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Surfboard Paddling Technique and Neuromechanical Control: A Narrative Review

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Abstract

Surfboard paddling is an essential activity when surfing. Research investigating surfboard paddling, especially as it pertains to neuromechanical control and techniques used, is limited. Previous research made use of swim ergometers to examine surfboard paddling demands. The validity of using swim ergometers in surfboard paddling research and training deserves further analysis. To establish ecologically valid findings, researchers have begun to use swim flumes and still-water paddling environments to investigate paddling efficiency and technique. This emerging body of research has reported that muscle activation patterns, intensities, and timings differ as surfers move through different paddle stroke phases. A deeper understanding of paddling's neuromechanical control may help enhance the understanding of how to improve paddle performance and perhaps reduce injury risk. Therefore, the purpose of this review was to identify the gaps in the existing literature to help identify future research directions in relation to surfboard paddling techniques and neuromechanical control.

Keywords: surfing, surfboard paddling phases, muscle activation, neuromechanical control

Introduction

Competitive surfing has grown rapidly over the past two decades. The Qualifying Series (QS) is an elite world tour competition in which the top ten surfers at the end of the season qualify to compete on the premier world Championship Tour (CT). The QS has grown from 891 males and 105 females in 2011 to 1295 males (45% increase) and 392 females (273% increase) in 2019 (World Surf League, n.d.). Since 2015 the number of spots available on the CT has been limited to 34 males and 20 females. As a result, competition among surfers on the QS who are trying to qualify for the lucrative CT is fierce. With surfing competitions often decided by less than one point on a 20-point scale, it seems logical that any competitive advantage, such as having increased paddling efficiency, may give the surfing athlete a critical edge over competitors.

Paddling is a fundamental skill required to compete successfully in surfing as it enables a surfer to reach the take-off zone and, importantly, to catch waves. Sustaining high levels of muscular endurance when paddling out to the take-off zone is a critical characteristic of surfing. During competitions, reaching the take-off zone first gives the surfer priority to select the wave of their choice (World Surf League, n.d.), potentially enabling them to catch higher quality waves during the heat. Additionally, increased sprint paddling performance that provides early wave entry may enable surfers to catch waves with more ease and to generate more speed, a critical aspect of competitive performance. Entering a wave with optimal speed is likely to result in higher wave scores due to the performance of manoeuvres at higher speed, which is

considered an essential part of the judging criteria applied to point-scoring during competition (World Surf League, n.d.). In the pursuit of a competitive edge, an increased focus on strength and conditioning has occurred in competitive surfing. This increased focus has largely come from multiple research studies profiling the physiological demands of recreational and competitive surfing (Barlow et al., 2015; Loveless & Minahan, 2010; Meir et al., 1991). Despite the fact that paddling constitutes between ~42% to 55% of the total time spent surfing (Farley et al., 2012b; Meir et al., 1991; Mendez-Villanueva et al., 2006; Secomb et al., 2015), a scarcity of research profiling the neuromechanical control and techniques of surfboard paddling exists. Developing a deeper understanding of this aspect of the sport may help to inform the development of sport-specific training programs and experiences as well as to better inform future research.

Given that all surfers, including elite competitors, need to have an efficient and effective paddling technique, exploring the factors that affect paddling performance is essential. This review aims to highlight the current state of the literature as it pertains to the science of surfboard paddling. More specifically, given the dearth of research in this area, this review will explore the current literature related to the techniques and the neuromuscular control of surfboard paddling to identify future research directions.

The Physiology and Physical Characteristics of Surfboard Paddling

To appreciate surfboard paddling technique and neuromechanical control, it is important first to understand the physiological and physical demands of surfboard paddling. Surfers spend ~50% of each surf session paddling (Mendez-Villanueva & Bishop, 2005). This requires a combination of both muscular endurance and power, dependent on the type of paddling activity (Mendez-Villanueva & Bishop, 2005). For instance, having increased muscular endurance is advantageous for the paddle out because having increased upper body anaerobic power may enable surfers to paddle faster for longer and thereby catch more and higher quality waves. The importance of paddling to the outcome of surfing has been reinforced by multiple studies investigating heart rate (HR) response (Farley et al., 2012b; Meir et al., 1991; Mendez-Villanueva & Bishop, 2005; Secomb et al., 2015) and oxygen consumption (VO_2) (Almeida et al., 2018; Barlow et al., 2015; Furness et al., 2018; Loveless & Minahan, 2010; Meir et al., 1991) while paddling in different environments. Furthermore, researchers have also started investigating other potential influencing factors, such as upper limb strength characteristics on paddling performance (Coyne et al., 2016; Coyne et al., 2017; Nessler et al., 2019; Secomb et al., 2013).

