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Jeff A. Nessler, Tayler Frazee & Sean C. Newcomer

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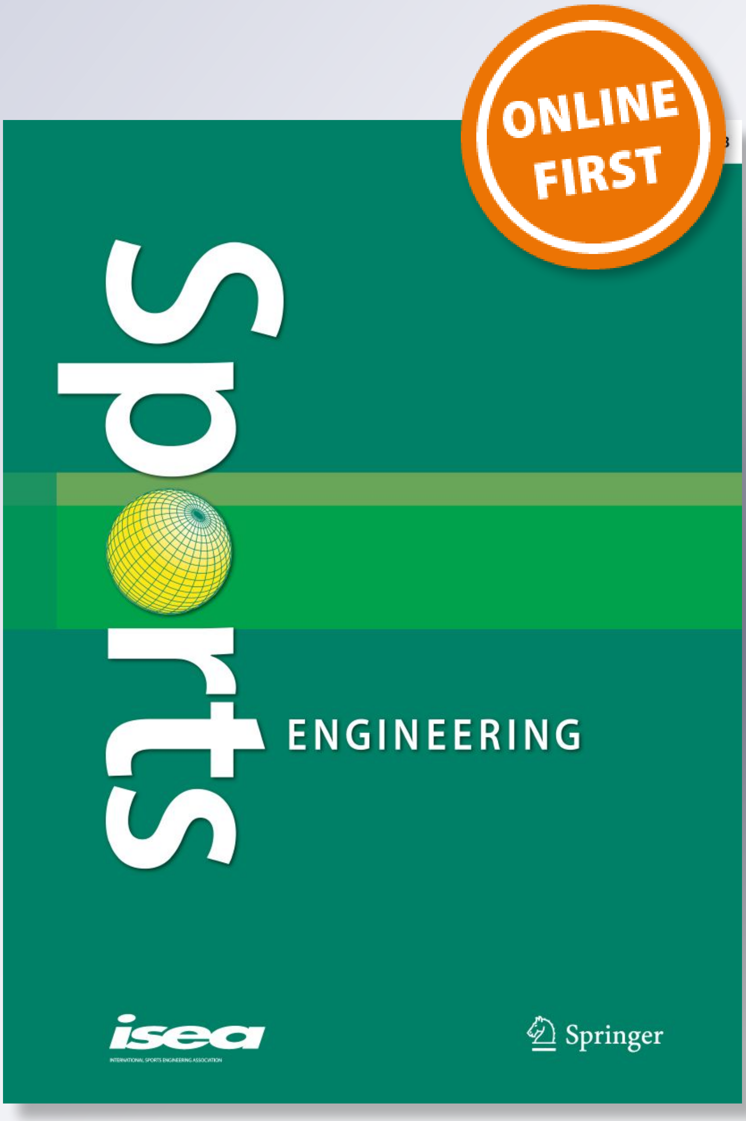

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ORIGINAL ARTICLE

The effect of foil on paddling efficiency in a short surfboard

Jeff A. Nessler[1] · **Tayler Frazee**[2] · **Sean C. Newcomer**[1]

Abstract Surfboard volume and shape affect human performance while riding waves, but little is known regarding the impact of these variables on paddling, where surfers spend a majority of their time. The purpose of this study was to determine whether changing the foil (fore/aft thickness profile) of a short surfboard will alter paddling mechanics and efficiency if surfers are allowed to self-select their prone position. Twenty recreational surfers paddled three different surfboards in a freshwater swim flume while measurements of drag force, board motion, body position, heart rate, and oxygen use were acquired. All boards shared the same volume (31 L) and gross dimensions (172.7 cm long × 50.8 cm wide × 6 cm thick), but the geometric center was placed in a different location along the fore/aft axis of each board. Surfers were blinded to the volume and shape of each board. Results indicated that surfers positioned their center of mass further forward in response to a more nose-heavy board and further aft in response to a more tail-heavy board (22.04 ± 6.34 mm difference in position between boards, $p = 0.008$). This self-selected positioning yielded no statistical difference in drag force, board angle and accelerations, heart rate, or oxygen use across the three boards. These data suggest that when surfboard volume and gross dimensions are fixed, foil has little effect on the efficiency of paddling a short surfboard in recreational athletes.

Keywords Surfing · Paddling · Surfboard volume · Foil

1 Introduction

Surfing is a popular and rapidly growing sport with over 20 million participants worldwide [1, 2]. Individuals across all age groups are known to participate and often generate physical activity levels consistent with recommendations by ACSM and the CDC for cardiovascular fitness and health [3–5]. Despite high levels of participation and the potential for improving or maintaining health, there is little research into equipment design to optimize performance and/or prevent injury. The surfboard itself is the most important piece of surfing equipment, yet there are several key questions about surfboard design that remain unclear.

