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ORIGINAL ARTICLE

Effect of wetsuit outer surface material on thermoregulation during surfing

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Abstract
While some research does exist on wetsuit thermoregulation, there is currently a paucity in the literature describing how various types of neoprene materials affect skin temperatures. The purpose of this study was to test the hypothesis that the slick neoprene would lead to higher skin temperatures in comparison to the jersey material. Participants wore a custom wetsuit with the torso made of half slick and half jersey neoprene materials ($n = 78$). Participants either participated in one of two field studies or engaged in a simulated surfing session in a flume after sunset, where the influence of direct sun exposure was eliminated. In the field, participants wore four thermistors placed on either side of the chest and the upper back ($n = 27$) or the abdomen and the lower back ($n = 31$). Skin temperatures were measured across typical surfing sessions. In the laboratory, the participants ($n = 20$) wore all eight sensors in the anatomical locations described above, and skin temperatures were recorded across a simulated surfing session. In the field study, the mean skin temperatures under the slick neoprene were significantly higher when compared to the jersey neoprene for the upper chest ($p < 0.001$), upper back ($p = 0.001$), and lower back ($p < 0.001$) at all time points. In the laboratory study, skin temperatures were significantly higher under the slick neoprene at the upper chest and lower back ($p < 0.001$). These findings may be a result of greater heat absorptive properties of slick neoprene during exposure to the sun and the water-retaining properties of jersey-lined neoprene.

Keywords Skin temperature · Action sports · Radiant heat

1 Introduction

Thirty-five to fifty million people participate in surfing worldwide [1, 2]. Growing popularity has stimulated research into the physiological and biomechanical demands [3–8], as well as ways to improve performance [9, 10] and safety [11]. Studies have focused on thermoregulation in surfers because of its relevance to both the safety and performance of athletes [3, 8]. Surfing presents unique challenges to thermoregulation because athletes interact with both the air and water, often in conditions that are cold and windy. Reductions in body temperature that occur with prolonged exposure in the ocean can lead to reductions in muscle function [12–14], and an inability to maintain a healthy body temperature can lead to hypothermia [15, 16].

Neoprene wetsuits aid in thermoregulation and are, therefore, important and widely used pieces of surfing equipment. Wetsuits are considered a critical piece of surfing equipment, the scientific literature describing their thermoregulatory properties, particularly during surfing, is sparse. Recent studies suggest that wetsuits are not optimally designed for surfers [3, 8]. In particular, different regions of the body were shown to lose heat at different rates while surfing in a wetsuit; the abdomen and lower back have different changes in temperature when compared to both the chest and upper back [3, 8]. Further, the greatest heat loss was recorded in regions of the body that interact with the water the most during surfing [3, 8]. Specifically, the skin temperature of the calf, thigh, and abdomen have been reported to be reduced by 5 °C during surfing [3, 8]. These reductions in skin temperature are not surprising, given that the thermal conductivity of water is 25% greater than air [17]. Historically, it appears that manufacturers have not considered these variations in heat loss in their wetsuit designs. These data suggest that opportunities exist for studying and improving multiple aspects of wetsuit design for surfers. One factor with the

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potential to improve wetsuit design involves the optimization of the type of neoprene used over various aspects of the body.

The type of neoprene material used in a wetsuit may influence thermoregulation while surfing, yet no work has been published examining how these materials might affect skin temperature. Neoprene itself is made of closed-cell rubber, which acts as a radiant barrier, to prevent the loss of body heat [18]. A common type of neoprene used in wetsuit composition is jersey-lined neoprene, which consists of an overlay of 0.15 mm nylon that lines the inside and outside of the wetsuit [19]. This lining contributes to the durability of the wetsuit and gives the outer layer of the wetsuit a matte appearance and rough texture. This outer lining of nylon is thought to reduce heat retention by holding water on the surface of the wetsuit, thereby increasing heat transfer from the body to the environment. Another type of neoprene that is used in wetsuit design is slick, or smooth neoprene which lacks the outer-lining of nylon. Without this outer-lining, there is a shiny finish on this material, which is thought to aid in heat absorption and retention of radiant heat. In addition, the embossed coating of slick neoprene acts as water repellent which may also aid in retaining body heat [20].