In order to understand the physiological demands of paddling, a better understanding of the physical demands of paddling is necessary. During a surfing session, surfers engage in mean paddling bouts ranging from 1 to 20 seconds during competition heats (Farley et al., 2012b; Mendez-Villanueva &

Bishop, 2005), and paddling bouts of 19 to 26 seconds during training or recreational sessions (Meir et al., 1991; Secomb et al., 2015). Paddling bouts can exceed 2 minutes, and bout durations are highly dependent on the reason for each specific paddle bout (e.g., paddling in open water out to the break, paddling in the line-up to re-position for an oncoming wave) (Meir et al., 1991; Mendez-Villanueva et al., 2006). Physiologically, a surfer's HR response reflects the varying muscular energy demands with studies reporting HR ranging between 140 and 190 beats per minute (bpm) during recreational, training, or competition surfing (Farley et al., 2012b; Meir et al., 1991; Mendez-Villanueva & Bishop, 2005; Secomb et al., 2015). It is evident that surfing requires a surfer to paddle at a range of intensities for varying periods of time. The above studies were unsuccessful in describing significant differences in HR response between recreational and competition level surfers. Thus, researchers have further attempted to distinguish the physiological differences between recreational and competition level surfers by investigating VO_2 during paddling (Almeida et al., 2018; Barlow et al., 2015; Loveless & Minahan, 2010; Mendez-Villanueva et al., 2005).

To achieve this, researchers have typically measured VO_2 while surfers paddled in less ecologically valid environments such as on swim bench ergometers. Studies reported relative $\text{VO}_{2\text{peak}}$ of recreational and competitive level surfers ranging from 31.25 to 54.2 $\text{ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$ (Almeida et al., 2018; Barlow et al., 2015; Farley et al., 2012a; Furness et al., 2018; Loveless & Minahan, 2010; Meir et al., 1991; Mendez-Villanueva et al., 2005). Some of these studies have reported conflicting results regarding the ability of VO_2 to distinguish between different skill levels of surfers. This suggested that either VO_2 is not a good determinant of the physiological demands of less ecologically valid paddling, or that perhaps no physiological difference between skill levels exists. It is clear that one must use caution when analyzing the results of these studies, not only because of these apparent limitations, but also because they employed different methodologies that may not be easily compared. Additionally, paddling in these less ecologically valid environments may differ in terms of the techniques used and the underlying neuromuscular control when compared to open surf paddling, or at the very least, during unrestrained still-water paddling. These potential alterations in technique and neuromuscular control may influence the physiological demands within the specific environment especially as they pertain to factors such as strength and power of the upper limb and the generation and application of force.

Strength and power during paddling may influence both endurance and sprint paddling performances of surfers. Endurance paddling performance has been reported to have the most significant difference between recreational and competitive surfers (Coyne et al., 2016; Coyne et al., 2017). Therefore, it has been suggested that recreational surfers will benefit most by improving their endurance paddling performance (Coyne et al., 2016; Coyne et al., 2017).

Competitive surfers, who may already have a strong endurance base, should focus on improving their sprint paddling performance (Coyne et al., 2017). Increased acceleration and sprint paddling skill have the potential to increase the number of waves caught, maximizing the wave-riding time and, therefore, the potential for high scoring waves during competition (Secomb et al., 2013). One way of increasing both endurance and sprint paddling performance is by strength training. This should target the muscles involved during the propulsive phase of a paddle stroke (Coyne et al., 2017; Nessler et al., 2019). In particular, Secomb et al. (2013) recommended improvements in relative upper-body pulling strength, which they speculated might lead to greater wave catching capability and wave entry speed. Such improvements may enable surfers to surpass their competitors in recreational and practice scenarios, thus enhancing their opportunity for wave-riding and potentially increasing their scoring advantage over competitors (Secomb et al., 2013).