Surfboard shapes have developed over 200 years and the craft of fabrication is known for its cultural and artistic history [6–8]. Until recently, designs have relied more on esthetics, experience, and anecdotal evidence and less on scientific data. While surfboard manufacturing remains to some degree an artisanal craft, there is a growing interest in data that can inform surfboard design [8–15]. Currently, surfboard design is primarily focused on wave riding performance, but recent data demonstrate that surfers spend a majority of their time paddling [3, 5, 16–18]. Fatigue resulting from an extended period of paddling can affect other aspects of surfing performance, and prolonged paddling across multiple sessions can lead to overuse injury in the neck, back, and shoulder [19]. Additional evidence suggests that surfboard design can alter a surfer's trunk

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✉ Jeff A. Nessler
jnessler@csusm.edu

Tayler Frazee
fraze005@cougars.csusm.edu

Sean C. Newcomer
snewcomer@csusm.edu

[1] Department of Kinesiology, California State University, 333. S. Twin Oaks Valley Rd., San Marcos, CA 92096, USA

[2] Biotechnology Program, California State University, San Marcos, CA, USA

angle and the pitch angle of the board while paddling, and this can lead to changes in muscle activation [9, 20]. Therefore, scientific investigation into the impact of surfboard design on paddling performance may hold several important implications.

Surfboard volume is assumed by many to affect a surfer's performance while paddling. This was supported by data from a recent experiment, where a strong linear relationship was reported between total board volume and oxygen use [9]. Surfboards of the same volume can be further altered by changing the placement of the center of volume throughout the board. This might be accomplished by increasing thickness at the fore or aft of the board (i.e., altering the "foil"), or by increasing thickness at the middle or lateral aspects of the board. Increasing the thickness of the board in a particular region will increase the buoyant force experienced at that location. Changing the distribution of buoyant force can alter a board's performance during both paddling and wave riding by altering the way that it interacts with the surfer [9, 20]. While it is clear from existing data that increasing the total volume of a surfboard can reduce the energy cost of paddling, it remains unclear whether moving the geometric center of a surfboard will impact paddling performance.

Altering a surfboard's foil may also affect the surfer's behavior. Surfer's are sensitive to the physical properties of a surfboard and can make fine adjustments in order to optimize paddling efficiency [9]. In particular, a strong relationship was reported between surfboard volume and pitch angle of the board while paddling [9], and it should be noted that pitch angle varied by only 1°–2° on average between boards of 28 and 37 L in volume. This suggests a high level of perceptual accuracy in surfers that were blinded to the actual volume of the board. Altering the foil may have a similar effect on a surfer's interaction with the board and their paddling performance, but this has not been investigated.

The purpose of this experiment was to provide an initial investigation of the effects of surfboard foil on paddling performance. Two primary questions were addressed. First, given three surfboards of the same size, dimension, and volume, does the surfboard's foil affect paddling mechanics and oxygen use in recreational surfers? Second, if surfers are allowed to self-select their position on the board, will they intuitively fine-tune their position in order to maintain consistent paddling mechanics and metabolic efficiency? Based upon existing data that demonstrate changes in both efficiency and behavior of surfers in response to changes in board volume [9], it was hypothesized that alterations in foil would result in significant changes in drag force, board motion (pitch, roll, and yaw), oxygen consumption ($\dot{V}O_2$), and heart rate. Further, it was hypothesized that experienced, recreational surfers would alter their prone position on each board in response to differences in foil.

2 Materials and methods

2.1 Subjects

Twenty male recreational surfers were recruited from the San Diego surfing population (age 27.4 ± 7.3 years, height 1.78 ± 0.06 m, mass 74.9 ± 8.7 kg). All participants were free of any cardiovascular, musculoskeletal, or neurological condition that might affect paddling a surfboard, and each subject indicated that they engaged in surfing for at least 4 h per week and had at least 2 years of surfing experience (mean 14.7 ± 9.6 years). Additional health screening was performed via questionnaire (AHA/ACSM Health/Fitness Facility Participation Screening Questionnaire). All participants provided written informed consent prior to participation, and all procedures were approved by the Institutional Review Board at California State University, San Marcos (IRB #813951-1).

