational surfers paddling on a land-based ergometer (15), although recent data suggest that using an ergometer to perform this test may underestimate peak $\dot{V}O_2$ (16). Three recreational surfers who participated here were able to paddle at relative velocities greater than 2.0 $m \cdot s^{-1}$ for at least 30 seconds. This is not consistent with studies that recorded maximal sprint velocities in a pool, which have typically reported maximal speeds of 1.7–1.8 $m \cdot s^{-1}$ (6,31,33). This discrepancy may be due to a number of factors, including differences in surfboard size or techniques used for measuring velocity. It is also possible that differences in behavior occur when paddling in still water rather than against a current, similar to biomechanical differences observed in treadmill vs. overground walking (18).

Surfboard roll range of motion was also related to paddling intensity (Figure 2). Increased roll of the surfboard may allow the athlete to insert their arms deeper into the water to generate greater propulsion. Increasing the proportion of the arm that is submerged would provide greater resistance to the stroke and may reduce the potential for "slip" when greater propulsive force is required. Slip refers to excessive motion of the arm with respect to the water, generally resulting in reduced drag (or reaction) force and therefore less propulsive force. The average range of motion for roll observed here is greater than that reported previously (8). However, roll range of motion seems to be related to surfboard volume, and the surfboard used in the current experiment was smaller than those used previously (8).

This experiment was designed to closely simulate paddling in the ocean. However, a number of limitations should be considered when interpreting these data. First, the freshwater in the swim flume results in less buoyant force when compared with salt water, and this may increase drag force and require increased muscle activation. In addition, aside from the current generated by the swim flume, the water was relatively calm and may not have required the surfer to work as hard to maintain an appropriate level of trunk and board stability when compared with paddling in open water where swells and wind are present. Finally, by testing performance at multiple levels of water velocity without giving participants time to rest in between trials, it is possible that a surfer may experience fatigue and end their test at a lower velocity than their true maximum velocity. This limitation may have been exacerbated in participants that performed a $\dot{V}O_2$ maximum test on the land-based ergometer before paddling in the swim flume. Future studies should evaluate the current results by comparing paddling at multiple water velocities, while simultaneously giving participants an opportunity for rest in between trials to facilitate paddling at as high a water velocity as possible. Future studies should also investigate EMG activity in other muscles that are also likely to be important to the paddling stroke (e.g., pectoralis major and serratus anterior).

Practical Applications

Land-based training programs are frequently used by surfing athletes to improve both paddling and wave riding performance. Surfers who are interested in conditioning to improve their paddling technique might benefit from an improved understanding of the contributions of upper extremity muscles to the paddling stroke. This experiment demonstrated that muscle activation increased as water velocity increased for all muscles studied here, but the change in muscle activation between slower paddling (endurance) and faster paddling (sprint) was greatest for latissimus dorsi and lowest for upper trapezius. At higher water velocities, the middle deltoid was activated earlier in the paddling stroke to contribute to propulsion. These data suggest that training techniques focused on strength and power during the propulsive phase of the paddling stroke may lead to improved sprint performance. The muscles that contribute to propulsion include the following: pectoralis major, latissimus dorsi, triceps brachii, and deltoid.

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