These suggestions are supported by research that has shown a strong correlation between one repetition maximum (1RM) upper body pull up strength and sprint paddling times, as well as peak sprint paddling velocity among competitive and recreational surfers (Coyne et al., 2016; Sheppard et al., 2012). In these research studies, as paddling distance increased, the correlation between 1RM pull-up strength and paddling performance diminished (Coyne et al., 2016). In fact, it was found that the correlation between 1RM pull-up strength and sprint paddling performance in competitive surfers reached a "threshold," at which point further improvements in 1RM pull-up strength did not increase sprint paddling performance (Coyne et al., 2016). Presumably this occurred because 1RM is a measure of pure strength while sprint paddling has a critical muscular endurance component not measured by 1RM. Beyond this threshold, competitive surfers may need to find other ways to improve their sprint paddling performance such as improving muscle endurance, paddling technique, and neuromechanical control, thereby potentially improving movement efficiency (Burkett, 2018).

From the emerging body of literature reviewed here, we have an early, yet incomplete, understanding of some of the physiological and physical factors related to surfboard paddling performance, particularly those attributes related to strength. Multiple studies have used less-ecologically valid paddling environments such as swim bench ergometers in an effort to identify these physical factors. Importantly though, there is no evidence within the current literature to suggest that these environments validly replicate the neuromechanical demands of paddling across water, let alone in the open surf. Research that develops our understanding of the neuromechanical control under different, but sport specific paddling conditions is therefore required if we are to inform better exercise prescription and strength and conditioning programming aimed at improving surfboard paddling performance.

Paddling Technique, Posture, and Muscular Control

Surfboard paddling is an intricate movement pattern that requires voluntary planning and execution to coordinate different anatomical segments with multi-articular muscle activations (Nessler et al., 2015). This action requires the activation of multiple muscle groups for the propulsion of the surfer and their surfboard through the water. These actions require cyclically involving arm recovery, shoulder joint stability while maintaining stability on the surfboard itself. Early investigations of the paddling technique employed qualitative analyses with observations of kinematic variables such as arm placement, arm recovery, and torso inclination to determine their effect on sprint paddling performance (Sheppard et al., 2013b). Other investigators have measured muscle activation patterns for paddling on a swim bench ergometer (Nessler et al., 2015) and, more recently, while paddling in a swim flume (Nessler et al., 2019). Given the importance of the principle of specificity in sport training, establishing the degree to which the neuromechanics of paddling are similar between less-ecologically valid environments such as ergometers and flumes, and more ecologically valid environments such as still and open water, is a critical area for research. Learning the results of such investigations are warranted before deciding whether a less-ecologically valid environment should be used as a substitute for in-water training or for surfboard paddle performance testing or research.

Neuromuscular recruitment strategies are used to physically coordinate requisite patterns of biomechanical movements. Understanding sport-specific movements such as surfboard paddling through the application of basic laws of force and motion should enable sports coaches and sports scientists to improve an athlete's performance using movement efficiency and proficiency (Burkett, 2018). In swimming, improved stroke mechanics are associated with increased efficiency, whereby lower energy expenditure achieves the same absolute swimming velocity (Fernandes et al., 2006). Given biomechanical similarities (Coyné et al., 2017; Nessler et al., 2019) between swimming and surfboard paddling, the same may be true of surfboard paddling. It appears logical that improved paddling mechanics could conceivably reduce energy requirements for propelling the surfer on their board along the surface of the water. To date, however, no research has detailed the kinematics of the upper limbs and trunk during surfboard paddling.

In contrast, the movements of the upper limbs during the front crawl swimming stroke have been well-investigated (De Martino & Rodeo, 2018; King, 1995; Pink et al., 1991). During the start of a front crawl swimming stroke, the hand enters the water, and the shoulder is in forward flexion with the humerus abducted and internally rotated (De Martino & Rodeo, 2018). As the hand propels through the water towards the end of the propulsive phase, the shoulder extends with the humerus adducting and internally rotated (De Martino & Rodeo, 2018). As the hand exits the water and returns to the hand entry

position, the shoulder moves from extension to flexion while the humerus abducts but stays internally rotated (De Martino & Rodeo, 2018). It is unclear how the movements translate when paddling on a surfboard; however, it does provide a general understanding of where studies should start investigating the techniques during paddling.