2.2 Surfboards

Paddling trials and drag force measurements were taken in a custom-sized swim flume (2.75 m wide × 4.9 m long, Endless Pool Elite, Fitness Machines, LCC, Aston, PA). Water temperature was maintained between 18 and 21 °C, and water flow velocity was held constant at 1.1 m s^{-1}. Flow velocity was verified throughout each trial with a flowmeter (Flowatch, NTech, USA, Holmen WI). All participants wore the same style 2 mm full wetsuit (Hurley™ Phantom 202) for all data collection trials. Three different surfboards were evaluated: a commercially available model with typical dimensions (Firewire™ Dominator, 172.7 cm long × 50.8 cm wide × 6 cm thick, 31 L—"standard") and two specially designed variations of the same model with the center of volume shifted either toward the nose by 2.5 cm (i.e., "nose-heavy") or toward the tail by 2.5 cm (i.e., "tail-heavy"). Shifting the center of volume forward by 2.5 cm resulted in a change in volume in the nose of the board by approximately 0.77 L for the nose-heavy board and −0.34 L for the tail-heavy board, with respect to the dimensions of the standard board (Table 1). Shifting the center of volume toward the tail of the board by 2.5 cm resulted in a change in volume in the tail of the board by approximately −0.35 L for the nose-heavy board and 0.73 L for the tail-heavy board, with respect to the dimensions of the standard board (Table 1).

Table 1 Comparison of board thickness

	Location of center of volume (distance from tail, cm)	Volume of board nose (L)[a, b]	Volume of board tail (L)[a, b]
Off the shelf	82.8	3.82	5.5
Nose distributed	85.3	4.59	5.15
Tail distributed	80.3	3.48	6.23

[a] Nose and tail were defined as the region 0–30.5 cm from respective end of the board

[b] Values are based upon computer-aided design (CAD) drawings from the surfboard manufacturer

The changes in foil utilized here were selected to represent the realistic limits of a short surfboard shape. Shifting the center of volume by 2.5 cm for a board that is 180 cm in length represents a variation that is much larger than that typically seen in surfboard design [7, 8]. The location of the center of volume for each surfboard used here was not directly measured. However, surfboards were designed using specialized 3D computer-aided design (CAD) software and shaped by computer numerical control (CNC) machine [21]. While no data exist to verify the precision of this process for surfboard shaping, CNC machining for other applications is commonly reported to have error tolerances of less than ±1 mm [22, 23]. All boards were equipped with the same size and model of fin, installed in a three fin "thruster" pattern. No leash was attached to any of the boards.

2.3 Data collection

Upon arrival, participants were asked to don a wetsuit, enter the pool, and begin paddling a randomly selected board for 30–60 s. To replicate as closely as possible the conditions under which they normally paddle, surfers were allowed to self-select their preferred position on each surfboard rather than requiring strict adherence to a particular position. When the participant indicated that they felt comfortable, the water flow was stopped, but the participant was asked to remain in the same position on the board while the drag measurement apparatus was prepared. Drag force was measured using a custom rigid linkage that attached on one end to the underside of the nose of the board via suction cup, and on the opposite end to a load cell (Transducer Techniques model SB0-200, Temecula, CA). The load cell was anchored to the front of the swim flume above the water line and wrapped in a protective plastic coating to avoid damage. Water flow was then resumed and the participants were asked to remain still on the board with their arms at their sides (Fig. 1). Once the board, surfer, water flow, and measurement apparatus reached a steady state, the tension in the load cell was recorded for a period of 30 s. The participant was then asked to hold their right hand forward and their left hand back, both above the water, to simulate mid-paddle stroke while tension data were recorded for an additional 30 s. This process was repeated for the other two boards, with each board presented in random order.

Following measurement of drag, participants were asked to paddle each board for a period of 3 min while measurements of board acceleration, body positioning, $\dot{V}O_2$, and heart rate were acquired (Fig. 2). Participants were given 3 min to rest between each trial, and those that were unable to complete all three trials were excluded from final analysis. Board motion was measured by attaching a wireless, three-axis accelerometer (Great Lakes NeuroTechnologies, Cleveland, OH) to the top of the nose of each board. Baseline measurements of board orientation were acquired via accelerometer during the resting periods in still water, and paddling data were acquired over the first 60 s of the 3-min paddling trial for each board. Participant position on each board was determined by placing a mark in the same location on the side of each board, corresponding to the center of volume of the commercially available (Firewire^{TM} Dominator) board. A second marker was placed on the side of the board a fixed distance away from the first to create a linear scale. A reference marker was also placed on the participant using an elastic strap wrapped around the upper torso just above the level of the heart rate monitor. A GoPro Hero4 camera (GoPro, Inc., San Matteo CA) was placed underwater on the right-hand side of the participant to capture the relative positions of the board and participant markers at 30 fps. Finally, oxygen consumption (i.e., $\dot{V}O_2$, expressed in mL kg^{-1} min^{-1}) was measured over each 3-min trial at 5-s intervals with a Metabolic Measurement System (type TrueOne 2400; ParvoMedics Inc., USA), using a Hans Rudolph Oro-Nasal mask and 5-m tube. Additional tube length was accounted for in calculations of $\dot{V}O_2$ using a mathematical offset per manufacturer recommendations. A heart rate monitor (type RCX5 receiver & T32 recorder, Polar, Finland) was strapped below the pectoralis major muscles of each participant and heart rate was also recorded at 5-s intervals. The first 2 min of each paddling trial was utilized for subjects to reach a steady state, following a protocol described previously [9]. Data from the final minute of