Currently, wetsuit design is based primarily on anecdotal evidence. While wetsuit designers are interested in making wetsuits as warm as possible, it is also important to balance warmth with other factors related to performance, such as flexibility and durability. Many prominent wetsuit manufacturers state that slick neoprene is warmer and less durable than jersey-lined neoprene, but have not presented data to support this claim. Therefore, comparing skin temperatures in surfers wearing wetsuits with different types of neoprene would help to inform wetsuit design. The purpose of this study was to compare skin temperatures under a slick neoprene material and jersey neoprene material during both a typical surf session in the ocean and a simulated surf session after sunset. Comparing skin temperatures in these different environments will help to separate the effects of sun derived radiant heat from other factors that might impact skin temperature, including variations in water retention by the neoprene material. We hypothesized that the slick neoprene would lead to higher skin temperatures than the jersey material.

2 Materials and methods

2.1 Participants

Seventy-nine male ($n=58$) and female ($n=21$) recreational surfers were included in this study. All participants had at least 1 year of prior surfing experience, were between the ages of eighteen to fifty, and reported no known injuries. Combined participant characteristics, across both field studies and the laboratory study are reported in Table 1. All prospective participants were informed of the procedures, completed a questionnaire about their surfing experience and activity levels, and provided their informed consent prior to participation. All procedures were approved by the Institutional Review Board at California State University, San Marcos (#1302181) in accordance with the declaration of Helsinki.

2.2 Experimental protocol

Following informed consent and completion of the physical activity questionnaire, participants were fitted to a custom 2-mm (mm) Hurley full-suit wetsuit (Hurley International, Costa Mesa, USA), instrumented with a Polar FT1 heart rate receiver (Polar Electro Inc., Kempele, Finland) attached to their wrist, and a Polar T31 transmitter secured across their sternum. Heart rate was measured, with an accuracy of ± 1 bpm per manufacturer specifications, in an attempt to quantify exercise intensity during surfing. For the first field study, four iButton DS1921L or DS1921G skin temperature loggers (Maxim Integrated/Dallas Semiconductor Corp., USA), with an accuracy of ± 1.0 °C per manufacturer specifications, were attached to the participant's left and right upper back (2 cm superior to the medial aspect of the spine of the scapula) and left and right chest (2 cm inferior to the

Table 1 Summary of subject characteristics

Sex (# of subjects)	Field study #1 $n=27$	Field study #2 $n=31$	Laboratory study $n=20$
Age (years)	29.7 ± 1.9	28.7 ± 2.4	26.1 ± 1.8
Height (cm)	175.9 ± 1.7	175.5 ± 2.1	175.1 ± 2.2
Mass (kg)	73.1 ± 2.5	72.0 ± 2.1	70.4 ± 2.0
Years surfing	12.1 ± 2.1	13.3 ± 2.1	12.4 ± 2.0
Self-reported competency	6.3 ± 0.3	6.4 ± 0.3	6.4 ± 0.2
Board length (cm)	198.7 ± 8.4	197.5 ± 9.1	192.0 ± 8.8

Values are means ± SE. Field study #1 refers to thermistors placement on chest and upper back. Field study #2 refers to thermistor placement on abdomen and lower back clavicle). For the second field study, the four thermistors were placed on the left and right abdomen (5 cm below the last palpable rib) and left and right lower back (5 cm above the posterior superior iliac spine). Each thermistor recorded skin temperature data every minute and was attached to the participant using waterproof 3 M Tegaderm Film (Nexcare™ Tegaderm™, USA). The custom 2-mm wetsuit was designed with the left half of the torso and back comprised of a slick neoprene material and the right half of jersey neoprene (Fig. 1). The jersey material was made up of 2 mm of neoprene sandwiched between two 0.15 mm nylon layers, whereas the slick material only had one layer of 0.15 mm nylon attached to the inside of the 2 mm neoprene (Fig. 1). Data were collected throughout the entirety of the surf session, and the duration was determined by each participant. Participants were asked to surf for 30 min, which began when the participant entered the water and ended when they exited. There was no instruction provided to subjects on the maximum surf duration. Both field experiments took place during daylight hours where radiant heat from the sun might contribute to thermoregulation. Water and ambient air temperatures were recorded from the National Oceanic and Atmospheric Administration's buoys located offshore at each surf session (surfline.com).