The first reported study of surfboard paddling technique and posture was conducted by Sheppard et al. (2013b) in collaboration with elite surf coaches. Using qualitative analytical techniques, these researchers concluded that surfboard paddling requires the surfer to lie in a prone position on the surfboard while extending the lower back and alternating left and right paddle strokes with the arms (Sheppard et al., 2013b). It is also important to note that paddling out to the take-off zone is typically performed while maintaining an extended back, which acts to keep the nose of the surfboard elevated and out of the water (Furness et al., 2014). This posture may also play a role in allowing the surfer to shift the center of gravity and buoyancy by increasing or decreasing the chest height, relative to the deck of the surfboard while navigating water and waves. This posture further allows for increased arm clearance while paddling and for the surfer's head to face the paddling direction (Furness et al., 2014). A consequence of this posture may be that this position results in lower back injuries that appear to be a product of total time spent in the prone position on the board (Furness et al., 2014; Lowdon et al., 1983; Meir et al., 2012). Minghelli et al. (2018) suggested that paddling with a greater trunk angulation (a higher chest position off the deck of the board) increases the overload stress on the spine, thereby increasing the risk of a lower back injury.

Sheppard et al. (2013b) identified three critical areas of paddle stroke technique that required examination. These were: (i) paddle stroke length (reach), (ii) the arm recovery, and (iii) torso inclination (chest position). Their results showed that paddling with a low arm recovery and low chest position resulted in better sprint paddling performance. Thus, not only does paddling with a high chest position increase the possible risk of injury, it might further decrease the sprint paddling performance of a surfer. High chest position paddling has been common practice when paddling to return to the take-off zone and is considered essential at times for the reasons listed above. Sheppard et al. (2013b) also revealed no significant difference in sprint paddle performance between a long and a short stroke length. Overall, these results indicated that technique might play a vital role in a surfer's paddling performance and their propensity for injury and, therefore, longevity in the sport. To more thoroughly understand the paddling technique and postural effects on performance and injury risk, one must consider the activation patterns of the muscles required to sustain such movements and postures. Furthermore, one must consider how and when these muscles and adjacent structures may be loaded.

The suggested aspects of focus by Sheppard et al. (2013b) above provided a good starting point for surfboard paddling analysis. Notwithstanding this, it has been proposed that the stroke cycle should be broken down further into phases (Nessler et al., 2015). This would enable a more systematic investigation and understanding of the timing of muscle activation patterns and loads placed on adjacent structures during execution of the movement patterns. Nessler et al. (2015) identified the two primary phases of a paddle stroke as the propulsive and recovery phases (see Figure 1). Figure 2 illustrates these two phases as performed on a swim bench ergometer.

Nessler et al. (2015) systematically investigated muscular activation patterns while surfers paddled on a swim bench ergometer and reported that the latissimus dorsi and triceps brachii were the primary muscles active during propulsion while the middle deltoid assisted in propulsion. For the recovery phase, the infraspinatus, middle trapezius, upper trapezius, and middle deltoid were the main muscles recruited. Furthermore, the erector spinae's primary role was identified as providing ipsilateral stability on the surfboard during forceful elbow and shoulder extension (Nessler et al., 2015).

Figure 1

The wrist movement from the sagittal plane during a single stroke cycle, showing the propulsive phase and the recovery phase.