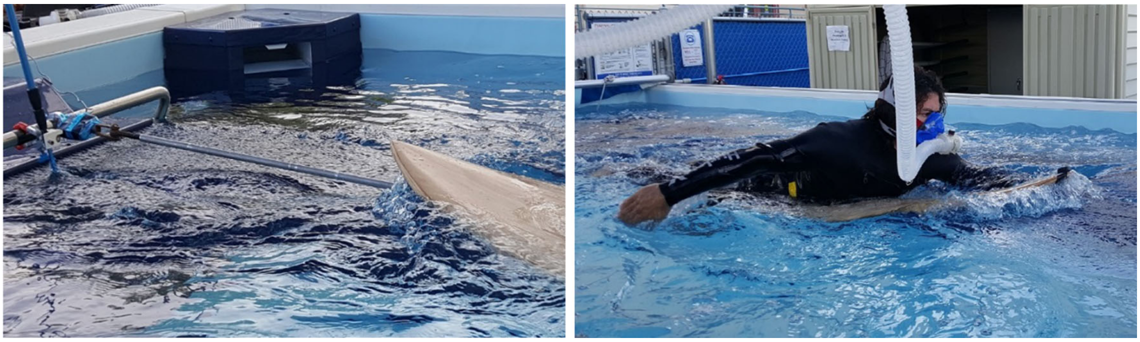


Fig. 1 Swim flume. *Left* apparatus for measuring drag force. *Right* paddling against the current while $\dot{V}O_2$, HR, and board accelerations are recorded. A Hans Rudolph Oro-Nasal mask and 5-m tube were used, and additional tube length was accounted for in calculations of $\dot{V}O_2$

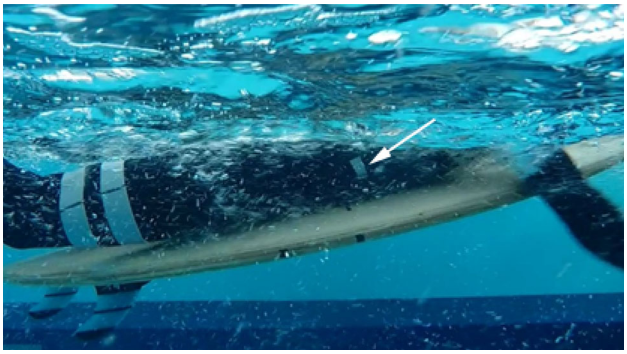


Fig. 2 Under water view of the surfer's position while paddling a surfboard in the swim flume. Two markers on the side of the board were used as a linear scale. The marker on the subject's torso (*denoted with arrow*) was used to determine position on the board

each paddling trial for both heart rate and $\dot{V}O_2$ were then averaged and compared across boards using the statistical analysis described below.

2.4 Data analysis

Drag force data were first filtered (fourth-order Butterworth, 20 Hz cutoff) and then averaged over the 30-s trial. Normalization to participant mass was deemed unnecessary because analysis was limited to within-subjects comparisons. Accelerometer data were also filtered (fourth-order Butterworth, 25 Hz cutoff) and used to calculate pitch angle, roll angle, and yaw acceleration. Pitch and roll angles were calculated by finding the projection of gravitational acceleration along the fore/aft axis (pitch) and mediolateral axis (roll) of the surfboard. Pitch angle per trial was defined as a simple average across the entire paddling trial. Roll angle and yaw acceleration data were first divided into individual strokes, and then, the range of motion was averaged across all strokes, and coefficient of variance was determined within each trial. Since yaw angle cannot be calculated using gravitational acceleration, the magnitude of yaw acceleration was analyzed and reported below. Two-dimensional video footage was analyzed in standard biomechanics software (MaxTraq, Innovision Systems Inc, Columbiaville, MI) in order to determine body position relative to the reference marker on each board. Separate repeated measures ANOVA were performed for each variable using the different surfboards as the within-subjects variable (IBM SPSS Statistics for Windows, version 20.0. Armonk, NY). Significant results were followed up post hoc with paired *t* tests to determine where significant differences lay, with Bonferroni adjustment to control for type I error among multiple comparisons (family-wise alpha 0.05).

