Graphene-infused nylon fleece versus standard polyester fleece as a wetsuit liner: comparison of skin temperatures during a recreational surf session

Received 11 July 2022
Revised 25 August 2022
Accepted 15 September 2022

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Abstract

Purpose – The purpose of this study was to determine whether there are differences in skin temperature under graphene-infused fleece and traditional polyester fleece materials in the interior of a wetsuit.

Design/methodology/approach – A total of 48 participants surfed for a minimum of 40 min in a custom wetsuit with a torso lined with graphene-infused fleece on one half and traditional polyester fleece on the other. Eight iButton thermistors were used to record skin temperatures bilaterally at the upper back, chest, abdomen and lower back every minute for the entire surf session. After surfing, participants responded to questions associated with their perception of warmth and comfort and their knowledge of fleece materials.

Findings – Skin temperatures did not differ between the two types of fleece at the upper back, chest and abdomen locations. Skin temperatures in the lower back were significantly warmer under the traditional polyester fleece compared to graphene-infused fleece. Participant responses associated with warmth were consistent with skin temperature measurements.

Practical implications – The results of this study indicate that a graphene-infused nylon fleece interior does not clearly influence skin temperature in surfers when compared to a traditional polyester fleece interior. While skin temperatures were significantly lower under the graphene-infused nylon fleece at the low back, the other three anatomical locations did not exhibit significant differences.

Originality/value – Thermoregulation is an important consideration for the safety and performance of surfers in the ocean. Evidence suggests that the inner lining of a wetsuit may impact thermoregulation while surfing; however, no prior studies have compared interior materials.

Keywords Surf, Wetsuit, Thermoregulation, Graphene, Skin temperature, Fleece

Paper type Research paper

The authors thank Dr Wallace J. Nichols for his input and assistance with interpretation of data. The authors also thank Hurley International for their generous donation of custom wetsuits for this experiment.

Funding: This study was not supported by external funding.

1560-6074
DOI 10.1108/RJTA-07-2022-0079

1. Introduction

Surfers are often exposed to cold water for extended periods of time. Surfing in cold water can lead to a decrease in body temperature through loss of heat to the surrounding environment, which can affect an athlete's performance through reductions in muscle strength, power and endurance (Drinkwater, 2008; Nimmo, 2004). Prolonged exposure to cold water can also lead to more serious conditions, including pain, numbness, hypothermia and death (Holmer, 2009).

Wetsuits are worn to assist with thermoregulation and can help to protect surfers from the effects of prolonged cold-water exposure by reducing heat loss to the environment (Naebe *et al.*, 2013; Corona *et al.*, 2018; Warner *et al.*, 2019). Wetsuits have been used for over 70 years (Rainey, 2009), but they have been the subject of limited research and innovation. Much of the existing research has focused on dive wetsuits, which are very thick (5–7 mm) and are often designed to restrict water infiltration (i.e. "dry" suits) (Lafere *et al.*, 2021; Bardy *et al.*, 2006). Surfing wetsuits, on the other hand, are typically thinner (1–4 mm) and reduce heat loss through insulation provided by both a layer of foamed neoprene and a thin pocket of water between the neoprene and the skin (Peng *et al.*, 2019). The dearth of information available for surfing wetsuits suggests that there is great potential for innovation (Romanin *et al.*, 2021), and as participation in surfing continues to increase, there is renewed interest in studying ways to improve their design.

Studies in surfing wetsuits have primarily focused on the impact of neoprene foam and its ability to insulate individuals while surfing in cold water (Wiles *et al.*, 2022; Skillern *et al.*, 2021). For example, the insulation provided by traditional surfing wetsuits was shown to be affected by the thickness of the neoprene foam (Naebe *et al.*, 2013; Kellogg *et al.*, 2020). However, increasing the thickness of neoprene can result in less flexibility and may impact a surfer's movement and performance (Navodya *et al.*, 2020; Nessler *et al.*, 2015). Wetsuit designs that achieve high thermal resistance (e.g. insulation) with minimal impact on movement are highly desired for surfing. Because neoprene foam is limited by a thickness versus performance tradeoff, there is a need to explore additional materials and design features that might improve wetsuit performance.

