Ergonomics

ISSN: 0014-0139 (Print) 1366-5847 (Online) Journal homepage: http://www.tandfonline.com/loi/terg20

Increasing surfboard volume reduces energy expenditure during paddling

Vuk Ekmecic, Ning Jia, Thomas G. Cleveland, Maya Saulino, Jeff A. Nessler, George H. Crocker & Sean C. Newcomer

To cite this article: Vuk Ekmecic, Ning Jia, Thomas G. Cleveland, Maya Saulino, Jeff A. Nessler, George H. Crocker & Sean C. Newcomer (2017) Increasing surfboard volume reduces energy expenditure during paddling, Ergonomics, 60:9, 1255-1260, DOI: 10.1080/00140139.2016.1261188

To link to this article: http://dx.doi.org/10.1080/00140139.2016.1261188

relative to other competitors (Beal 1995; Rubin 1999). Although the focus of surfing is commonly associated with wave riding, recent field observations suggest that paddling and remaining stationary comprise the bulk of time in the water for recreational (Meir, Lowdon, and Davie 1991) and competitive surfers (Mendez-Villanueva, Bishop, and Hamer 2006; Farley, Harris, and Kilding 2012; Farley, Abbiss, and Sheppard n.d.). Recreational and competitive surfers appear to have similar activity patterns; both were observed to spend a majority of their time paddling, or remaining stationary, and little time wave riding (~5% of time) (Meir, Lowdon, and Davie 1991; Mendez-Villanueva, Bishop, and Hamer 2006). Additionally, heart rate (HR) has been reported to be ~80% of maximum during paddling (Meir, Lowdon, and Davie 1991). The time dedicated to, and the HR values associated with paddling indicate that it is likely the most energetically costly portion of a surfing bout.

Maximising paddling performance is integral to the success of the recreational and competitive surfer. Improved paddling ability would allow the recreational surfer to catch more waves, enter into waves earlier and paddle through more challenging environmental conditions. Similarly, improved paddling ability in competitive surfers would allow them to take advantage of positioning and wave-priority rules. Therefore, altering the surfboard with the goal of optimising paddling could have a considerable impact on energy expenditure, fatigue and potentially performance. One plausible method to impact energy expenditure during paddling may be to alter surfboard buoyancy. From anecdotal evidence, surfboard shapers have long utilised the parameter of board volume (BV) to alter buoyancy, and impact locomotion. However, there is currently a lack of empirical evidence describing the relationship between the paddling efficiency and BV. The purpose of this study was to investigate how BV affects energy expenditure during paddling. We hypothesised that paddling surfboards with higher volumes would reduce energy expenditure.

Methods

Participants

Twenty recreational surfers from the coastal region of Southern California (30.4 ± 7.9 years; 1.77 ± 0.06 m; 75.5 ± 9.3 kg) participated in the study. Mean years surfing was 16.3 ± 10.3 years and mean self-reported surf competency was 6.5 ± 1.4 on a 1–10 scale (10 being most competent). Participants were recruited by convenience sampling from San Diego County. Inclusion criteria consisted of surfing for exercise and being able to paddle the board with the least volume at 1.1 m/s, the constant velocity used for this study.

Experimental overview

A single-blind, within-subjects design was used to compare oxygen consumption (VO_2), HR, cadence, pitch, and roll across five surfboards of different volumes. Upon arrival, subjects gave their informed consent and completed a surfing activity questionnaire, which included questions about surfing habits. Subjects paddled in a swim flume (Endless Pool Elite, Fitness Machines, LCC, Aston, PA) at 1.1 m/s for ten 3-min increments, each separated by 3 min of seated rest. A paddling speed of 1.1 m/s was chosen based on field study measurements which represents paddling speeds observed during positioning rather than wave catching and the 3-min paddling duration ensured that measurements were obtained during steady state. Surfboards were randomised for each subject and each board was paddled twice in rotational order. Water speed and temperature were measured prior to each paddling bout using a flowmeter (Flowatch, NTech USA, Holmen, WI). Ambient air temperature was recorded with a portable weather station (Vantage Vue, Davis Instruments, Hayward, CA). This study was approved by the CSUSM Investigational Review Board.

Surfboard characteristics

Five surfboards (178 × 51 cm) of different volumes were shaped specifically for this investigation (Todd McFarland, Encinitas, CA). Board volumes were verified using a portable digital scanner (Go!Scan 3D, Creaform USA Inc., Costa Mesa, CA) with a resolution of 0.1 mm^3. The five boards of matched height and width were selected because they represented surfboards one might typically observe in the surfing community.

Physiological variables

Heart rate and VO_2 were sampled every 5 s and data from the last minute of paddling were used for analysis. A metabolic cart (TrueOne 2400, Parvo Medics, Sandy, UT) measured the subject's VO_2 using an oro-nasal mask (Hans Rudolph 7700 V2 Mask™, Hans Rudolph, Inc., Shawnee, KS) and a 15-ft hose to connect the mask to the metabolic cart. The gas analyzers and pneumotach on the metabolic cart were calibrated prior to each subject using known O_2 and CO_2 concentrations and a 3-L syringe (Hans Rudolph, Inc., Kansas City, MO), respectively. Heart rate was measured using a HR monitor (Polar RCX5 & T31, Polar Electro Inc., Kempele, Finland).

Board angles and cadence

A commercially available digital camera (Hero 4, GoPro Inc., San Mateo, CA) was encased in a waterproof housing and placed approximately 6 inches below the surface of the water. The camera was attached directly to the inside lining of the swim flume using a suction cup mount and positioned such that the entire length of the surfboard was visible. Two black markers (20-mm diameter) were placed on the side rail of each surfboard at the same location. These markers were easily visible underwater and were utilised to determine mean pitch angle and roll angle range of motion. Underwater footage of the sagittal plane was recorded at 30 frames per second and the last minute of each paddling bout was analysed.

Two-dimensional video footage was analysed using motion analysis software (MaxTRAQ, Innovision Systems, Inc, Columbiaville, MI). Twenty strokes were manually digitised in order to assess surfboard angle. Pitch angle was calculated in the motion analysis software using a horizontal reference line on the far side of the pool. Roll angle was calculated using a custom routine in MATLAB that utilised motion of the board markers in the vertical direction (following correction for pitch angle). Distance between the two black markers on the surfboard was used as a linear scale. Paddling cadence was calculated from the roll angle motion. Time series data for board angles were filtered (4th order Butterworth, 25 Hz cut-off) then reduced as follows: average pitch angle was calculated as the mean of the entire trial, pitch angle range of motion was calculated as the difference between the maximum and minimum values of the entire trial, and roll angle range of motion was calculated by first finding the range of motion for each stroke and then the average across all strokes. Mean cadence was calculated as the inverse of the time between each surfboard roll.

Statistical analysis

Values reported are means and standard errors. Correlation and linear regression described how VO_2, HR, board angles or cadence changed with board volume. Statistical Package for the Social Sciences (SPSS) version 22 was used to perform all statistical tests at $\alpha = 0.05$.

Results

Environmental and controlled variables

Volumes of the five boards were 28.43, 31.18, 32.23, 35.06 and 37.36 L, respectively. Air temperature (25.8 ± 2.6 °C) and water temperature (23.6 ± 1.6 °C) did not differ between boards. Water flow in the flume was the same for all subjects on all boards (1.1 ± 0.0 m/s).

VO_2 and HR decreased as board volume increased

Mean VO_2 and HR for all subjects were negatively correlated with board volume (VO_2 vs. BV, $r = -0.984$, $p = 0.003$; HR vs. BV, $r = -0.972$, $p = 0.006$). Linear regressions for VO_2 vs. BV and HR vs. BV were: $VO_2 = 32.2 - 0.263$*BV and HR = 167 – 0.822*BV (Figure 1).