3 Results

3.1 Drag force

There were no significant differences detected in drag force between the 3 boards for either the hands-at-side trials (42.1 ± 6.27, 42.8 ± 7.29, and 42.4 ± 6.92 N for the standard, nose-heavy, and tail-heavy boards, respectively, $F_{2,19} = 0.420$, $p = 0.661$) or simulated paddle trials (41.6 ± 6.67, 41.1 ± 6.83, and 41.3 ± 7.28 N, $F_{2,19} = 0.470$, $p = 0.629$, Fig. 3). Strong correlations were noted between drag force and participant mass for all three boards ($r_{18} = 0.845$, $p < 0.001$, $r_{18} = 0.825$, $p < 0.001$, and $r_{18} = 0.781$, $p < 0.001$ for the standard, nose-heavy, and tail-heavy boards, with arms at the side), and between all comparisons of drag force across boards (e.g., $r_{18} = 0.931$, $p < 0.001$ for standard vs nose-heavy board with arms at the side). These correlations provide a measure of validity by indicating that this approach was able to distinguish relationships in force where they are expected to exist (i.e., heavier participants yielded higher drag forces).

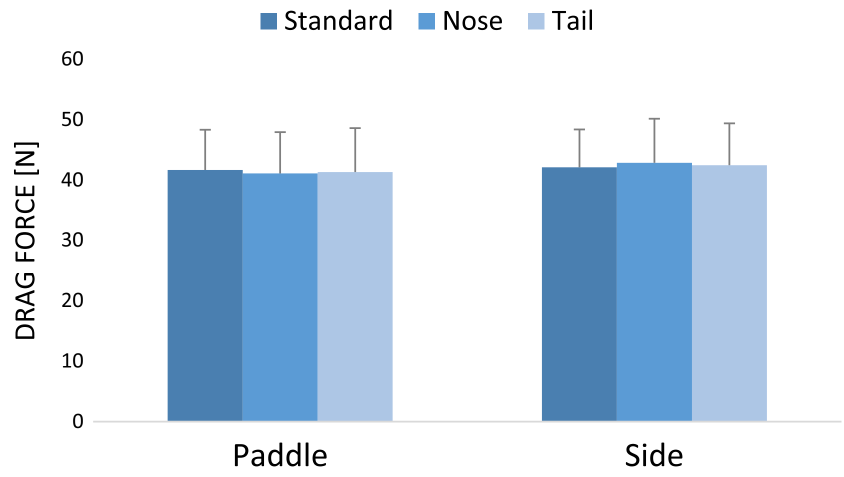


Fig. 3 Drag force results for the off-the-shelf (*Standard*), nose distributed volume (*Nose*), and tail distributed volume (*Tail*) boards. *Paddle* simulated paddle position. *Side* arms at side. *Bars* represent standard error of the mean

3.2 HR and $\dot{V}O_2$

All 20 participants were able to complete all three paddling trials. There were no significant differences in $\dot{V}O_2$ (23.4 ± 6.60, 23.1 ± 6.47, and 23.0 ± 6.26 mL kg^{-1} min^{-1}, for the standard, nose-heavy, and tail-heavy boards, respectively, $F_{2,19} = 0.511$, $p = 0.604$) or HR (134.2 ± 82.4, 134.4 ± 82.0, and 133.0 ± 80.2 bpm, $F_{2,19} = 0.270$, $p = 0.765$) when participants paddled each board (Fig. 4).

3.3 Board motion

There were no significant differences in pitch angle (10.4° ± 2.08°, 9.83° ± 1.18°, 9.84° ± 1.89° for the standard, nose-heavy, and tail-heavy boards, respectively, $F_{2,19} = 0.094$, $p = 0.914$), roll angle range of motion (18.1° ± 4.03°, 18.9° ± 3.77°, and 18.5° ± 3.22°, $F_{2,19} = 0.156$, $p = 0.856$), or yaw acceleration (0.760 ± 0.193, 0.768 ± 0.178, and 0.760 ± 0.149 g, $F_{2,19} = 0.050$, $p = 0.951$) while paddling the three boards (Fig. 5). Yaw acceleration was significantly correlated with $\dot{V}O_2$ ($r_{18} = 0.732$, $p < 0.001$) and HR ($r_{18} = 0.721$, $p = 0.001$), but this relationship was similar across all three boards.