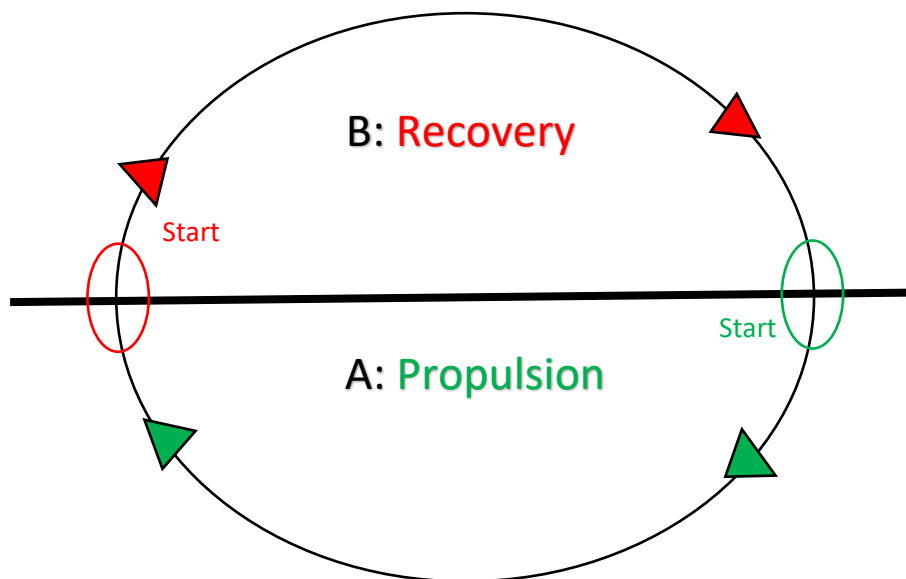
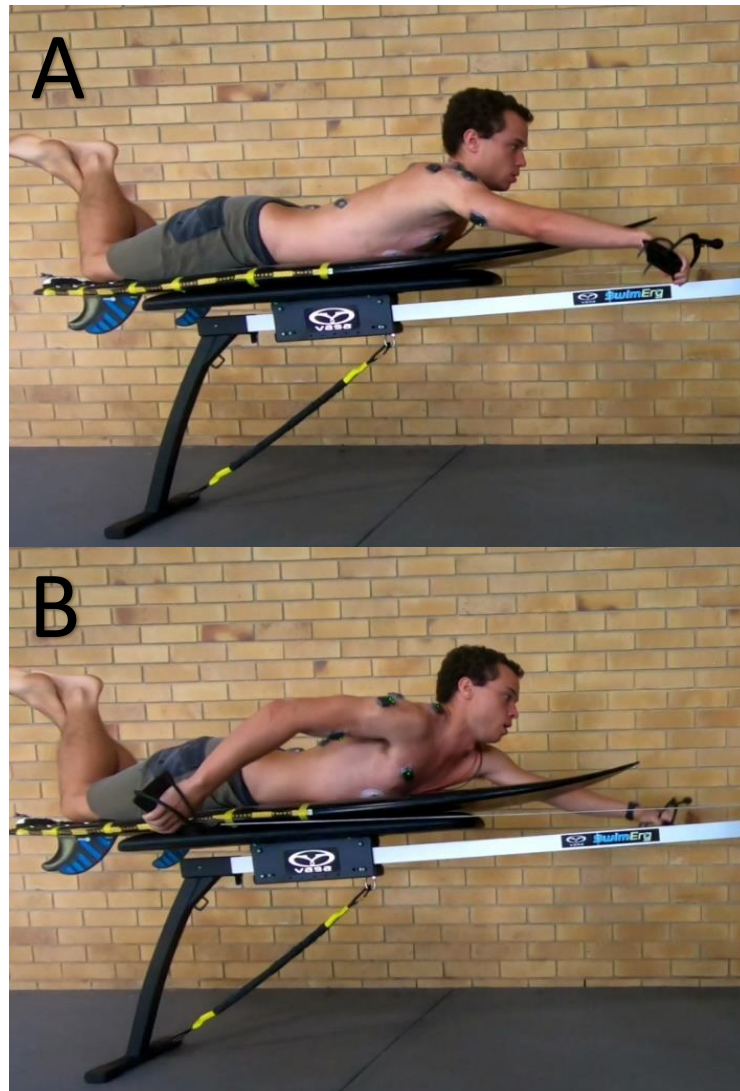


Figure 2

Demonstration of the two phases (i.e., propulsion and recovery) of prone surfboard paddling on a swim bench ergometer.



Note: A: Depicts the start of the propulsive phase with the hand/wrist at the most anterior position. B: Depicts the start of the recovery phase with the hand/wrist at the most caudal/posterior position.

A follow up study by Nessler et al. (2019) examined muscle recruitment patterns at different paddling intensities in a swim flume. This time they identified three paddling phases (i.e., propulsion, return or placement of the arm, and scapular rotation phase) and reported muscle activations during a single stroke cycle (Nessler et al., 2019). They used surface electromyography (sEMG) to collect muscle activation patterns for five upper limb muscles

(latissimus dorsi, upper trapezius, middle trapezius, posterior deltoid, and middle deltoid) during endurance and sprint paddling in the flume. Nessler et al. (2019) reported that while paddling at a speed of $0.8-1.1\text{m}\cdot\text{s}^{-1}$ (endurance paddling speed), the latissimus dorsi was most active during propulsion. For scapular rotation, the upper and middle trapezius were most active, while the middle and posterior deltoid were most active during the return phase. In addition, Nessler et al. (2019) stated that the intensity of muscle activation increased with increased paddling velocity. Although these increases in activation were not uniform, they found that the latissimus dorsi had the most considerable increase in muscle recruitment compared with the other four muscles tested. Furthermore, the muscle activation timing relative to the stroke phases changed as paddling intensity increased from endurance to sprint type paddling (Nessler et al., 2019). For example, the middle deltoid activated much earlier in the stroke cycle during sprint paddling compared to endurance paddling. This may be due to an increased paddling rate resulting from a shortened paddle stroke (Nessler et al., 2019). The middle deltoid, posterior deltoid, and upper trapezius all had significantly longer activation patterns during sprint paddling (Nessler et al., 2019) with the middle deltoid and posterior deltoid contributing more to propulsion. These results suggested that there may be a difference in neuromechanics between endurance and sprint paddling. Together with postural differences observed by Sheppard et al. (2013b) it is reasonable to conclude that paddling technique changes with changes in paddling intensity (Nessler et al., 2019). These findings clearly indicated a need for a more comprehensive analysis of both the temporal and spatial characteristics of muscle activation patterns and movement kinematics, respectively, between different paddling scenarios and throughout stroke phases.