Evidence suggests that the interior lining may impact the thermal resistance of a wetsuit (Lafere *et al.*, 2021). Wetsuit manufacturers have responded by incorporating several different materials in the interior of their products (Dickerson, 2019). For example, some surfing wetsuits use graphene-infused fibers in the interior fleece lining as a strategy to enhance comfort and thermoregulation (Flemister, 2021). Graphene has several interesting properties, including high mechanical strength, light weight, flexibility and durability (Bhattacharjee *et al.*, 2019; Sang *et al.*, 2019). Graphene is also well known for its high thermal conductivity, which exceeds that of any other known material and is approximately 5–8.5 times that of water (Sang *et al.*, 2019). Because effective insulation is associated with lower thermal conductivity (or high thermal resistance, conversely) in clothing (Matusiak and Sybilska, 2016; Makinen and Jussila, 2014), it stands to reason that the use of graphene-infused fleece is unlikely to improve the insulation provided by a wetsuit. However, little is known regarding the behavior of graphene-infused fleece in water, or how it might interact with other aspects of wetsuit function. Also, because wetsuits with graphene-infused fleece are currently marketed to consumers, there is a need to evaluate the impact that this material might have on thermoregulation in surfers.

The purpose of this study was to determine if there are differences in skin temperature under graphene-infused fleece versus traditional polyester fleece materials in the interior of a wetsuit. Research in clothing indicates that a material layer with low thermal conductivity is more likely to improve garment insulation and lead to higher skin temperatures (Matusiak and Sybilska, 2016; Makinen and Jussila, 2014). Because of graphene's high thermal conductive properties, it was hypothesized that graphene would have no impact on insulation and there would be no differences in skin temperatures under graphene-infused fleece and traditional polyester fleece materials.

2. Materials and methods

2.1 Participants

A total of 54 male recreational surfers from Marin County, San Francisco County, Santa Cruz County, San Luis Obispo County and North San Diego County were recruited by word-of-mouth for this study. All participants had at least one year of prior surfing experience; were between the ages of 18–50; were able to fit into a small, medium or large wetsuit; and reported no known injuries at the time of data collection. All prospective participants were informed of the procedures, completed a questionnaire about their surfing experience and activity levels and provided written informed consent prior to participation. All procedures were approved by the Institutional Review Board at California State University, San Marcos (#1302181). Participants who did not surf for at least 40 min were excluded from the final analysis.

2.2 Experimental protocol

The experimental protocol was similar to previous experiments (Smith *et al.*, 2020). All participants wore a custom-designed 2 mm Hurley full-length, back-zip wetsuit (Hurley International, Costa Mesa, USA). At the torso, the layers of the wetsuit included a nylon jersey exterior, polychloroprene closed-cell foamed neoprene in the middle and one of two different types of fleece material as the interior lining. On one side of the torso, the inner lining was composed of traditional 100% polyester fleece and the other half included graphene-infused nylon fleece fibers (graphene material was infused into synthetic nylon yarns and knitted into fleece jersey; Figure 1). The proprietary nature of the fleece and graphene-infused yarn prevents a full description of the physical characteristics of the materials, including fiber loft height and the amount of graphene that was added to the nylon fibers. While no coating or additive was applied to either the polyester or graphene-infused nylon fleece, both materials were finished with a milling process that produced a pre-specified pattern of varying loft heights in the fibers. The original loft height of all fibers

Note: Different patterns were milled into the fibers of each material during finishing (Hurley International, Costa Mesa, USA)

Figure 1. Left: graphene synthetic fleece material (red). Center: Hurley 2-mm full-suit back zip wetsuit turned inside out showcasing graphene-infused nylon fleece on the left aspect of the torso (red/gray) and traditional polyester fleece on the right aspect of the torso (gray)

was consistent (both polyester and graphene-infused nylon), but the final milled pattern was different between the two materials, and is illustrated in Figure 1.

Two wetsuits of each size (S, M, L) were used for this study: one wetsuit with the graphene-infused nylon fleece on the right half of the torso and the other wetsuit with graphene-infused nylon fleece on the left half of the torso (six wetsuits in total). Wetsuit layers were identical for both arms and legs: nylon jersey on the interior, polychloroprene closed-cell foamed neoprene in the middle and nylon jersey on the exterior. All neoprene panels were combined using a traditional double-glued and blind-stitched technique that was impermeable to water and reduced the flushing of the water layer between the wetsuit interior and the skin. This was a double-blind study and the graphene side of the wetsuit was randomized between subjects.