3.4 Body positioning

There was a significant difference in body positioning across the three boards, expressed here as the distance behind the location of the center of volume for the standard board (21.3 ± 11.7, 10.1 ± 9.94, and 32.1 ± 10.1 mm for the standard, nose-heavy, and tail-heavy boards, respectively, $F_{2,19} = 4.15$, $p = 0.026$, Fig. 6). In general, participants adjusted their position along the long axis of the board in the same direction as changes in center of volume, though the average distance of this adjustment was less than 2.5 cm. On average, participants positioned themselves 1.12 ± 3.30 cm forward for the nose-heavy board and 1.08 ± 2.80 cm toward the back of the board for the tail-heavy board with respect to their position on the standard board (Fig. 6). Post hoc analysis revealed a significant difference in position between the nose and tail-heavy boards ($p = 0.008$), but not between the standard board and nose-heavy board ($p = 0.157$) and standard and tail-heavy board ($p = 0.208$).

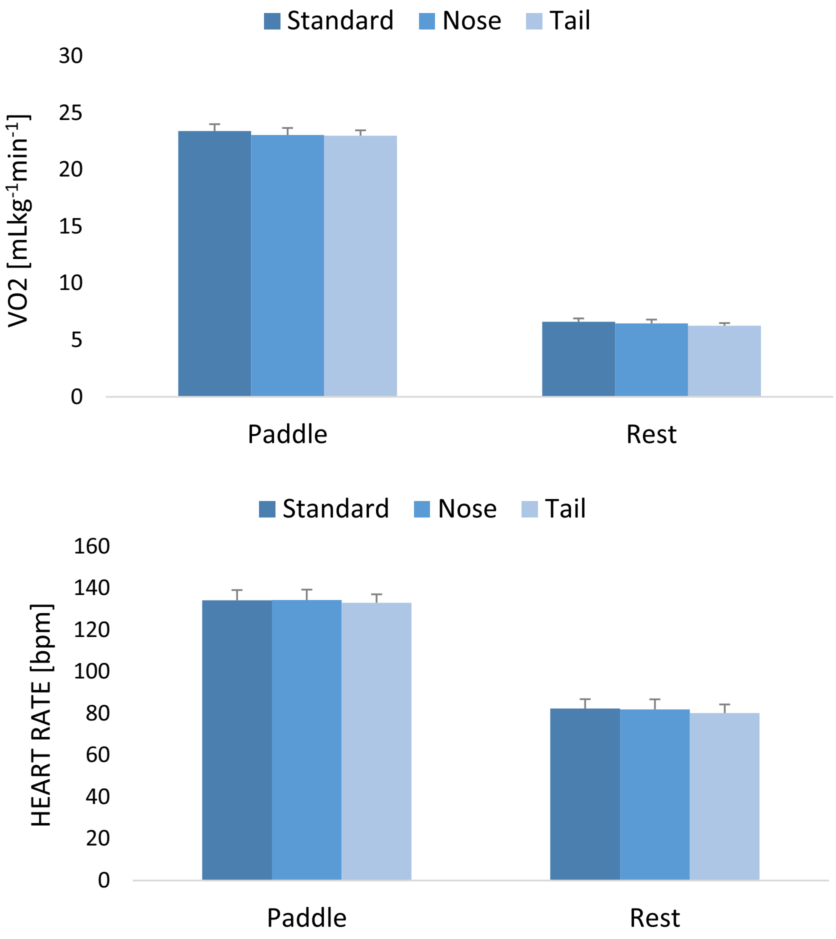
4 Discussion

There were two primary results to this study. First, when participants were allowed to self-select their position on the three surfboards evaluated here, variations in surfboard foil did not affect drag force, board accelerations, oxygen use, or heart rate while paddling at a constant velocity. Second, participants altered their position on the board in response to changes in foil in order to maintain consistent paddling efficiency and performance. Additional results included a strong negative relationship between yaw acceleration of the nose of the board and metabolic efficiency while paddling. Finally, pitch and roll angles measured here using an accelerometer were comparable to those found in a previous study that used underwater cameras to track board motion while paddling [9]. This comparison demonstrates the utility of using an inertial measurement unit (IMU) to track board motion.