Future Research Considerations

It is evident that paddling is an important skill for surfing that directly influences a surfer's performance during competition. The preceding section has shown that research investigating technique, posture, and muscle control during surfboard paddling is limited. Although some insights have been made providing direction, research lacks systematic comprehension while also not being ecologically valid. As such, most studies to date have limitations in this regard and a great deal of additional work is needed. For example, a limitation of the Sheppard et al. (2013b) study was that they only investigated two extremes of each of the paddle stroke techniques rather than a possible optimization of stroke length, chest position, and arm recovery. Studies have yet to investigate the exact joint rotations and muscle activation patterns as it pertains to surfboard paddling in the water.

Studies that have looked at muscle activation patterns while paddling has their own limitations. Nessler et al. (2015) investigated the neuromechanical demands of surfboard paddling on a swim bench ergometer. The validity of

using a swim ergometer for this purpose has been questioned (Coyne et al., 2017) mainly due to swim ergometer paddling being classified as an open-chain kinetic activity rather than a quasi-closed kinetic chain activity of actual paddling (Farley et al., 2013). Furr et al. (2019) found that the muscular activation patterns during the final stages of an incremental paddling test were significantly higher for the upper trapezius in the swim flume, and in contrast, significantly higher for the latissimus dorsi on the swim ergometer. This suggested that there was a difference in paddling mechanics on the swim ergometer compared to paddle mechanics in the swim flume (Furr et al., 2019). Only the upper trapezius and latissimus dorsi were examined when comparing the neuromechanical control between paddling under different modalities. This indicated that a more comprehensive analysis that included more muscles around the upper limbs is necessary. As such, a more thorough evaluation that compared paddling in water with paddling on a swim bench ergometer is essential. This research would provide more ecologically appropriate information regarding training and coaching practice in the sport of surfing (Sheppard et al., 2013a).

As research has established differences in muscle activation patterns while paddling at different intensities, studies involving comparisons between paddling on a swim bench ergometer and paddling in water should also include endurance and sprint paddling conditions. Such an analysis would further contribute to the existing and growing body of research in surfing. It will help to clarify the validity and specificity of using swim ergometers for testing and training purposes. This will inform surfing coaches on whether or not swim ergometer surfboard paddling can be used as a substitute to train surfboard paddling when open water environmental conditions do not allow. Furthermore, this will provide guidance to surf coaches and sports scientists as to whether the use of a swim ergometer is a valid tool for exercise testing, prescription, and technique analysis. Ultimately, this may result in a more comprehensive understanding of paddling demands at different intensities, with this knowledge being used to improve paddling performance.

Conclusions

Currently, a dearth of research existed on the techniques and neuromechanical demands of surfboard paddling in different paddling environments and paddling conditions. Researchers have used swim bench ergometers (Nessler et al., 2015), and more recently, the use of swim flumes (Nessler et al., 2019) to determine the muscular demands of surfboard paddling. To date, no research study has focused on comparing muscle activation patterns when paddling on a swim ergometer or paddling in still or controlled water. In addition, only one study has previously investigated muscle activation patterns at different paddling intensities. This study found that muscle activation patterns and intensities differed when paddling at different intensities (Nessler et al., 2019). Therefore, it appeared justifiable that further investigation is needed,

particularly concerning a closer analysis of paddling's neuromechanical execution in different environments and at different intensities. Investigating kinematic variables and muscle activation patterns of water-based and ergometer-based surfboard paddling as well as water-based steady-state and sprint surfboard paddling will determine whether any differences exist in the neuromechanical execution of paddling activities. These studies will provide both the coach and surfer with greater insight and understanding of the techniques and neuromechanical control needed for surfboard paddling.

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