Eight iButton skin temperature thermistors (model: DS1922L, Maxim Integrated/Dallas Semiconductor Corp., USA) were attached to the participant's left and right upper back (2 cm superior to the medial aspect of the spine of the scapula), left and right chest (2 cm inferior to the medial aspect of the clavicle), 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). Sensor placements were identical to those used in a prior study (Smith *et al.*, 2020). Each thermistor was attached to the participant using waterproof 3M Tegaderm Film (Nexcare^{TM} Tegaderm^{TM}, USA) and skin temperature was recorded and logged once every minute throughout the surf session. Sensor accuracy is reported to be ±0.5°C (Maxim Integrated Products, 2015).

Participants were asked to surf for a minimum of 40 min but were permitted to surf longer at their leisure. Previous experiments have demonstrated that the inclusion rate of surfers begins to drop significantly after a duration of 40 min (Corona *et al.*, 2018; Warner *et al.*, 2019); therefore, this duration threshold was selected to maximize participant inclusion. For data collection purposes, the session began when the participant entered the water (ankle height) and ended when they exited the water (Kellogg *et al.*, 2020). Water and ambient air temperatures, wind strength and direction as well as predominant wave height, period and direction were recorded from the National Oceanic and Atmospheric Administration's (NOAA) buoys located offshore during each surf session. NOAA and Wunderground BestForecast^{TM} personal weather stations historical data were used when participants were surfing in an out-of-service location where the researcher was unable to access real-time meteorological data.

Following the surf session, participants were asked a series of questions about their perceptions of wetsuit comfort and their knowledge of wetsuit fleece material and graphene. After 12 participants had completed the study, researchers determined that additional qualitative questioning would enhance this portion of the findings. Therefore, all remaining participants were also asked the following questions:

Q1. Which side kept you drier?

Q2. Which side felt more comfortable?

Q3. Have you heard of graphene?

Q4. Where did you hear about graphene?

Q5. Do you think graphene is warmer than normal fleece?

The following questions were asked of each participant after they were handed a dry wetsuit to evaluate:

Q6. Which side looks warmer?

Q7. Which side feels warmer?

Q8. Which side looks more comfortable?

Q9. Which side feels more comfortable?

2.3 Data analysis

Where appropriate, perceptual data were evaluated using Chi-square goodness of fit test that compared the distribution of observed responses with an expected outcome of equal numbers of participants preferring each side of the wetsuit. Skin temperature data from individual thermistors were uploaded to One Wire Viewer (Maxim Integrated/Dallas Semiconductor Corp., USA) and copied into a Microsoft Excel spreadsheet for further analysis. R Studio (R Foundation for Statistical Computing, Vienna, Austria) was used for data reduction and statistical analysis. Data from each thermistor were reduced to eight time points (epochs) by averaging temperature across 5-min increments from minute 1 to minute 40. Data from surf sessions that were longer than 40 min were truncated to include only the first 40 min of the session for statistical analysis. Two-way repeated measures ANOVA was used to compare wetsuit material (traditional polyester fleece vs graphene-infused fleece) across time at each thermistor location. Post hoc analysis used paired t-tests to compare skin temperatures between traditional polyester fleece and graphene-infused fleece at each epoch for each significant thermistor location. Benjamini–Hochberg analysis was used to control for false discovery rate (Benjamini and Hochberg, 1995), and statistical significance was set at p-value < 0.05. Values were reported as mean $\pm$ standard error (SE).

3. Results

3.1 Population and surf session

Data from six participants were excluded from the final analysis because they did not surf for at least 40 min. The remaining 48 male recreational surfers were distributed across the five counties as follows: Marin County (n = 22), San Francisco County (n = 9), Santa Cruz County (n = 3), San Luis Obispo County (n = 2) and North San Diego County (n = 12). Of the 48 participants included in the analysis, 5 participants had incomplete data for one of their sensor locations because of sensor malfunction. In each of these cases, the incomplete data were omitted from analysis, while data from the other anatomical regions were retained. Participant characteristics (n = 48) are reported in Table 1. The average surf session duration was 54.2 $\pm$ 2.3 min. Meteorological data were separated by location and are displayed in Table 2.

3.2 Thermoregulatory characteristics

The main effect for wetsuit material was not significant at the upper back, chest or abdomen (Figures 2–4), but it was significant for the lower back (F = 23.55, p = 0.015; Figure 5). The interaction effect (wetsuit material $\times$ time) at the lower back was also significant (F = 3.12, p = 0.0008). Post hoc analysis revealed significant differences in skin temperature at all time points for the low back (Figure 5) with greater skin temperatures under traditional polyester fleece.

3.3 Thermal perception

A majority of participants stated that they did not perceive any differences between graphene-infused fleece and traditional polyester fleece halves for warmth (60.42%) or dryness (69.44%), and a plurality stated they did not perceive any difference in comfort (41.67%) while surfing in the experimental wetsuit (Table 3). After examining a dry wetsuit, a statistically significant number of participants expressed a preference for traditional polyester fleece over graphene synthetic fleece in look and feel for both its warmth and comfort potentials (Table 3).

When asked if they had heard of graphene, 22 out of 36 (61.11%) subjects replied "yes," and 14 out of 36 (38.89%) subjects replied "no." Participants who replied "yes" were asked where they had heard of graphene. The most common response was "Billabong." When these same participants were asked if they thought graphene was warmer than normal fleece, 6 out of 22 (27.27%) answered "yes," zero out of 22 (0%) answered "no," and 16 out of 22 (72.72%) responded that they did not know.

Table 1. Participant characteristics

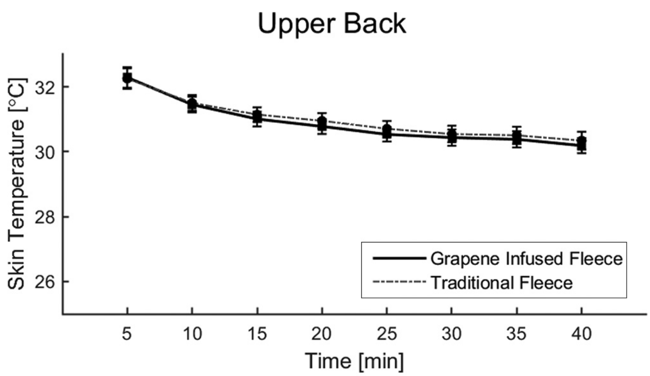
Participants	Age (years)	Height (cm)	Mass (kg)	Years surfing	Competency (1–10)
48	24.7 ± 0.8	181.4 ± 0.5	76.7 ± 2.8	10.9 ± 1.0	6.5 ± 0.2

Notes: Data reported as mean ± SE; all data were self-reported by participants

Table 2. Relevant meteorological data by location

Variable	San Diego (Winter)	Bay Area (Summer)	Central Coast (Summer)	Total
Number of participants	12	31	5	48
Water temperature (°C)	15.8 ± 0.1	15.8 ± 0.2	16.1 ± 0.3	15.8 ± 0.1°C
Air temperature (°C)	15.6 ± 1.8	14.2 ± 0.3	14.6 ± 0.1	14.6 ± 0.5°C
Wind speed (kts)	4.3 ± 0.7	10.3 ± 0.7	5.2 ± 0.4	8.3 ± 0.6
Wind direction (°)	176.2 ± 32.4	256.9 ± 6.4	238.4 ± 24.2	234.8 ± 10.6°
Predominant wave height (ft)	2.6 ± 0.3	3.8 ± 0.2	3.8 ± 0.2	3.5 ± 0.1
Predominant wave interval (sec)	15.3 ± 0.9	12.3 ± 0.7	13.5 ± 1.8	13.1 ± 0.6
Predominant wave direction (°)	253 ± 6.7	252.4 ± 5.0	237.6 ± 18.5	251.0 ± 4.2°

Note: Data reported as mean ± SE

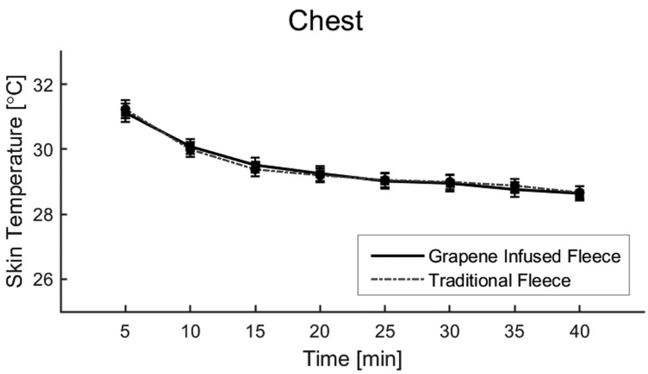


Notes: No significant differences in skin temperature were found between materials (p-value > 0.05). Bars represent SE

Figure 2. Mean skin temperature under traditional polyester fleece and graphene-infused fleece across a 40-min surf session at the upper back

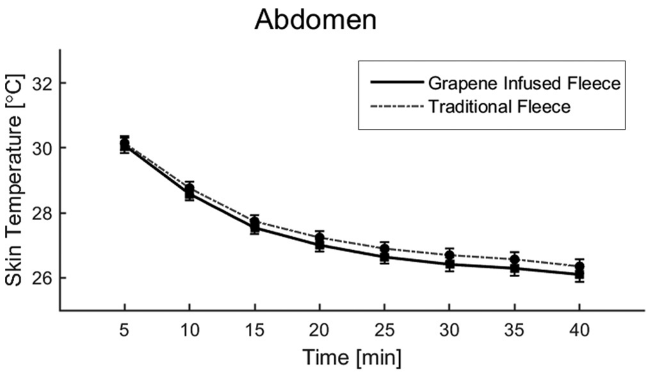
4. Discussion

This study compared skin temperature under two different materials lining the inside of a wetsuit: graphene-infused fleece and traditional polyester fleece. Results revealed that skin temperature was not significantly different under the two materials at the upper back, abdomen and chest locations (Figures 2–4). This supported the hypothesis that adding graphene to the interior layer of a wetsuit would not increase skin temperatures because of graphene's high thermal conductive properties. There was a difference in skin temperature under the two materials at the lower back; the traditional polyester fleece interior resulted in warmer skin temperatures when compared to the graphene-infused fleece interior (Figure 5). Perceptual responses were consistent with most skin temperature measures. A majority of participants stated that the graphene-infused fleece and traditional polyester fleece wetsuit halves felt equal in warmth (Table 3). Although participants were familiar with graphene as a material, they were unsure whether it would promote increased warmth. Finally,



Notes: No significant differences in skin temperature were found between materials (p-value > 0.05). Bars represent SE

Figure 3. Mean skin temperature under traditional polyester fleece and graphene-infused fleece across a 40-min surf session at the chest



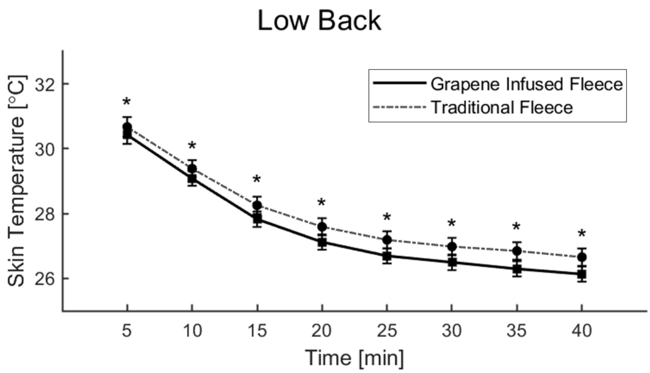
Notes: No significant differences in skin temperature were found between materials (p-value > 0.05). Bars represent SE

Figure 4. Mean skin temperature under traditional polyester fleece and graphene-infused fleece across a 40-min surf session at the abdomen

participants indicated that both graphene-infused fleece and traditional polyester fleece felt similar in terms of comfort.

4.1 Skin temperature

Graphene is known for its very high thermal conductivity, which indicates that it is not an effective insulator (Peng *et al.*, 2019; Sang *et al.*, 2019). This is the most likely explanation for the result that graphene-infused fleece did not yield warmer skin temperatures. However, an ineffective insulator could also lead to lower skin temperatures because it would theoretically facilitate a greater amount of heat loss to the environment (Makinen and Jussila, 2014; Matusiak and Sybilska, 2016). The current results indicated that there was no difference in bilateral skin temperatures at the upper back, abdomen and chest (Figures 2–4). This result can likely be attributed to the effect of the neoprene and perhaps to a lesser extent the fleece fibers that may have acted to trap air between the skin and neoprene (Makinen and Jussila, 2014; Mangat *et al.*, 2015). Any impact graphene-infused



Notes: Significant differences in skin temperature between materials were found at all time points (*denotes p-value < 0.05). Bars represent SE

Figure 5. Mean skin temperature under traditional polyester fleece and graphene-infused fleece across a 40-min surf session at the low back

Table 3. Summary of perceptual data

Question	Participants	Graphene Fleece	Standard Fleece	No difference
Which side felt warmer?	48	*n* = 10 (20.83%)	*n* = 9 (18.75%)	*n* = 29 (60.42%)
Which side felt drier?	48	*n* = 6 (16.67%)	*n* = 5 (13.89%)	*n* = 25 (69.44%)
Which side felt more comfortable	48	n = 10 (27.78%)	*n* = 11 (30.56%)	*n* = 15 (41.67%)
Which side looks warmer?	36	*n* = 15 (41.67%)	*n* = 21 (58.33%)	NA
Which side feels warmer?	36	*n* = 10 (27.78%)	*n* = 26 (72.22%)	NA
Which side looks more comfortable?	36	*n* = 12 (33.33%)	*n* = 24 (66.67%)	NA
Which side feels more comfortable?	36	*n* = 8 (22.22%)	*n* = 28 (77.78%)	NA

Note: Number of participants who gave each response following their surf session fleece may have had on reducing skin temperature appears to have been attenuated by the insulation provided by other materials in the wetsuit at these sites.

4.2 Low back

Skin temperature was significantly warmer under the traditional polyester fleece material compared to the graphene-infused fleece material at the low back. In fact, these differences were apparent as early as the first 5-min epoch of the surf session (Figure 5). Because this effect was not observed in the current data at any of the other anatomical sites, it may be related to the unique pattern of intermittent water submersion that occurs at the low back with changes in activity [i.e. paddling, sitting and duck diving (Mendez-Villanueva *et al.*, 2006; Barlow *et al.*, 2014)]. In addition, because the low back is further from the neck and wrist openings of the wetsuit, the water layer may be flushed at a slower rate when compared to the upper back and chest. Finally, this difference may also be because of the concave body geometry of the low back, which can sometimes result in "cupping" or poor conformity of the wetsuit to the contours of the body. If this were to occur, a larger pocket of air and water may have formed around the low back sensors, and this may have impacted skin temperature measures. This condition can occur in wetsuits that are oversized for a particular surfer. While each surfer wore a wetsuit that was the best fit for their height and weight, per manufacturer guidelines, some variability is known to occur in the size and shape of individuals who wear the same size wetsuit.

Skin temperatures for the low back measured here are comparable to data that have been reported in prior studies in surfers. For example, the average skin temperature profile across time observed here is similar to data reported for female surfers at the lower back location while wearing a commercially available 2-mm full wetsuit (Warner *et al.*, 2019). In addition, the current skin temperature data for the lower back was colder, but followed a similar trajectory, when compared to skin temperature at the lower back in male recreational surfers wearing a 2-mm wetsuit (Corona *et al.*, 2018). Finally, differences between left and right low back, even as early as the first epoch, were reported in a previous study comparing outer surface materials on different wetsuit halves (smooth skin vs jersey) (Smith *et al.*, 2020). Further research is needed to determine whether there are unique properties at the low back that may result in different temperatures when compared to other anatomical sites.

4.3 Perception

An individual's perception of warmth and comfort is an important aspect of how they evaluate the performance of their wetsuit. Participant responses after their surf session were consistent with skin temperature measures at the upper back, chest and abdomen: a majority of participants (60.42%) reported that the two sides felt equal in temperature (Table 3). However, most participants stated that they did not perceive a difference between the two sides at the low back. This result is interesting, because humans are remarkably sensitive to changes in skin temperature and have shown the ability to discriminate between temperatures with a difference as small as 0.003°C (Hardy and Oppel, 1937). This suggests that surfers should theoretically be very sensitive to the differences in skin temperature recorded here, which at times was greater than 0.5°C at the low back (Figure 5). However, adults have been reported to exhibit lower thermal sensitivity to cold while exercising (Ouzzahra *et al.*, 2012). It is unclear whether this effect would also occur during aquatic exercise, and additional research is needed to determine how sensitivity to temperature differences can vary across anatomical regions in surfers. Further study is also needed to help identify other factors that might contribute to discrepancies between an individual's perception of comfort and physical characteristics such as skin temperature while surfing.

The color, appearance, pattern and texture of the fleece is one factor that may affect consumer perception of a wetsuit liner. For example, while examining a dry version of the wetsuit, some participants indicated that the red color of the fibers reminded them of warmth, whereas gray fibers reminded them of winter. Some participants indicated that they would have expected graphene to be gray. A statistically significant majority of participants stated that the traditional polyester fleece (gray) looked and felt like it would be warmer and more comfortable than the graphene-infused fleece (red). Together, this information provides some insight into how consumers might be influenced by their initial perception of comfort, based on the look and feel of interior material, while examining a wetsuit in a store.

All participants were blinded as to which side contained graphene-infused fleece. It is possible that their responses may have been different had the researcher identified each side and suggested that the graphene side was expected to be warmer. Marketing studies have shown that suggestions of a product's benefits may trigger a placebo effect that influences the consumer's behavior when trying a product for the first time (Irmak *et al.*, 2005). For wetsuits, the placebo effect might contribute to an expectation by the consumer for the graphene-infused fleece to be warmer than the traditional fleece. Wetsuits with various types of lining materials have been marketed with claims of improved warmth (Dickerson, 2019), often with little data to support them. Because research studies require significant time and resources to carry out, it is possible that wetsuit companies have determined that marketing with strategic use of the placebo effect is a more cost-effective approach.

4.4 Study limitations

There was more than one difference between the two interior linings compared here. These included differences in the type of fibers (polyester vs nylon) and differences in the pattern of loft between the two materials. Both of these factors may impact insulation separately, because a higher loft or different type of fiber may help to trap more air between the wetsuit and skin. Increased air in this layer will increase insulation because air is approximately 25 times less conductive than water (Mangat *et al.*, 2015). Therefore, these confounding variables made it impossible to isolate the impact of graphene on skin temperature in this study. However, the two types of fleece studied here are representative of commonly used surf wetsuit liners, and therefore the comparison between them is an important contribution to wetsuit design, particularly because this study is the first, to the best of the authors' knowledge, to examine interior materials. In the future, it would be helpful to isolate the effects of graphene by ensuring that all aspects of the fleece liner are consistent, other than the infusion of graphene on one side. Further, additional study is needed to determine whether different fibers, patterns and loft of fleece can impact insulation and skin temperature in surfers.

This study compared graphene-infused fleece and traditional polyester fleece materials in a narrow range of water temperatures. Future research should test these and other materials in a larger range of water temperatures and environmental conditions. Finally, the graphene-infused fleece and traditional polyester fleece materials were limited to the torso in the wetsuits used here. Because the two materials were close in proximity (at the midline), the water under the two materials could have cross-contaminated or interacted. However, this experimental design (comparing materials bilaterally at the torso) was shown to uncover subtle differences in skin temperature because of differences in outer wetsuit material in a previous study (Smith *et al.*, 2020).

4.5 Recommended research

Future studies might investigate whether extending graphene-infused fleece into the extremities can result in higher skin temperatures in those regions. For example, because graphene is known to conduct heat efficiently, this may result in a more homogeneous distribution of skin temperature across the body as excess warmth from the chest and back is transferred to the lower limbs. This might occur as the upper back is heated by radiant heat from the sun, or from a heating element included in a wetsuit design. Small, lightweight battery heaters have been used effectively in clothing (Shin *et al.*, 2017), and wetsuit manufacturers have developed designs that incorporate similar heaters in either a full wetsuit (e.g. Rip Curl H-Bomb Heated Wetsuit, Rip Curl, Torquay, Australia) or as a vest (e.g. Quiksilver Cypher Heated vest, Quiksilver, Huntington Beach, CA, USA).

Graphene may also enhance the strength and durability of a wetsuit, particularly if it can be used in areas that experience greater mechanical stress, such as the knees, hips and/or elbows. It is unclear from the current data if graphene-infused fleece results in any changes to the durability of the wetsuit. However, graphene is known to have extremely high tensile strength and a very thin and lightweight structure (Shen and Oyadiji, 2020), which would allow for several possibilities for integration into a wetsuit. For example, wetsuits often suffer from durability issues at the seams where neoprene panels are stitched together, and this issue might be addressed with graphene-infused thread and/or graphene-infused tape to seal and strengthen seams. Future research should also focus on various uses for graphene to improve wetsuit durability.

5. Conclusion

The interior lining of a wetsuit may contribute to its ability to insulate and enhance the thermoregulation of surfers in cold water. The results of this study indicate that fleece with graphene-infused fibers did not result in skin temperature differences when compared with traditional polyester fleece at three of the four anatomical locations studied here. At the low back, traditional polyester fleece resulted in higher skin temperatures than those of graphene-infused nylon fibers. Further, surfers were unable to perceive any differences in skin temperature or comfort between the two materials. Additional research is needed to evaluate other ways that graphene might be used in a wetsuit.

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