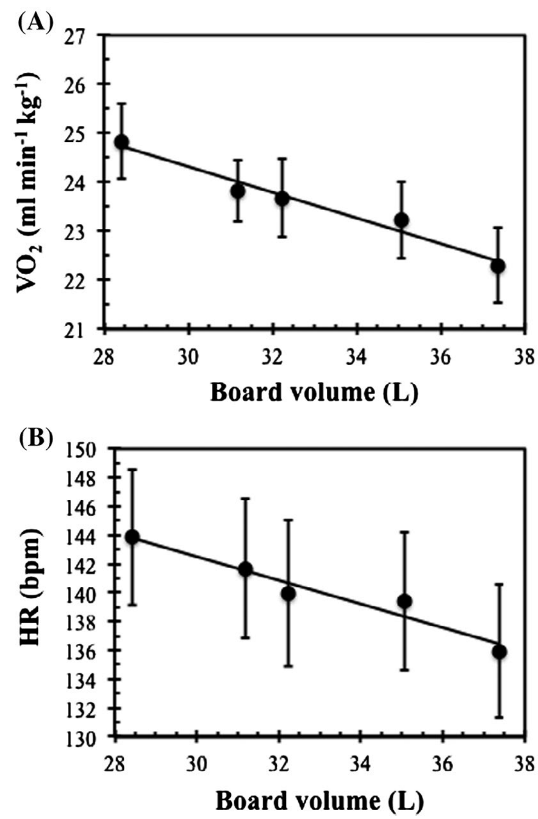

Figure 1. Oxygen consumption (VO_2, *panel A*) and heart rate (HR, *panel B*) during paddling vs. board volume (BV).
Notes: Values are means ± standard errors. Linear regressions for VO_2 vs. BV and HR vs. BV are $VO_2 = 32.2 - 0.263$*BV and HR = 167 – 0.822*BV.

Pitch and roll angles decreased as board volume increased

Mean pitch angle and roll angle range of motion were negatively correlated with BV (Pitch: $r = -0.995$, $p < 0.001$; Roll: $r = -0.911$, $p = 0.031$). Linear regressions for pitch vs. BV and roll vs. BV were: Pitch = 13.1 – 0.125*BV and Roll = 33.7 – 0.273*BV (Figure 2). Cadence was not significantly correlated with BV ($r = 0.659$, $p = 0.227$) and averaged 54.7 ± 3.5 strokes/min for all boards.

Discussion

Results from this study indicate that recreational surfers are more metabolically efficient when paddling thicker surfboards of matched height and width. Cadence did not change with increasing BV, and therefore distance per stroke also remained unchanged. However, we found that pitch angle decreased as BV increased, suggesting less resistance to forward progress. Roll angle also decreased as BV increased which may suggest that less force was

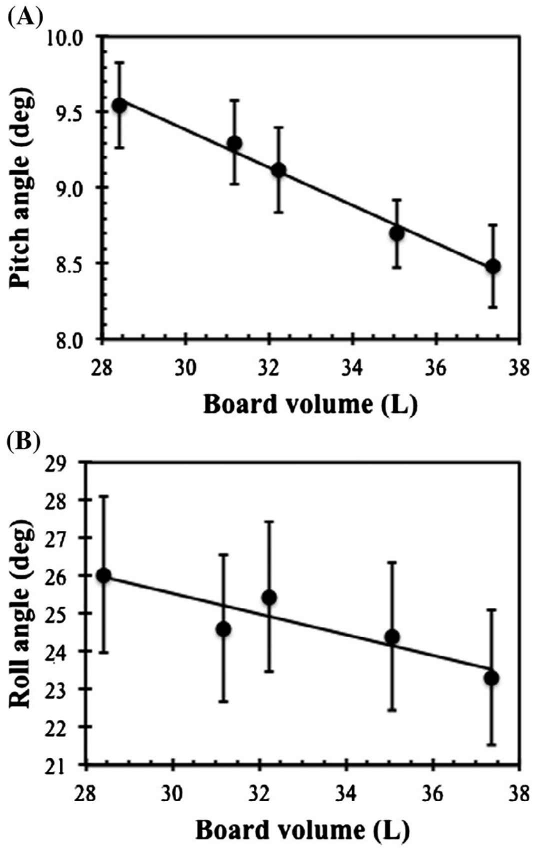

Figure 2. Pitch angle (*panel A*) and Average roll angle range of motion (*panel B*) during paddling vs. board volume (BV).
Notes: Values are means ± standard errors. Linear regressions for pitch vs. BV and roll vs. BV are Pitch = 13.1 – 0.125*BV and Roll = 33.7 – 0.273*BV.

applied per stroke to maintain the constant speed. Taken together, these data support our original hypothesis that energy expenditure decreases as BV increases. These findings are the first to support the idea that changes in BV through changes in thickness can alter energy expenditure during paddling.

HR and VO_2

Our data revealed a linear relationship for HR vs. BV as well as and VO_2 vs. BV. Although novel in surfers, studies on swimmers have reported that wetsuit-induced increases in buoyancy to be correlated with faster swim times (Cordain and Kopriva 1991) or lower energy expenditure at similar speeds (Trappe et al. 1996). Data from the present study indicate that the cost of paddling can be reduced by 1 ml/kg/min for every 4 litres of volume added to a surfboard. Therefore, 1 hour of paddling on a board with an additional litre of foam would equate to a savings of 6 kcal in a 70-kg surfer. Although the savings in energy expenditure per litre may seem insignificant, typical board volumes range from 20 to 120 L and could reflect a difference of 600 kcal per hour of paddling.

Pitch, cadence and roll

We observed that greater BV resulted in a more horizontal board position. Changes in buoyancy are associated with an altered pitch angle in swimmers (Cordain and Kopriva 1991). The centre of buoyancy is typically higher than the centre of gravity in humans (Gagnon and Montpetit 2016), and a discrepancy between these two centres results in the sinking of the legs while swimming. Also in swimming, forward motion with a more vertical body position has shown to be more energetically costly than a more horizontal position (Chatard, Lavoie, and Lacourl 1990). This is consistent with our observation that modifying buoyancy through increased BV decreased pitch angle and reduced energy expenditure. Therefore, manipulation of board volume may impact a surfer's paddling experience.

We also observed a significant linear decrease in roll with increasing BV. In swimming, oscillating trunk roll about the long axis of the body mirrors stroke cadence during the front crawl (Yanai 2004), and increasing this trunk roll has been prescribed as a method of improving swimming performance (Counsilman 1968). Given these findings, one can speculate that the reduced roll on boards with increased volume may be due to either greater stability and/or less effort needed to paddle at a given pace.

We did not observe a difference in cadence across the five surfboards. An explanation for the similar stroke rates we observed could be due to using a standardised current speed for all boards. This finding is consistent with data in swimmers demonstrating that stroke rate was unaltered by manipulating buoyancy with wetsuits at variable (Chatard et al. 1995) or constant speeds (Hue, Benavente, and Chollet 2003). It is important to note that this phenomenon may be unique to upper extremity or aquatic activities, given that models suggest an optimal cadence during locomotion exists for each power output (Sargeant 1994), which has been supported by data collected in elite cyclists (Foss and Hallén 2004).

Taken together, the changes in pitch and roll angles but not cadence with BV suggest thicker surfboards provide more stability, are more buoyant and require less energy expenditure to paddle. Because subjects paddled at the same speed and cadence, their distance per stroke was similar. Therefore, one can speculate that less roll associated with shallower paddling strokes on a thicker board was due to less propulsive force needed per stroke, similar to the relationship between roll angle and arm depth described in swimmers (Counsilman 1968).

Limitations

The most notable limitation of the current investigation is the use of a laboratory setting during data collection.

Surfers paddling in the ocean interact with dynamic environmental conditions such as waves, wind, and currents. While we found greater board volume correlated with increased metabolic efficiency in a constant current, a more buoyant surfboard could prove less manoeuvrable during wave riding or going under waves (duck diving). For this reason, future studies should investigate altering buoyancy without manipulating board volume through the use of different materials, thereby maximising buoyancy without compromising manoeuvrability.

Surfing is commonly associated with wave riding, while our study examined the impact of BV on paddling efficiency. Although time spent on a wave is the primary focus of surfing, almost half of the time spent in the water is dedicated to paddling (Meir, Lowdon, and Davie 1991; Mendez-Villanueva, Bishop, and Hamer 2006) while wave riding accounts for only 5% of a surfing bout. Therefore, more efficient paddling may have implications for reducing mechanical stress on the shoulder and back throughout a surfing bout. Further, more efficient paddling could arguably improve a surfer's experience in the water by allowing them to reach waves more quickly, catch more waves and improve surfing productivity.

The surfboards used in this study ranged from 28.4 to 37.4 L and are representative of the range one might typically observe for a surfboard of our length and width in the surfing community. It is important to note our range of board volumes was fairly narrow as surfboards vary in height and width with volumes ranging from 20 to 120 L. It is also important to note that although the relationships between metabolic and mechanical measures in this study correlated with board volume, these linear relationships may or may not hold across boards at extreme ends of the spectrum.

Conclusions

This is the first study to demonstrate that altering a surfboard's volume significantly impacts the energy expenditure of paddling. Specifically, these changes in energy expenditure are associated with pitch and roll angles, but not stroke rate. Therefore, these mechanical changes likely reflect modifications to other aspects of the paddling motion, like stroke length and/or depth. Future studies will need to characterise biomechanical changes in stroke mechanics when altering BV. Results from this study can be applied by surfboard manufactures to design surfboards that increase paddling efficiency without impacting wave-riding manoeuvrability.

Acknowledgements

We would like to thank Todd McFarland for his generous donation of the surfboards used in this study. In addition, we would like to thank Michael Cannady, Jenny Lou Cardinal, Joanne Cayabyab, Brian Cisneros, Aaron Galutera, Christine LaLanne, Ryan Martineau, Joseph Moon, Nathaniel Navarro, Madison Silvas, Danica Taylor, Zach Tieger and Kevin Valdez for their help with data collection.

Disclosure statement

No potential conflict of interest was reported by the authors.

References

Beal, Becky. 1995. "Disqualifying the Official: An Exploration of Social Resistance through the Subculture of Skateboarding." *Sociology of Sport Journal* 12 (3): 252–267.

Benjanuvatra, Nat, G. Dawson, Brian A. Blanksby, and Bruce C. Elliott. 2002. "Comparison of Buoyancy, Passive and Net Active Drag Forces between Fastskin™ and Standard Swimsuits." *Journal of Science and Medicine in Sport* 5: 115–123. doi:10.1016/S1440-2440(02)80032-9.

Buckley, Ralf. 2002. "Surf Tourism and Sustainable Development in Indo-Pacific Islands. I. The Industry and the Islands." *Journal of Sustainable Tourism* 10 (5): 405–424. doi:10.1080/09669580208667176.

Chatard, J. C., J. M. Lavoie, and J. R. Lacourl. 1990. "Analysis of Determinants of Swimming Economy in Front Crawl." *European Journal of Applied Physiology and Occupational Physiology* 61 (1–2): 88–92. doi:10.1007/BF00236699.

Chatard, J. C., X. Senegas, M. Selles, P. Dreanot, and A. Geyssant. 1995. "Wet Suit Effect: A Comparison between Competitive Swimmers and Triathletes." *Medicine and Science in Sports and Exercise* 27 (4): 580–586.

Clarys, J. P. 1979. "Human Morphology and Hydrodynamics." In *Swimming III*, edited by Terauds J, and Bedingfield EW, 3–41. Vol. 8. Baltimore, MD: University Park Press.

Cordain, L., and R. Kopriva. 1991. "Wetsuits, Body Density and Swimming Performance." *British Journal of Sports Medicine* 25 (1): 31–33. doi:10.1136/bjsm.25.1.31.

Counsilman, J. E. 1968. *The Science of Swimming*. Upper Saddle River, NJ: Prentice-Hall.

Farley, Oliver R. L., Chris R. Abbiss, and Jeremy M. Sheppard. n.d. "Performance Analysis of Surfing." *Journal of Strength and Conditioning Research*. doi:10.1519/JSC.0000000000001442.

Farley, Oliver R. L., Nigel K. Harris, and Andrew E. Kilding. 2012. "Physiological Demands of Competitive Surfing." *Journal of Strength and Conditioning Research* 26 (7): 1887–1896. doi:10.1519/JSC.0b013e3182392c4b.

Foss, Øivind, and Jostein Hallén. 2004. "The Most Economical Cadence Increases with Increasing Workload." *European Journal of Applied Physiology* 92 (4–5): 443–451. doi:10.1007/s00421-004-1175-5.

Gagnon, Micheline, and Richard Montpetit. 2016. "Technological Development for the Measurement of the Center of Volume in the Human Body." *Journal of Biomechanics* 14 (4) Elsevier: 235–241. doi:10.1016/0021-9290(81)90068-3.

Hue, O., H. Benavente, and D. Chollet. 2003. "The Effect of Wet Suit Use by Triathletes: An Analysis of the Different Phases of Arm Movement." *Journal of Sports Sciences* 21 (12): 1025–1030. doi:10.1080/0264041031000140419.

Kyle, C. R. 1989. "The Aerodynamics of Handlebars and Helmets." *Cycling Science* 1 (1): 22–25.

Leeworthy, V. R., J. Bowker, J. Hospital, and E. Stone. 2005. *Projected Participation in Marine Recreation: 2005 and 2010. National Survey on Recreation and the Environment 2000*. Silver Spring, MD: National Oceanic and Atmospheric Administration.

Meir, Rudi A., Brian J. Lowdon, and Allan J. Davie. 1991. "Heart Rates and Estimated Energy Expenditure during Recreational Surfing." *Australian Journal of Science and Medicine in Sport* 23 (3): 70–74.

Mendez-Villanueva, Alberto, David Bishop, and Peter Hamer. 2006. "Activity Profile of World-class Professional Surfers during Competition: A Case Study." *Journal of Strength and Conditioning Research/National Strength & Conditioning Association* 20 (3): 477–482. doi:10.1519/16574.1.

Pendergast, D., P. Di Prampero, A. Craig, and D. Rennie. 1978. "The Influence of Selected Biomechanical Factors on the Energy Cost of Swimming." In *Swimming Medicine IV*, edited by Eriksson B, and Furberg B, 367–378. Baltimore, MD: University Park Press.

Pendergast, D., J. Mollendorf, P. Zamparo, and A. Termin II. 2005. "The Influence of Drag on Human Locomotion in Water." *Undersea & Hyperbaric Medicine* 32 (1): 45–57. Undersea & Hyperbaric Medical Society.

Richardson, R. S., and S. C. Johnson. 1994. "The Effect of Aerodynamic Handlebars on Oxygen Consumption While Cycling at a Constant Speed." *Ergonomics* 37 (5): 859–863. doi:10.1080/00140139408963695.

Rubin, B. D. 1999. "The Basics of Competitive Diving and Its Injuries." *Clinics in Sports Medicine* 18 (2): 293–303. doi:10.1016/S0278-5919(05)70145-9.

Sargeant, A. J. 1994. "Human Power Output and Muscle Fatigue." *International Journal of Sports Medicine* 15 (03): 116–121. doi:10.1055/s-2007-1021031.

Tiozzo, Eduard, G. Leko, and L. Ruzic. 2009. "Swimming Bodysuit in All-out and Constant-pace Trials." *Biology of Sport* 26 (2): 149–156.

Trappe, T. A., D. L. Pease, S. W. Trappe, J. P. Troup, and E. R. Burke. 1996. "Physiological Responses to Swimming While Wearing a Wet Suit." *International Journal of Sports Medicine* 17 (02): 111–114. doi:10.1055/s-2007-972817.

Warshaw, Matt. 2010. *The History of Surfing*. San Fransisco, CA: Chronicle Books.

Yanai, Toshimasa. 2004. "Buoyancy is the Primary Source of Generating Bodyroll in Front-crawl Swimming." *Journal of Biomechanics* 37 (5): 605–612. doi:10.1016/j.jbiomech.2003.10.004.

Zdravkovich, M. M. 1992. "Aerodynamics of Bicycle Wheel and Frame." *Journal of Wind Engineering and Industrial Aerodynamics* 40 (1) Elsevier: 55–70.