4.1 Implications for surfboard design

Surfboard designs are primarily focused on the performance of the board during wave riding, and shapers and manufacturers are particularly interested in altering the foil of a surfboard for this purpose. For example, concentrating

Fig. 4 Metabolic results (HR and $\dot{V}O_2$) for the off-the-shelf (*Standard*), nose distributed volume (*Nose*), and tail distributed volume (*Tail*) boards. *Paddle* data from 3-min paddling trials. *Rest* data from 3-min rest periods. *Bars* represent standard error of the mean



a greater amount of volume toward the rear of the surfboard can alter the inertia of the board, which may be helpful during quick turns that involve pivoting about the tail. The current results suggest that such changes in foil that are designed to impact a surfer's performance while riding waves are unlikely to have a significant effect on the efficiency of paddling a surfboard. In particular, the current data suggest that alterations in foil have little effect on oxygen use, heart rate, drag force, and board motion. This is an important consideration because surfers spend a majority of their time in the water paddling and increased levels of fatigue associated with paddling can shorten a surfing session and can affect performance in other aspects of surfing, such as paddling to catch a wave [3].

A shift in the location of the center of volume of only 2.5 cm may at first appear to be relatively small. However, when applied to a short surfboard under 180 cm in length this shift is more significant than variations that are typically observed in the average surfboard [7, 8]. Altering the foil of a surfboard beyond the values examined here may have a significant, negative impact on the wave riding performance of the board and therefore limit its marketability. Since the shapes evaluated here represent the feasible limits for a short surfboard, it is likely that smaller changes in foil more commonly observed in commercially available surfboards will also have little effect on paddling.

Changing other aspects of board design may have a greater effect on paddling efficiency. While the alterations in foil examined here had little effect on drag force, changes that alter the gross dimensions of a surfboard may serve to reduce drag and may reduce the metabolic cost of transport in water. For example, increasing the length-to-width ratio of the board will alter its waterline length and Froude number [10, 15]. Additionally, changes in board density may have an effect on paddling efficiency by altering the buoyant force-to-mass ratio of the surfboard, thereby raising a greater percentage of the surfer and board above the water level. Several new materials have been introduced recently that significantly reduce the density of a surfboard [8, 24–26]. Currently, no data exist relating surfboard density to surfing performance.

4.2 Implications for performance

Experienced surfers appear to have the ability to fine-tune their prone position to achieve a consistent level of

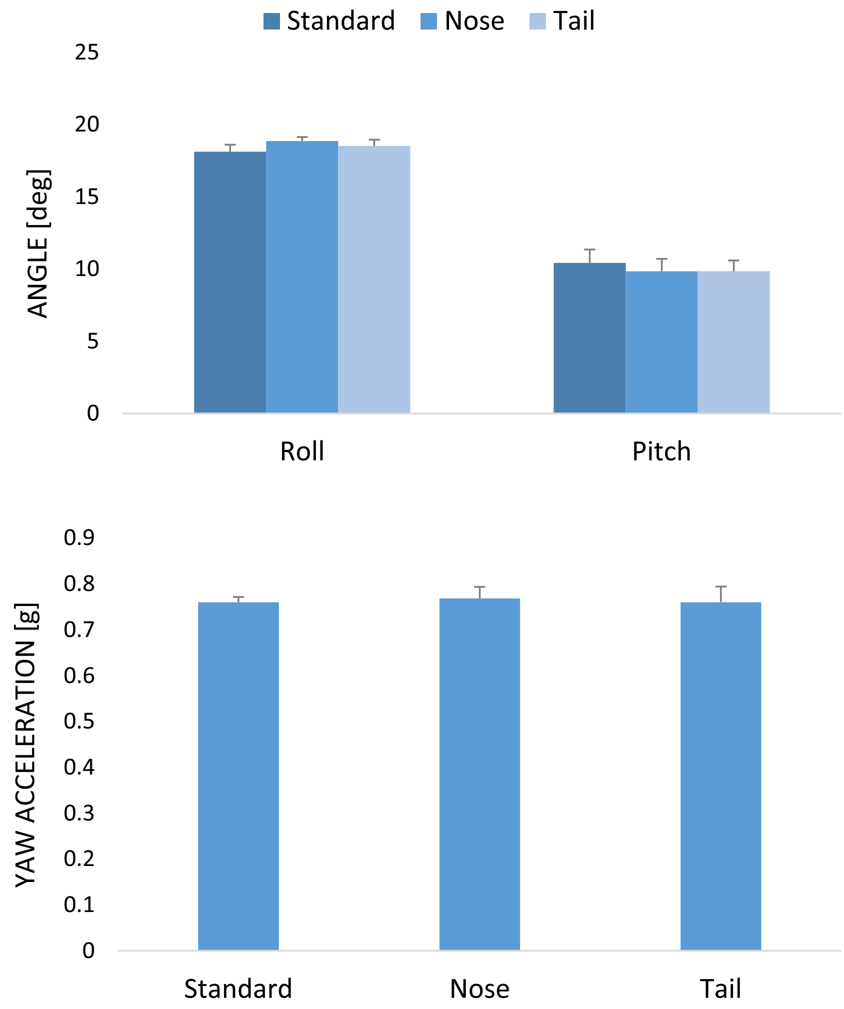


Fig. 5 Board kinematics for the off-the-shelf (*Standard*), nose distributed volume (*Nose*), and tail distributed volume (*Tail*) boards. *Bars* represent standard error of the mean

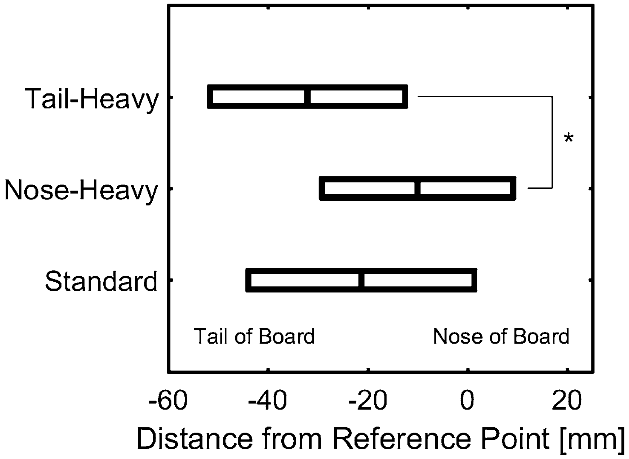


Fig. 6 Body position data. Range of body positioning with respect to the location of the center of volume of the standard board (i.e., reference point, or "0" position). *Bar centers* represent mean position and *bar lengths* represent 95% CI across subjects

metabolic output across boards of the same volume but differing shape. In the current data, the center of volume was shifted by only 2.5 cm in each direction, and surfers responded by shifting their position, on average, by 1.1 cm in each direction (Fig. 6). This relationship was not 1:1, and this may be due to differences in density and buoyant force experienced by the surfer relative to the board. Interactions between these two masses are not straightforward since weight acts through center of mass and buoyant force acts through the center of volume of the submerged portion of an object. In this experiment, the board remained mostly submerged in each condition with little change in the volume of water that it displaced, while the surfer may have altered the percentage of their lower body that was submerged in each condition as they changed prone position. By submerging more of their lower body, the surfer would experience a greater amount of buoyant force acting on their legs. This interaction between multiple forces acting on different aspects of the surfer and board will determine the board's pitch angle, and it is likely that even minor changes in a surfer's prone position will impact performance. The current data combined with those of a previous analysis [9] suggest a high degree of detail and accuracy in determining the proper position on a board. To date, these data have only been acquired in experienced, recreational surfers. It remains to be determined how this ability is developed in beginners, and whether elite athletes demonstrate greater precision and consistency in their behavior.

Yaw acceleration of the nose of the surfboard was correlated with oxygen use and heart rate while paddling. These data suggest that measurement of yaw acceleration may provide a simple method for estimating paddling efficiency. This may be especially useful for acquiring data in the ocean, for example, while a surfer is attempting to catch a wave. It also provides a simple method of assessment for surf coaches and athletes seeking to improve paddling performance. Additional study of yaw acceleration as a proxy for paddling efficiency is necessary to provide a more robust description of the relationship with $\dot{V}O_2$.

While the current data show that there were no differences in metabolic efficiency or board kinematics, it is possible that other aspects of performance were altered when paddling boards with differing foil. For example, changing one's position on the surfboard may alter muscle activation in the low back and shoulder [20]. If changes in muscle activation occurred in the current data, these did not result in changes in overall metabolic cost. However, previous analyses of the paddling motion demonstrate that small but significant changes in muscle activation patterns may still occur without altering heart rate or oxygen use [27]. In addition, this study examined steady-state paddling at a moderate speed. It is possible that paddling at higher speeds, to catch a wave for example, may yield more appreciable differences in paddling mechanics and efficiency.

4.3 Summary

These data indicate that changes in surfboard foil have little effect on the mechanics and efficiency of paddling. Further, recreational surfers demonstrated the ability to fine-tune their prone position to achieve a consistent paddling performance for boards with different foils. While this study addresses an important question in regard to the center of volume in surfboard design, many additional questions remain. These include, for example, the effects of altering the center of volume along a mediolateral axis, altering the center of volume for boards of larger size, and changes in the gross dimensions of a surfboard (to alter waterline length and Froude number) on a surfer's paddling performance. Other questions include the effects of foil on wave catching and riding performance, as well as differences in board density that can be achieved with different types of material and design. Future investigation into these questions will help to improve human performance in the sport of surfing and may help to encourage greater participation in the sport among youth and older recreational athletes.

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