Fig. 1 **a** Custom designed 2 mm wetsuit. The right upper body was constructed of slick neoprene and left upper body was constructed of jersey covered neoprene. **b** Cross-sectional images of slick and jersey neoprene construction

A separate experiment was performed in the laboratory with a different set of participants, all of whom met the same inclusion criteria. After providing informed consent and completing physical activity questionnaire, participants were fitted with one of the three (small, medium, or large) custom 2-mm full wetsuits described above, instrumented with a Polar RCX5 heart rate receiver attached to their wrist, and a Polar T31 transmitter secured across their sternum. Thermistors were secured over the skin in all eight previously stated anatomical locations (four from field study one and four from field study two) (Fig. 2). Participants then completed a predetermined protocol designed to simulate a typical surf session in an outdoor Elite Endless Pool flume (Commercial Elite Endless Pools®; Aston, PA) with a water temperature set at 16 °C. A Global Water Flow Meter (Global Water Instrumentation; College Station, TX) was installed at the front of the flume to measure water velocity during the surf simulation. The protocol began with one minute laying on a 177.8 × 7.78 × 0.89 cm surfboard, followed by a duck dive into immediate paddling for 1 min at 1.4 $m{\cdot}sec^{-1}$. This speed was selected based on paddling speeds of surfers observed in the field by Farley et al. [4]. The participant then sat on the surfboard for one minute, and again duck dove followed by 1 min of paddling at the same speed. Participants repeated this sequence for 60 min. All procedures took place after the sun had set to compare the effects of wetsuit materials on skin temperature without radiant sun exposure. Ambient air temperature was recorded at the beginning of each simulated surf session using a Davis Vantage VUE weather station (Davis Instruments©; Hayward, CA).

Participant's thermal perception of slick vs. jersey neoprene was assessed following completion of both the field and laboratory studies. Specifically, participants were asked to identify the side of the wetsuit that felt warmer or if both sides felt equal. This information was recorded in the participant's datasheet.

2.3 Data management

The mean heart rate data across the surf session was retrieved from the Polar FT1 and RCX5 heart rate receivers immediately after the participant exited the water. Skin temperature data from individual thermistors was uploaded onto One Wire Viewer (Maxim Integrated/Dallas Semiconductor Corp., USA), and copied into an Excel spreadsheet at one-minute intervals for further analysis. Custom routines in Matlab (R2017, Natick MA) were then used to aggregate and organize skin temperature data for statistical analysis.

2.4 Statistical analysis

All experiments followed a similar analysis. First, data from each thermistor were reduced into 12 intervals of time (epochs) by averaging temperature across five-minute increments from 1 min to 60 min. For the field experiments, while all individuals surfed for at least 30 min, some did not surf for the entire 60 min. Therefore, statistical analysis of minutes 40–60 only included participants who surfed for these durations. Two way repeated measures ANOVA was then used to compare wetsuit material (slick vs. jersey) across time (12 epoch means) at each thermistor location. The Greenhouse–Geisser adjustment was applied for cases where the assumption of sphericity was violated [21]. Post hoc analysis involved comparison (paired t-test) of slick vs.

Fig. 2 Image of thermistor and heart rate transmitter placement for laboratory study

jersey temperature at each of the 12-time points for thermistor locations with a significant ANOVA result. The Benjamini–Hochberg analysis was utilized to control for false discovery rate due to multiple comparisons [22]. Significance was set at a p-value < 0.05. Values were reported as means ± standard error (SE).

3 Results

3.1 Surf session characteristics

For the field studies, the mean duration of surf sessions was 68.4 ± 3.6 min. The mean water and air temperatures were as follows: field study one: 18.4 ± 0.1 °C and 19.5 ± 0.4 °C, field study two: 15.4 ± 0.2 °C and 16.3 ± 0.6 °C, laboratory: 16.0 ± 0.1 °C and 19.0 ± 1.4 °C. The mean heart rate during field study one, field study two and the laboratory study were 135 ± 5 bpm, 139 ± 3 bpm and 108 ± 6 bpm, respectively.

3.2 Thermoregulatory characteristics

For the first field experiment, two way repeated measures ANOVA indicated a significant main effect for wetsuit material for the upper chest ($p < 0.001$, $\eta^2_{\text{partial}} = 0.519$) and upper back ($p = 0.001$, $\eta^2_{\text{partial}} = 0.472$) locations (Fig. 3). There was also a significant interaction effect of wetsuit material by time for both the upper chest and upper back (both $p < 0.001$, $\eta^2_{partial} = 0.346$) locations. The main effect for time was not significantly different for either sensor location. Post hoc analysis revealed significant differences in temperature between wetsuit material at all time points.

For the second field experiment, two way repeated measures ANOVA indicated a significant main effect for wetsuit material for the lower back ($p < 0.001$, $\eta^2_{\text{partial}} = 0.579$) but not the abdomen (Fig. 4). There was also a significant main effect for time for both the abdomen ($p < 0.001$, $\eta^2_{\text{partial}} = 0.522$) and lower back ($p = 0.005$, $\eta^2_{\text{partial}} = 0.290$) locations.

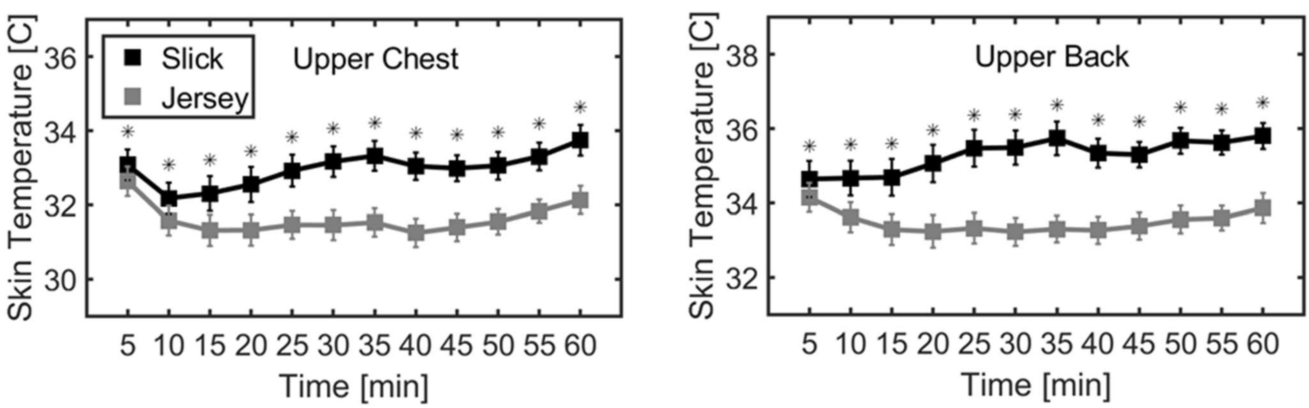

Fig. 3 Comparison of skin temperature between the jersey and slick neoprene on both the chest and upper back while surfing in the ocean. Bars represent standard error of the mean. Asterisk (*) indicates a significant difference between jersey vs. slick neoprene ($p < 0.05$)

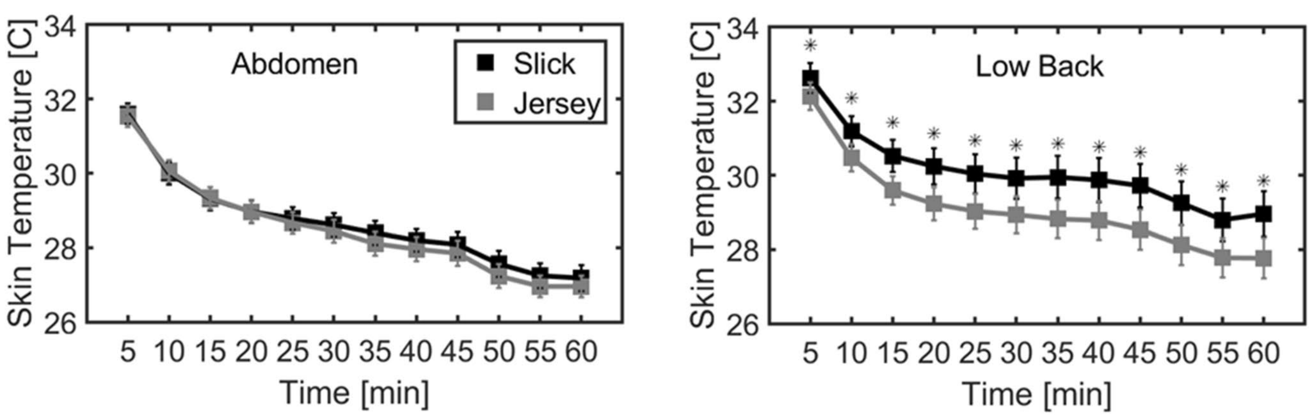

Fig. 4 Comparison of skin temperature between the jersey and slick neoprene on the abdomen and the lower back while surfing in the ocean. Bars represent standard error of the mean. Asterisk (*) indicates a significant difference between jersey vs. slick neoprene ($p < 0.05$)

The interaction effect (wetsuit material by time) was not statistically significant for either sensor location. Post hoc analysis revealed significant differences in temperature between wetsuit material at all time points for the lower back sensor location.

For the simulated surf session (experiment 3), two way repeated measures ANOVA indicated a significant main effect for wetsuit material for the upper chest ($p<0.001$, $\eta^2_{\text{partial}}=0.501$) and lower back ($p<0.001$, $\eta^2_{\text{partial}}=0.490$), but not for the upper back or abdomen (Fig. 5). There was also a significant main effect for time for the upper chest ($p<0.001$, $\eta^2_{\text{partial}}=0.811$), the abdomen ($p<0.001$, $\eta^2_{\text{partial}}=0.874$), and the lower back ($p<0.001$, $\eta^2_{\text{partial}}=0.673$), but not the upper back. Finally, there was an interaction effect for the upper chest ($p<0.001$, $\eta^2_{\text{partial}}=0.316$), upper back ($p<0.001$, $\eta^2_{\text{partial}}=0.497$), and lower back ($p=0.001$, $\eta^2_{\text{partial}}=0.324$), but not the abdomen. For both the upper chest and lower back, post hoc analysis revealed significant differences in temperature between slick and jersey material at all time points except for 5 and 10 min.

3.3 Thermal perception

In all three experiments combined, a total of 48 out of 78 (61.5%) participants reported that the slick side of the wetsuit felt warmer (Table 2). The remaining 30 out of 78 (38.5%) participants reported to feel no difference between slick and jersey side of the wetsuit (Table 2). No participants reported that the jersey neoprene side of the wetsuit felt warmer than the slick neoprene side.

Table 2 Thermal perception

	Field study #1	Field study #2	Laboratory study
Slick (# of subjects)	$n=19$	$n=20$	$n=9$
Jersey	$n=0$	$n=0$	$n=0$
Equal	$n=8$	$n=11$	$n=11$

Values represent the number of subjects that responded that the slick or jersey side of the wetsuit felt warmer during either field or laboratory study. Equal represents subjects reporting that there were no distinguishable differences in warmth between slick and jersey sides of the wetsuit

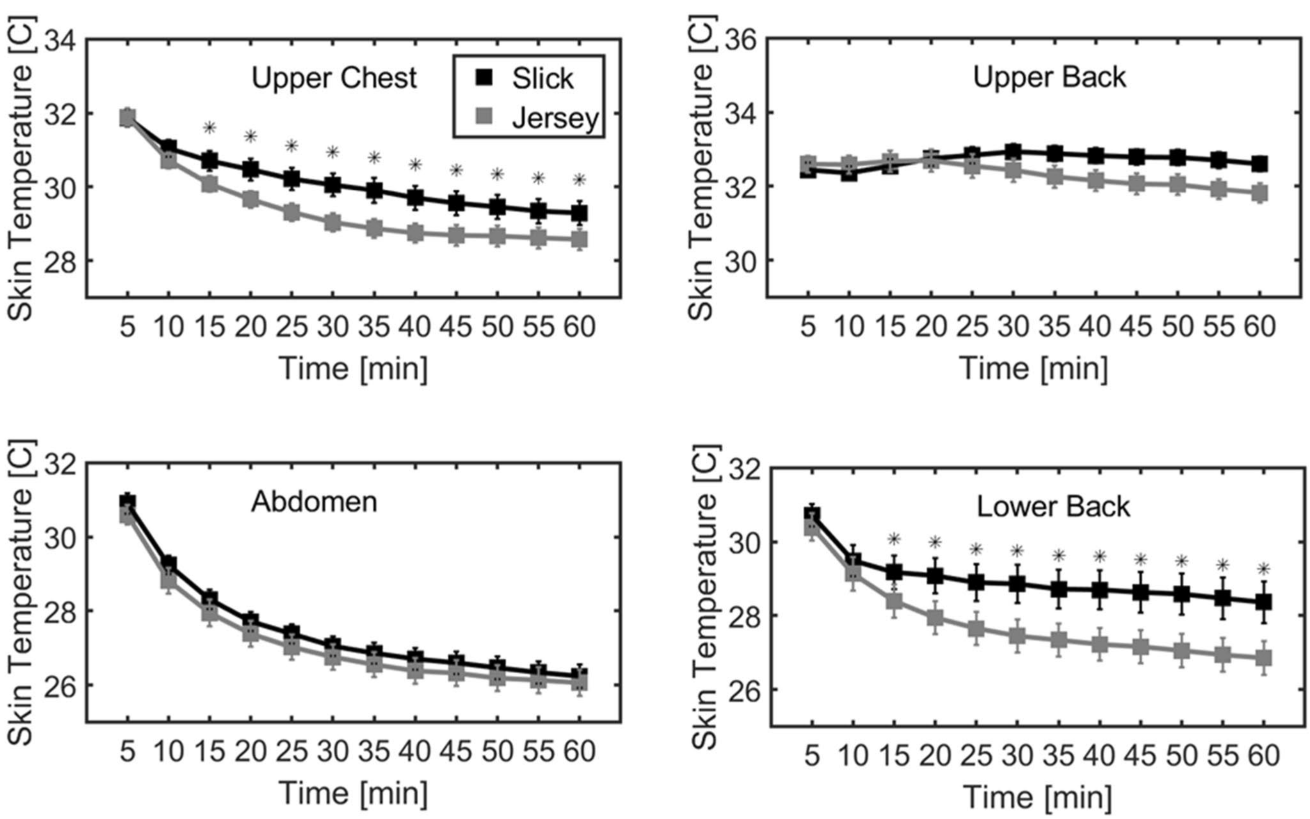

Fig. 5 Comparison of skin temperature between the jersey and slick neoprene at four anatomical locations while completing a simulated surf session after sunset. Bars represent standard error of the mean. Asterisk (*) indicates a significant difference between jersey vs. slick neoprene ($p<0.05$)

4 Discussion

This study is the first to demonstrate that during surfing slick neoprene provided significantly greater insulation than jersey neoprene. Specifically, data obtained from the first field study demonstrated that wearing slick neoprene resulted in a 1.5 °C greater skin temperature in the chest and upper back when compared to wearing jersey neoprene. However, the mechanisms underlying these differences in skin temperature between materials could not be elucidated from the results of the first field study. Therefore, two additional studies were performed in an attempt to provide insight into the factors that contribute to differences in insulation capacity between slick and jersey neoprene during recreational surfing.

A second field study was initiated that measured skin temperatures in abdomen and lower back. These two anatomical regions were selected because they have greater interactions with water and less exposure to radiant heat from the sun than the chest and upper back during surfing. The results of the second field study demonstrated that lower back skin temperature under the slick neoprene was significantly greater by an average of 0.7 °C when compared to skin temperatures under jersey neoprene. These differences in lower back skin temperatures between materials are about half of the skin temperature values reported in the upper back location. This may be a result of the material covering the lower back having greater exposure to water than the material covering the upper back during the seated resting phase of surfing. No significant differences in abdominal skin temperature between the two wetsuit materials were detected. Combined, these results suggest that differences in skin temperature under slick and jersey neoprene can be attributed, at least partially, to exposure to radiant heat from the sun. The abdomen has no exposure to radiant heat from the sun during both prone paddling and resting and only limited exposure during seated resting as the abdomen falls below the waterline when sitting on the standard low volume shortboard used in these studies. The lower back has more exposure to radiant heat from the sun during prone paddling and rest, and the upper chest and back have the greatest exposure.

We performed a third study that had participants take part in a flume based simulated surfing protocol at night to eliminate the influence of exposure to radiant heat from the sun. The results of this study demonstrated that chest and lower back skin temperatures under the slick neoprene were significantly greater than those under the jersey neoprene. Interestingly, the difference in mean chest skin temperature between slick and jersey neoprene were significantly less in conditions of no sun exposure (0.8 ± 0.2 °C) compared to those reported in conditions of sun exposure (1.5 ± 0.3 °C). Similarly, significant differences in mean upper back skin temperatures under slick and jersey neoprene that were reported in conditions of sun exposure (1.5 ± 0.4 °C) were no longer significant in an environment where there was no exposure to the sun (0.5 ± 0.3 °C). These findings suggest that the embossed outer layer of slick neoprene is able to absorb radiant heat from the sun more efficiently than the nylon outer layer of jersey neoprene.

Differences in skin temperature between slick and jersey neoprene cannot solely be attributed to absorptive properties between materials since there were significantly greater chest and lower back skin temperatures under slick compared to jersey neoprene in the no sun exposure condition. This suggests that properties associated with the outer layer of the neoprene and how it interacts with water may also contribute to the differences in the insulation capacity of the two materials. One can speculate in conditions associated with intermittent neoprene water submersion that the embossed outer layer of the slick neoprene repels water when it is exposed to air, whereas the nylon outer layer of the jersey neoprene retains water on the surface of the wetsuit. This retention of water on the outer surface of the jersey neoprene likely leads to enhanced heat transfer from the body to the environment when compared to the slick neoprene. Further, the difference in the outer layer of slick and jersey neoprene become negligible in thermoregulation in areas of the body that are in constant contact with water during all surfing activities except wave riding. An example of this would be in the abdomen where we found no differences in skin temperature under the slick or jersey neoprene in either the field or the laboratory studies. Taken together the data from these three studies suggest that both water and radiant heat exposure from the sun contribute to increases in skin temperature under the slick neoprene compared to the jersey neoprene.

Recent data in the area of thermal perception suggests that skin temperature changes as small as 0.003 °C are capable of producing thermal sensation in humans [23]. Given this information, it is not surprising that the majority (61.5%) of the participants in our study reported that the slick neoprene side of the wetsuit was warmer than the jersey neoprene side of the wetsuit. Interestingly, in the field studies 67% of the participants reported that the slick neoprene side was warmer, with this value reducing to 45% in the laboratory study. These perceptual data align closely with the reported skin temperature differences between slick and jersey neoprene and suggest that slick neoprene provides greater thermal comfort to participants than jersey neoprene. One can speculate that the increased thermal comfort of slick neoprene may translate into a more enjoyable surf experience. However, a limitation to the current study was that the participants were not blinded to the neoprene condition and preconceived ideas of the warmth of these materials may have influenced their responses. Other limitations of the study that need to be acknowledged were an inability to control for environmental factors in the field and the use of only 2 mm neoprene.

5 Conclusion

This series of studies provides the first empirical evidence that skin temperatures under slick neoprene are significantly greater than those under jersey neoprene in anatomical locations that are exposed to radiant heat from the sun and have intermittent interaction with water during surfing. These findings can be used by wetsuit manufactures to help inform the regions on the body that slick neoprene would provide the greatest benefit to thermoregulation and thermal comfort. Specifically, the data from this study suggests that wetsuit manufactures should consider designing wetsuits that have panels of slick neoprene located in the chest and back of the wetsuit. Given the limited durability of slick neoprene, wetsuit manufactures should also seek to develop a more durable neoprene that can mimic both radiant heat absorption and water-shedding properties of slick neoprene. Future wetsuit research should test these new materials for durability, flexibility and insulation capacity.

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Data availability All data is available upon request.

Compliance with ethical standards

Conflict of interest Not applicable.

Ethical approval All procedures were approved by the Institutional Review Board at California State University, San Marcos (#1302181).

Consent to participate All prospective participants provided their informed consent prior to participation.

Consent for publication All authors have approve the submission of this manuscript.

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