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ORIGINAL ARTICLE

Foamed neoprene versus thermoplastic elastomer as a wetsuit material: a comparison of skin temperature, biomechanical, and physiological variables

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Abstract
Surf wetsuits are made of foamed chloroprene (neoprene), a synthetic rubber that is hard to recycle. Thermoplastic elastomer foam (TPE) may be a more sustainable replacement for neoprene in wetsuit design, but its impact on human thermoregulation and movement has not been evaluated. The purpose of this study was to compare skin temperature, oxygen consumption, heart rate, muscle activation, and arm kinematics while paddling in a thermoplastic elastomer vs. standard neoprene wetsuit. Thirty-three experienced surfers participated in one of two studies: a 60 min simulated surf session in a freshwater swim flume designed to evaluate skin temperature ($n=18$), or a dry-land ergometer session designed to evaluate physiological and biomechanical aspects of surfboard paddling ($n=15$). Skin temperatures under neoprene were significantly warmer than under thermoplastic elastomer at several anatomical locations including the upper chest ($p<0.01$, $\eta^2_{partial}=0.291$), lower abdomen ($p<0.001$, $\eta^2_{partial}=0.527$), lower back ($p<0.005$, $\eta^2_{partial}=0.416$), lower arm ($p<0.001$, $\eta^2_{partial}=0.537$), upper leg ($p<0.001$, $\eta^2_{partial}=0.717$), and lower leg ($p<0.001$, $\eta^2_{partial}=0.802$). However, most participants did not perceive any temperature differences (50%) or felt that the thermoplastic elastomer was warmer (19%). There were no significant differences for any of the other physiological and biomechanical variables analyzed here ($p>0.05$). These results suggest that thermoplastic elastomer foam is the less efficient insulator when compared to neoprene, but this difference may be imperceptible to the average surfer. Further, the thermoplastic elastomer wetsuit does not appear to add resistance to or alter upper extremity motion while paddling a dry land ergometer.

Keywords Surf · Wetsuit · Neoprene · Paddle · Thermoregulation

1 Introduction

Surfing is an action sport that is rapidly increasing in popularity [1–3]. Although surfing is typically associated with warm and tropical climates, it often occurs in colder environments where exposure to elements can impact the performance and safety of athletes [4–10]. Therefore, it is important that surfers are well equipped with a wetsuit that can assist in thermoregulation and facilitate performance at a high level. Wetsuits support thermoregulation by creating two layers of insulation: a layer of neoprene, and a layer of trapped water between the skin and the suit, which is then heated by the body [11]. Neoprene, also known as polychloroprene, has been the primary material in wetsuit design since its first use in 1952 [12]. It is a petroleum-based, synthetic, vulcanized rubber with high tensile strength and stretch, resistance to water, deterioration, and temperature change [13]. Closed cell neoprene, or polychloroprene foam, used in wetsuit construction contains bubbles of air, nitrogen, or hydrogen gas that can help to insulate users during activity [11, 14].

Unfortunately, neoprene foam is not a sustainable material for wetsuit design. Techniques such as rubber pyrolysis are commonly used for recycling synthetic rubbers, but recycling polymers, such as polychloroprene, can be challenging

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because they contain chlorine [15, 16]. For example, synthetic rubbers accounted for 47,000 tons of waste in Japan in 2004, but only 44% were recycled [17]. Further, chloroprene is used to make neoprene and is currently classified in Group 2B by the International Agency for Research on Cancer (IARC) because it may be carcinogenic to humans based on experimental trials in animals [18–20]. While neoprene foam is relatively safe, manufacturing it can lead to the release of chloroprene into the environment, which has been detected in industrial wastewaters of China, Russia, and Japan [21–24]. Cases of chloroprene rubber exposure in Armenia, China, and Russia, have been linked to an increased risk of developing cancer [19, 25, 26].

These factors have led wetsuit manufacturers to explore alternative materials for wetsuit design. Thermoplastic elastomer foams (TPE) are a promising alternative because they combine the thermal properties of thermoplastics with the flexibility of rubber [27, 28], and some types of TPE exhibit material properties that are similar to those of neoprene [29, 30]. In addition, TPE waste can be recycled [28] and unlike neoprene, TPE can be re-used through melt extrusion and injection molding [27]. Finally, thermoplastic polyurethanes (or TPU, a subset of TPE) have been shown to be non-carcinogenic, non-toxic, exceptionally tough, hydrolytically stable, and chemically inert [29, 31–34].

For TPE to be considered a valid replacement for neoprene, the new wetsuit must demonstrate mechanical and insulation properties that meet or exceed those of current neoprene wetsuits. Currently, there are no studies that measure these factors in surfers while wearing wetsuits made from alternative materials. Therefore, the purpose of this study was to determine if experienced surfers exhibit differences in skin temperature and paddling performance while wearing a traditional neoprene wetsuit and a comparable wetsuit made of an alternative material (TPE). Research indicates that surfers spend 50% of an hour-long session paddling; therefore, a wetsuit's impact on paddling performance is an important consideration [4, 6, 35]. Since wetsuits of similar thickness were compared here, it was hypothesized that there would be no significant differences in skin temperature, heart rate response, oxygen use, upper extremity range of motion, or muscle activation while wearing wetsuits with TPE vs neoprene insulation.

2 Methods

2.1 Study design

Two experiments were completed to compare the performance of TPE and neoprene wetsuits. The first experiment compared skin temperatures while wearing a hybrid wetsuit with neoprene and TPE on opposite sides, and this protocol was carried out during a simulated surf session in a custom designed freshwater pool. The second experiment compared arm motion and muscle activation during simulated paddling on a dry-land ergometer while wearing separate neoprene and TPE wetsuits. Each experiment involved a different set of participants, and data were analyzed separately. While the wetsuits differed between experiments, the same neoprene and TPE foams were used in each case.

2.2 Participants

Thirty-five male recreational surfers aged 18–50 were recruited for these experiments (Table 1). Participants were required to have at least 5 years of shortboard surfing experience and fit into a medium or large custom 2 mm wetsuit (experiment #1, $n = 18$) or medium-sized wetsuit only (experiment #2, $n = 17$). Wetsuit fit was estimated from personal wetsuit sizes reported by prospective participants, and individuals who required a small or extra-large wetsuit were excluded from participation. Participants were a convenience sample recruited via word of mouth at California State University San Marcos and throughout San Diego County beaches. Potential participants were excluded if they were female due to differences in skin temperature profiles between sexes [9, 36], or if they were below 18 or greater than 50 years of age [37]. Participants provided written informed consent and completed an AHA/ACSM Health/Fitness Facility Preparticipation Screening Questionnaire prior to beginning the protocol. A Surfing and Physical Activity Questionnaire was also completed to gauge self-reported surfing preference, competency, and frequency (unverified by the investigators). All experimental procedures and questionnaires were reviewed and approved by the California State University-San Marcos Institutional Review Board (IRB#1478043), which provides oversight on ethics in human subjects research.

Table 1 Participant characteristics

Experiment	Participants	Height (m)	Mass (kg)	Age	Years surfing	Competency (1–10)
Thermoregulation	18	1.68 ± 0.37	71.97 ± 5.59	24.47 ± 6.94	12.39 ± 8.83	7.17 ± 1.21
Biomechanics	17	1.8 ± 0.1	70.2 ± 6.1	25.0 ± 7.4	12.6 ± 9.6	6.7 ± 1.2

Participant characteristics (mean ± SD); age, years surfing, and surfing competency were self-reported

2.3 Wetsuits

All wetsuits were constructed of either neoprene foam or TPE foam, surrounded by two layers of jersey material (Fig. 1). The same TPE was used for both experiments and was a proprietary material designed to exhibit mechanical and thermoregulatory properties similar to neoprene. The same jersey material (82% nylon and 18% spandex) was laminated to both sides of the neoprene or TPE foam layer, which ensured that participants could not visually distinguish between the two designs. The neoprene and TPE foam layers were the same thickness at each region of the body. The dimensions and details for wetsuits are provided in Table 2.

For the first experiment, four 2 mm-thick custom full-length wetsuits were available for participants to wear during the protocol (2 medium and 2 large size) fabricated by Hurley (Hurly International, Costa Mesa, USA). Each wetsuit was designed with half neoprene and half TPE, split on either side of the seam running vertically along the midline of the body (Fig. 2). The wetsuits were constructed such that the neoprene and TPE were on different sides for each medium and large wetsuit (to assist with randomization). Once the appropriate size was determined, participants were randomly assigned a single wetsuit to wear for the entire protocol.

For the second experiment, two custom made wetsuits were patterned after a medium-sized Hurley Advantage Elite 3/2+ mm model with a thickness of 2 mm in the arms, 3 mm in the chest and back, and 3.5 mm in the legs (Fig. 2). The neoprene wetsuit had a dry mass of 1.36 kg and the TPE wetsuit had a dry mass of 1.02 kg.

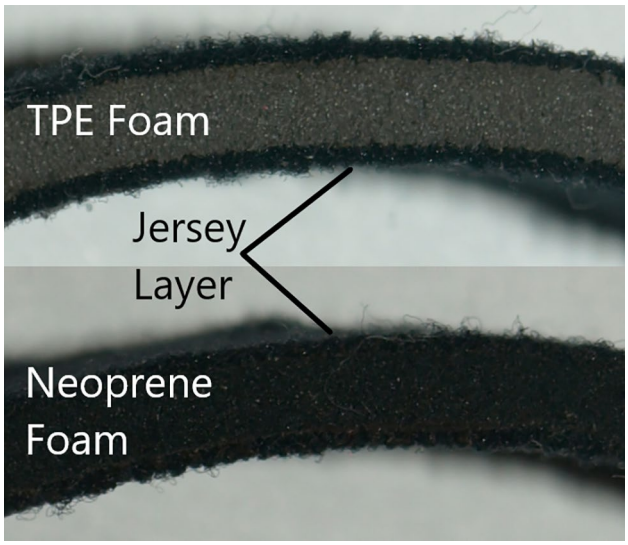


Fig. 1 Cross-sectional view of wetsuit construction. For all wetsuits a layer of jersey material (82% nylon and 18% spandex) was laminated to both sides of the neoprene or TPE foam

2.4 Experiment 1—skin temperature

2.4.1 Thermistors

Following written consent, participants were equipped with sixteen 1-Wire iButton Thermocron model DS1922L thermistors (Thermochron, Baulkham Hills, NSW, AUS), placed in eight locations on both their left and right side for bilateral comparison of the neoprene and TPE material. The thermistors were placed directly on the skin above the upper fibers of the pectoralis major, the rhomboid, the lateral triceps brachii, the inferior rectus abdominis, the inferior portion of latissimus dorsi, the flexor carpi radialis, the lateral vastus lateralis, and the medial gastrocnemius (Fig. 2) [9, 10]. Thermistors used at each location were randomized for each protocol to control for any unexpected variance in sensor behavior. The thermistors were secured to the skin with 6 × 7 cm, 3 M Nexcare Tegaderm Film. Surface skin temperatures were recorded on the thermistors at 60 s intervals. At the completion of the study, data were extracted from the thermistors in OneWire Viewer (Maxim Integrated/Dallas Semiconductor Corp., USA) and then saved as an Excel Spreadsheet for further analysis. Thermistor accuracy was reported by the manufacturer to be ± 0.5 °C [38]. The accuracy of each thermistor was each data collection session by placing them on a hotplate (Four E's Scientific Co., Guangzhou, China) set at 32 °C for a 5-min protocol

Table 2 Wetsuit characteristics

Experiment	Wetsuit design	Thickness [mm]	Dry mass neoprene [kg]	Dry mass TPE [kg]	Sizes	Jersey material
Thermoregulation	One side TPE and one side Neoprene, split along midline of the body	2—entire wetsuit	NA	NA	2 medium 2 large	82% nylon 18% spandex
Biomechanics	Separate neoprene and TPE wetsuits	2—arms 3—legs 3.5—abdomen	1.36	1.02	2 medium	82% nylon 18% spandex

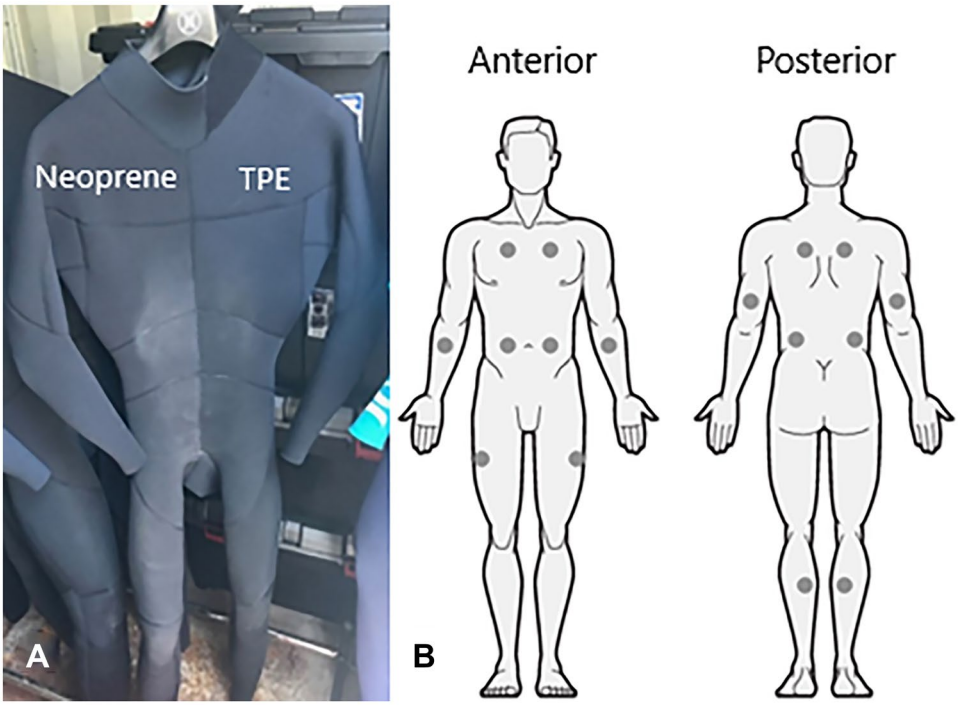


Fig. 2 **A** Custom wetsuit designed with one side neoprene and the other side TPE, divided along the midline of the body. **B** Anatomical locations of the 16 thermistors from the anterior and posterior views

collecting data at 60 s intervals. Thermistors exceeding 1 °C error were discarded and replaced.

2.4.2 Experimental protocol

Participants completed a simulated surfing protocol in the Endless Pool Elite Flume (Commercial Elite Endless Pools®; Aston, PA) for a total of 60 min at a set water temperature of 15–16 °C to imitate local water temperatures. Water temperature, ambient air temperature, and relative humidity were recorded for each protocol. A standardized 5′10 × 19 ¾ × 2 ¼ [177.8 × 50.2 × 5.7 cm] surfboard was used for each participant. The Global Water Flow Meter (Global Water Instrumentation; College Station, TX, USA) was installed before each protocol to measure the speed of the water flow in the flume. Participants were asked to paddle against three speeds throughout the protocol: 1.2, 1.4, and 1.6 m/s. The speed was increased every 20 min. Participants began the protocol by entering the flume and laying prone on the board without paddling for the first 60 s. Simultaneously, the current was turned on and the participant was instructed to perform a shallow duck-dive before paddling for the next 60 s. Following the paddling interval, the participant sat on the board for another 60 s. The participant repeated this sequence of sitting—duck-diving—paddling—laying—duck-diving—paddling for the remaining 60 min. Following the simulated surf session, participants were asked if they were able to detect a difference in flexibility or warmth between the two sides of the wetsuit (perceptual data). As this was a double-blind study, neither the participant nor the researcher had knowledge of which wetsuit side included TPE or neoprene [the sides were also randomized between wetsuits].

2.4.3 Data analysis

Data obtained from the thermistors were downloaded in OneWire Viewer immediately following the simulated surf session. After simple processing and visualization of the data in Excel they were further analyzed in MATLAB (R2020a, Natick, MA). This process involved compiling skin temperature data for each sensor location into 12 intervals (epochs) by averaging temperature every 5 min across the 60-min protocol, similar to analyses described previously [10, 39]. A two-way repeated measures ANOVA was used to compare wetsuit material (TPE and neoprene) across time (12 epochs) at each anatomical location (eight locations). Significant results between material at each sensor location were followed up using paired t test to determine the time points (epochs) at which the two different materials differed significantly. The Benjamini–Hochberg analysis was used to control for false discovery rate [40].

2.5 Experiment two—paddling biomechanics

2.5.1 Equipment

Participants were instrumented with a Polar T31 heart rate monitor (Polar Electro Inc, Bethpage, NY, USA) placed just below the sternum recording at 1 Hz. A Polar RCX5 wristwatch used to receive the data was placed on the nose of

the surfboard ergometer during paddling bouts. Participants were also instrumented with seven wireless surface electromyography (EMG) electrodes (Trigno, Delsys Inc., Natick, MA, USA) recording at 1200 Hz on the right side of the body [41]. The EMG electrodes were placed over the following muscles: middle deltoid, posterior deltoid, latissimus dorsi, upper trapezius, middle trapezius, serratus anterior and erector spinae following the guidelines described previously (Fig. 3) [42, 43]. All electrodes were held in place with a standard dual-sided adhesive and Tegaderm® (3 M) bandages.

An 8-camera 3D motion capture system (Oqus 5, Qualisys AB, Gotenborg, Sweden) was used to track 21 reflective markers at 120 Hz. Markers were placed on the skin or wetsuit in the following locations: right and left iliac crest, right and left posterior superior iliac spine, mid-thoracic region (T10 vertebrae), C7 vertebrae, right back (medial to the scapular spine), right and left acromion, both medial and lateral epicondyles, styloid process of both radius and ulna, lateral aspect of both humerus midway between the shoulder and elbow, and the lateral aspect of both forearms midway between the elbow and wrist (Fig. 3). Finally, participants were connected to a metabolic cart (TrueOne 2400, Parvo Medics, Sandy, UT, USA) by a 5 m hose and oro-nasal mask (7450 Series Silicone V2, Hans Rudolph Inc., Shawnee, KS, USA) with a two-way non-breathing valve (Hans Rudolph Inc). Absolute and relative oxygen consumption were recorded at 15-s intervals during each trial.

A modified swim bench ergometer (VASA Inc., Essex Junction, VT, USA) was used to simulate in-water paddling during testing. The ergometer was modified to include a surfboard held at an angle of 10° relative to the ground to simulate the average surfboard pitch angle observed while paddling in-water [44, 45]. The fore/aft position of the surfer on the board was measured from the crown of the head to the tip of the surfboard nose while laying prone with their head down. Participants were required to paddle in the same position for each trial. Additionally, a footrest behind the tail of the surfboard was used to help simulate the buoyancy of the legs in-water and help alleviate fatigue or discomfort while paddling.

2.5.2 Experimental protocol

Participants performed three trials in which they paddled continuously for seven minutes while maintaining a power output of 20 W and a cadence of 40 strokes per minute (SPM), and they were given 30 min of rest between each trial (consistent with procedures in [43]). Adherence to the 40 SPM pace was facilitated through an audible metronome app (EUMLab). Participants also viewed their real-time power output through a tablet screen (Samsung) with a live feed from a digital camera (Hero 7 Silver, GoPro Inc., San Mateo, CA, USA) facing the live power output of the ergometer. Left and right arm power, SPM, velocity, and total distance were recorded using a SimulANT + Power Meter (Dynastream Simulations Inc, Alberta, Canada). