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Characterisation of regional skin temperatures in recreational surfers wearing a 2-mm wetsuit

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ABSTRACT
The purpose of this study was to investigate skin temperatures across surfers' bodies while wearing a wetsuit during recreational surfing. Forty-six male recreational surfers participated in this study. Participants were instrumented with eight wireless iButton thermal sensors for the measurement of skin temperature, a Polar RCX5 heart rate monitor, and a 2 mm full wetsuit. Following instrumentation, participants were instructed to engage in recreational surfing activities as normal. Significant differences ($p < 0.001$) in skin temperature (T_{sk}) were found across the body while wearing a wetsuit during recreational surfing. In addition, regional skin temperature changed across the session for several regions of the body ($p < 0.001$), and the magnitude of these changes varied significantly between regions. We show for the first time that significant differences exist in skin temperature across the body while wearing a wetsuit during a typical recreational surfing session. These findings may have implications for future wetsuit design.

Practitioner Summary: This study investigated the impact of wearing a wetsuit during recreational surfing on regional skin temperatures. Results from this study suggest that skin temperatures differ significantly across the body while wearing a 2 mm wetsuit during recreational surfing. These findings may have implications for future wetsuit design.

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Thermal comfort; clothing design and testing; physiology; sports ergonomics

Introduction

There are an estimated 37 million people participating in the sport of surfing worldwide (Moran and Webber 2013) and more than 2.1 million surfers in the United States alone (Meir, Lowdon, and Davie 1991; Loveless and Minahan 2010). Despite the increase in popularity, there is a paucity of research on the physiological aspects of recreational surfing, and more specifically, the thermoregulatory responses to prolonged partial submersion in seawater in the context of surfing. Surfing presents a unique challenge to studying thermoregulation; a typical surfing session consists of a combination of activities that include 44% paddling, 35% stationary and 5% wave riding (Meir, Lowdon, and Davie 1991; Farley, Harris, and Kilding 2012; LaLanne et al. 2016). The dynamic nature of surfing causes certain parts of the body to move in and out of water, which results in variable rates of convective heat loss through both water and air. For example, paddling in a prone position exposes the ventral aspect of the torso to water, whereas the dorsal aspect remains out of water and exposed to solar radiation. In addition, during the stationary phase surfers sit upright with the lower extremities immersed, while the upper torso remains above water. In this position, it is likely that upper and lower body regions lose heat at different rates, in part because the thermal conductivity of water is 25% greater than that of air, which results in convective heat loss being 3–5 times greater in water compared to air (Nimmo 2004). In each case, the skin assists in maintaining thermal homeostasis by sensing temperature disturbances caused by environmental conditions (wind, ambient temperature, water temperature, etc.) and internal metabolic processes (muscle contraction, glycolysis, vasodilation, etc.). However, due to the high thermal conductivity of water, thermophysiological responses are often insufficient in maintaining balance between heat loss and heat production (Castellani et al. 1998). Because of the thermoregulatory challenge presented by higher rates of heat loss from regions of the body immersed in water, surfers utilize wetsuits to assist with maintenance of normothermia.

Wearing a neoprene wetsuit, as an additional layer of insulation on the skin surface, is a convenient means to reduce convective heat loss (Wakabayashi et al. 2008). The neoprene material allows small amounts of water

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to filter through the wetsuit without escaping, thus providing a layer of warmer water against the body (Naebe et al. 2013). This layer of water reaches a temperature close to the body's skin temperature, creating a thermal protection barrier (Naebe et al. 2013). Several previous studies indicate that this thermal barrier generated by a wetsuit can facilitate longer immersion periods and lead to other physiological benefits (Kang et al. 1983; Shiraki et al. 1986). For example, previous research has investigated the impact of wearing a wetsuit on skin temperatures across the body during complete immersion (Wakabayashi et al. 2008; Riera et al. 2014). Findings from these studies suggest that wearing an additional layer of thermal protection is an efficient way to maintain body temperature. In addition, experiments focusing on triathletes found that subjects wearing wetsuits retained higher skin temperatures during the swimming phase when compared to those without a wetsuit (Groeller 1990). Although evidence shows that wetsuits assist with thermoregulation, regional skin temperatures differ across the body in thermoneutral environments (Huizenga et al. 2004) and adjust during exercise as a thermoregulatory response (Fernandes et al. 2016).

It remains unclear whether regional skin temperatures differ while surfing in a dynamic environment; therefore, the purpose of this study was to investigate regional skin temperatures across surfers' bodies while wearing a 2 mm wetsuit during recreational surfing. It was hypothesized that the torso and upper extremities of surfers wearing a wetsuit would maintain higher skin temperatures when compared to lower extremities, due to the more frequent immersion of the lower body in water during a typical surfing session.

Methods

Participants

Forty-six adult male recreational surfers (age: 30.6 ± 1.4 years, height: 1.78 ± 0.01 m, weight: 77.4 ± 1.1 kg, body mass index: 24.5 ± 0.4 kg/m^2, surface to mass ratio: 0.0253 ± 0.0001 m^2/kg, surfing experience: 14.4 ± 1.5 years) from beaches in Southern California facing approximately 225°–260° participated in this study. Eligibility for participation required at least one year of previous recreational surfing experience. Participants completed a questionnaire whose criteria included: (a) personal demographics, (b) wetsuit preferences, and (c) board preferences. Prior to data collection, all participants gave their informed, written consent to procedures approved by the Institutional Review Board at California State University, San Marcos (Protocol #769612-1).

Experimental overview

Following informed consent, participants were instrumented with small wireless iButton thermal sensors (type DS1921G; Maxim Integrated/Dallas Semiconductor Corp., USA) which were set to measure skin temperatures at 1-min intervals. Thermal sensors were secured to the chest (skin of superior pectoralis major), back (skin of rhomboid), arm (skin of lateral tricep brachii), lower abdomen (skin of inferior rectus abdominis), lower back (skin of inferior portion of latissimus dorsi), forearm (skin of flexor carpi radialis), thigh (skin of lateral vastus laterali) and calf (skin of medial gastrocnemius) (Figure 1) with waterproof dressings (Nexcare™ Tegaderm™, USA). Excessive body hair was removed with razors to maximize the sensor's contact with the skin. A heart rate monitor (Polar Electro Inc., Kempele, Finland), which included a transmitter (T31) strapped transversely across the sternum and a watch receiver (RCX5) secured onto the subject's right wrist, was instrumented and set to measure heart rate at 1-min intervals. All subjects were fitted according to size into a black 2 mm full wetsuit (Hurley, USA; not commercially available) which was worn over all thermal sensors and heart rate monitor. Surfers wore no garments underneath wetsuit (swimsuit, rash guard or underwear). Environmental conditions such as: water temperature, air temperature, wave interval, wave direction, wave height, wind speed and tide, were obtained prior to each subject's surf session at their beach location using information directly from the National Oceanic and Atmospheric Administration's buoys located offshore (Surfline.com). Data collection for all equipment was synchronized with the session's start and end times. Start and end times were defined as the moment at which the subject entered and exited the water. Participants were then instructed to engage in recreational surfing activities as normal.

Data analysis

Skin temperature data were retrieved and downloaded from the thermal sensors by using the OneWireViewer (Maxim Integrated/Dallas Semiconductor Corp., USA) Java™ application. Only skin temperature measurements recorded within the start and end time of each participant's session were utilized, the rest were omitted. Heart rate data was retrieved and downloaded using polarpersonaltrainer.com website. Samples that measured zero beats-per-minute were omitted and expressed as no data.

Statistical analyses

Thermistor data were analyzed using an 8 (sensor) × 8 (time) mixed model ANOVA. Data from each sensor were

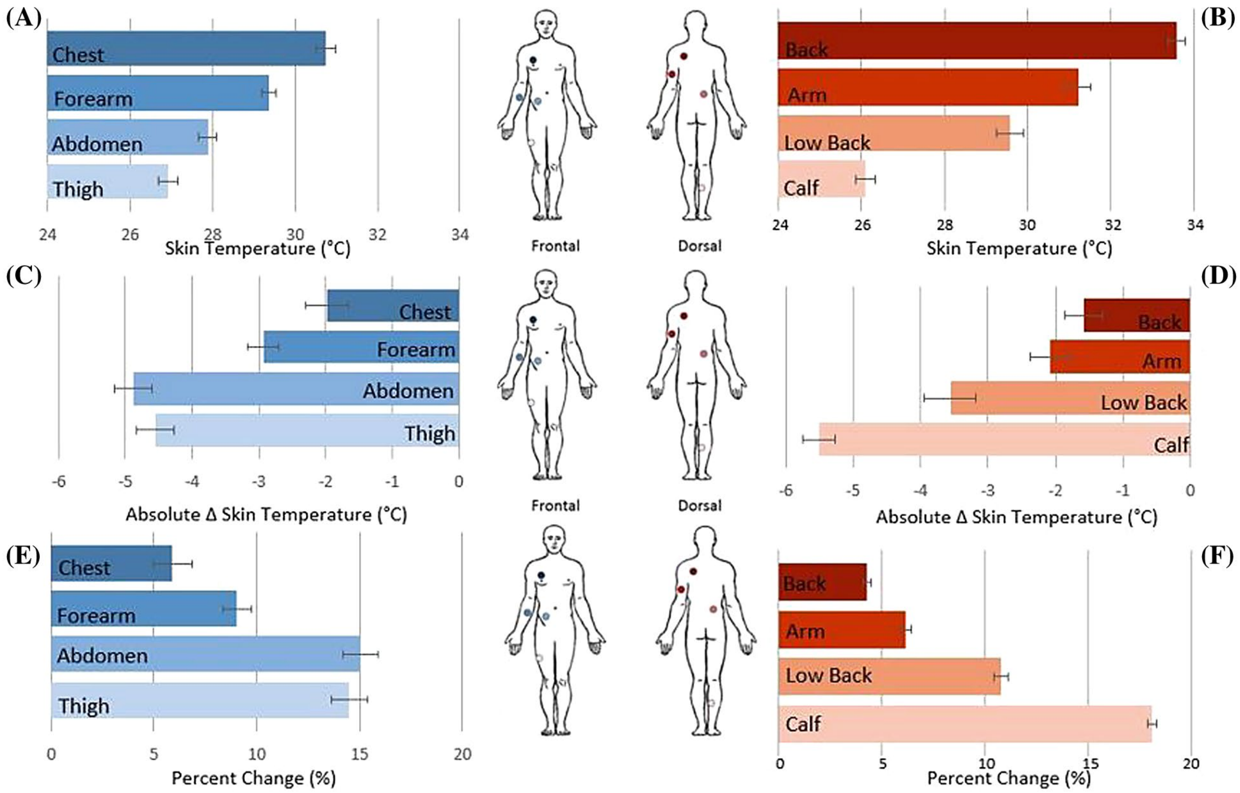

Figure 1. Mean skin temperatures over time (A and B), absolute change in skin temperature (C and D), and percent change (E and F) across frontal and dorsal regional parts of the body during recreational surfing. Data expressed in mean ± SE.

grouped into five-minute epochs from 0 to 40 min, and the average temperature across each epoch was used to generate 8 time points for analysis. Statistical analyses were restricted to data acquired from 0 to 40 min in order to maintain an adequate sample size, but data collection continued up to 65 min for those who surfed more than 40 min. Post hoc comparison for the main effect of sensor location was performed using Tukey's multiple comparison test with a Bonferroni adjusted alpha level of 0.006. Post hoc analysis for the main effect of time was performed using dependent t-tests comparing mean temperature for minutes 1–5 with minutes 36–40 for all 8 sensors. Finally, *post hoc* comparison of the interaction effect was accomplished by first calculating the percent change in temperature from minutes 1–5 to minutes 36–40 and then comparing percent change pairwise among all 8 sensors. The Benjamini-Hochberg analysis was applied to all t-tests in order to control for false discovery rate (Benjamini and Hochberg 1995). Values reported are means and standard errors (SE).

Results

Surf session characteristics

The average duration for all included surf sessions ($n = 46$) was 81.0 ± 4.3 min during which the average and maximal heart rates was 136 ± 2 and 178 ± 2 beats per minute, respectively. Forty-six surfers participated for at least 40 min, and 28 surfers participated for more than 65 min. Across all surf sessions, water temperature averaged 16.0 ± 0.1 °C with an average wave size of 0.94 ± 0.03 m at an average interval of 13.0 ± 1.0 s and an average wave direction of 250 ± 5°. Average air temperature was 18.7 ± 0.4 °C with an average wind speed of 7.8 ± 0.7 km/h, and an average wind direction of 196 ± 11°.

Regional skin temperatures

Figure 2 displays regional skin temperature throughout all 46 surf sessions up to 65 min. Skin temperatures were significantly different between nearly all of the anatomical locations examined here (main effect for sensor: $F_{7,45} = 88.09$, $p < 0.001$). More specifically, *post hoc* comparison of skin temperature at each sensor location revealed significant differences between all but two pairwise comparisons: upper chest vs. upper arm and forearm vs. low back (Table 1).

Changes in skin temperature

Regional skin temperature decreased as a function of time at all skin sites during the surfing session (main effect for

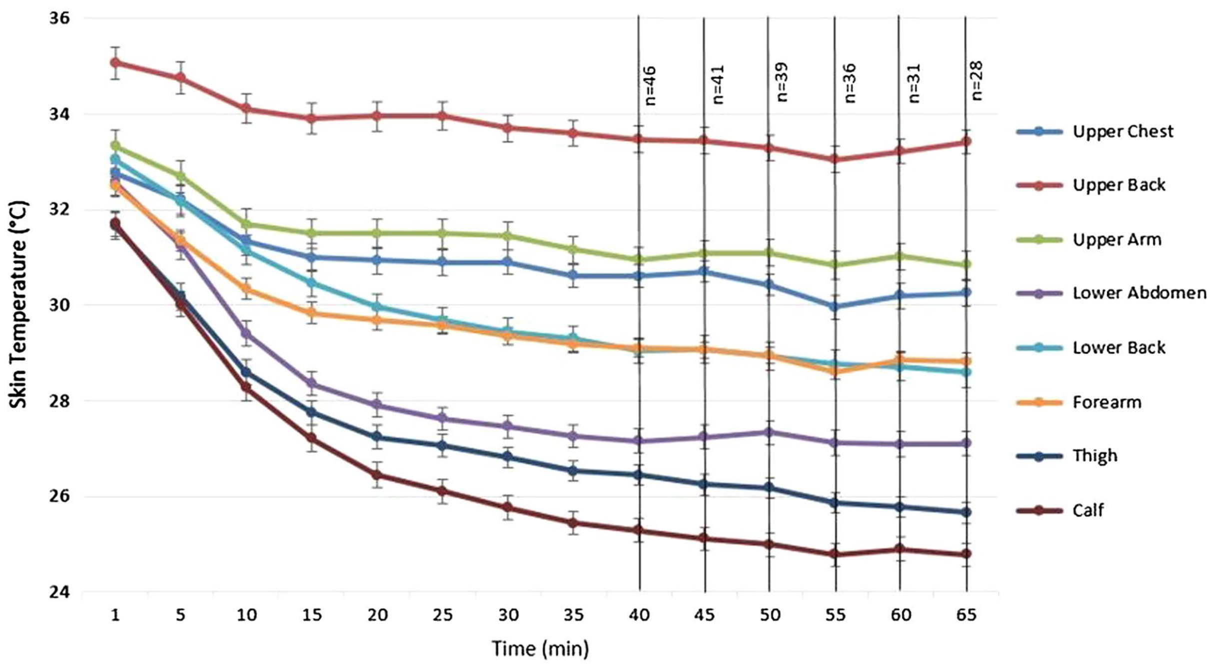

Figure 2. Regional skin temperatures throughout 46 recreational surf sessions up to 65 min (mean ± SE). *Data analysis performed at 40 min and displayed up to 65 min.

Table 1. *P*-value for pairwise comparisons of skin temperature across different anatomical locations ($n = 46$, 0–40 min).

		Means							
	Thermistor	Chest	Back	Arm	Low Abd	Low Back	Forearm	Thigh	Calf
Percent change	Chest		$p < 0.001$	0.129*	$p < 0.001$	0.001	$p < 0.001$	$p < 0.001$	$p < 0.001$
	Back	0.115*		$p < 0.001$	$p < 0.001$	$p < 0.001$	$p < 0.001$	$p < 0.001$	$p < 0.001$
	Arm	0.812*	0.028		$p < 0.001$	$p < 0.001$	$p < 0.001$	$p < 0.001$	$p < 0.001$
	Low Abd	$p < 0.001$	$p < 0.001$	$p < 0.001$		$p < 0.001$	$p < 0.001$	0.001	$p < 0.001$
	Low Back	$p < 0.001$	$p < 0.001$	$p < 0.001$	0.002		0.520*	$p < 0.001$	$p < 0.001$
	Forearm	0.004	$p < 0.001$	0.002	$p < 0.001$	0.196*		$p < 0.001$	$p < 0.001$
	Thigh	$p < 0.001$	$p < 0.001$	$p < 0.001$	0.533*	0.002	$p < 0.001$		0.002
	Calf	$p < 0.001$	$p < 0.001$	$p < 0.001$	$p < 0.001$	$p < 0.001$	$p < 0.001$	$p < 0.001$	

*Denotes comparisons that were not statistically significant following Benjamini-Hochberg analysis.

time: $F_{7,45} = 472.57$, $p < 0.001$; Tukey's multiple comparison test, $p < 0.001$). Average decrease in skin temperature from minutes 5 to 40 in the water ranged from 4.3% (upper back) to 18.1% (lower leg), with a percent change of 10.5 ± 5.0% across all 8 sensor locations (Figure 1). The interaction of time x sensor location was also significant ($F_{7,45} = 15.57$, $p < 0.001$). This resulted in considerable variation in the magnitude of change in skin temperature across regions, with four notable exceptions: upper back v. upper chest, upper chest v. upper arm, lower abdomen v. thigh, and low back v. forearm (Table 1).

Discussion

Despite increases in the popularity of surfing, thermoregulatory responses to variable rates of convective heat loss during recreational surfing with a wetsuit have received little to no attention. In an effort to elucidate the distribution of skin temperatures across recreational surfers' bodies while wearing a 2 mm wetsuit, we conducted a field study and recorded skin temperatures at eight regions of the body during typical surf sessions in Southern California between the months of March and May. Results from this study indicate that regional skin temperatures of recreational surfers differ significantly across nearly all anatomical regions examined. In addition, these data indicate that skin temperatures decrease significantly across a typical surf session. Although the magnitude of decrease in skin temperature varied between anatomical locations, these data suggest that percent change in skin temperature was significantly different between most locations. Altogether, these data support our initial hypothesis that a non-uniform distribution of skin temperatures would exist while wearing a wetsuit during recreational surfing bouts.

Many investigators have published similar findings regarding regional differences in skin temperature in neutral conditions (Huizenga et al. 2004; Fernandes et al. 2016), in static cold water immersions with (Riera et al. 2014) and without (Tikuisis 2003) wetsuits, in cold water immersions involving exercise (Hayward, Collis, and Eckerson 1973; McArdle et al. 1992), and while swimming with wetsuits (Trappe et al. 1995). However, the majority of investigations prior to the present study have obtained findings under conditions simulating actual environments (i.e. accidental ocean immersion, triathlon swimming). Despite the fact that previous studies have components that are similar to recreational surfing (i.e. cold water, wetsuits, swimming), to our knowledge these data are the first to demonstrate that these regional differences in skin temperature are exacerbated when an individual participates in recreational surfing while wearing a 2 mm wetsuit. One can speculate that these differences in skin temperatures among different regions are driven by the manner in which surfers interact with their environment while surfing. Due to the dynamic nature of surfing, surfers can lose heat in cold water significantly faster than in cold air (Gonzalez 1988). Considering the fact that the least amount of time is spent wave-riding, surfers spend most of their time waiting for a wave to ride (Meir, Lowdon, and Davie 1991; Farley, Harris, and Kilding 2012; Bravo et al. 2015) by either paddling in a prone position or sitting on their surfboard. Surfers typically paddle their boards with a slight upwards pitch angle (Ekmecic et al. 2016) which positions their lower torso and lower extremities in constant contact with seawater. Likewise, while sitting on their boards, surfers' legs become submerged. Thus, constant seawater movement against lower regions of the body increases convective heat loss by continuously altering exposure of the skin and wetsuit to different temperatures (Schilling 1984; Young, Sawka, and Pandolf 1996). In addition, similar to previous thermographic findings following swimming activity (Hayward, Collis, and Eckerson 1973), heat production through muscle activation of the upper extremities and back during paddling likely also contribute to the regional differences in skin temperature reported in the current investigation. The current data demonstrate a 10 °C difference between upper back and lower leg skin temperatures is likely attributable to these mechanisms (Figure 1).

The current findings have important physiological implications since reductions in skin temperature can negatively influence muscle function (Bennett 1984; Holewijn and Heus 1992). These data indicate that on average surfers experience a −6.4 °C change in lower leg skin temperature during a typical surfing period. Reductions in lower extremity skin temperatures of a similar magnitude have been associated with decreases in internal muscle temperature, which in turn lead to decreases in average force production (−48%), power output (−32%), maximal force production (−21%) and take-off velocity during a vertical jump (−18%) (Bergh and Ekblom 1979; Sargeant 1987; Oksa, Rintamaki, and Rissanen 1997). These reductions in skeletal muscle performance could significantly affect surf performance, as surfers must rapidly transition from a prone paddling to wave riding position. This is of great importance to all surfers because the most important feature of competitive surfing is the ability to ride waves (Sheppard et al. 2012), which requires lower extremity strength and velocity. Therefore, given these novel findings, one can speculate that the significant decreases in lower extremity skin temperatures may in fact be impeding surfing performance. Altering wetsuit design by either increasing neoprene thickness and/or changing wetsuit material in the lower extremities may increase skin temperatures and enhance performance during recreational surfing. However, it is important to note that increasing the thickness of the neoprene may also potentially negatively impact performance by both increasing garment weight and altering range of motion. Future research will need to evaluate the impact that modifications to lower extremity wetsuit design has on thermoregulation and performance.

These data also demonstrate that upper extremities experience smaller reductions in skin temperature relative to lower extremities. Other researchers have reported similar findings (Guéritée et al. 2015), suggesting that subjects experience minimal skin temperature changes in the chest, back and upper arms, while wearing a full wetsuit. Although surfers primarily utilize wetsuits to reduce heat loss, a recent study has demonstrated that neoprene wetsuits have an impact on the biomechanics of surfing by altering the patterns of repetitive motion of the upper extremities when paddling (Nessler et al. 2015). Paddling is an important factor for competitive success as it is the most time-demanding activity of surfing and is directly related to an athlete's ability to catch waves (Meir, Lowdon, and Davie 1991; Sheppard et al. 2012). While additional research is needed, it is possible that subtle changes in the paddling motion might be beneficial to performance and therefore encouraged through wetsuit design. The current findings suggest that altering upper extremity wetsuit design in order to enhance surf performance will have minimal influence on upper body thermoregulation.

Conclusion

These data are the first to demonstrate that significant differences in skin temperature profile exist across the body while wearing a 2 mm wetsuit during recreational surfing bouts. Specifically, reductions in skin temperature were greatest over the lower body which may significantly hinder surfers' lower extremity muscle performance and, ultimately, competitive success. Because previous findings demonstrate that wetsuits alter upper extremity paddling mechanics, the current findings suggest that upper body wetsuit design should be tailored more toward mobility while thermal insulation should remain paramount over the lower body. These implications could potentially enhance surf performance. Future tests of this hypothesis should incorporate perceptual metrics to evaluate the impact of zoned insulation (or lack thereof) on thermal sensation and comfort during surfing. In addition, future research will need to determine the extent to which differences in skin temperature occur with varying environmental conditional and wetsuit thicknesses, similar to those conditions recreational surfers are exposed to while surfing in the far northern and southern latitudes of the world.

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Disclosure statement

The authors declare no conflicts of interest.

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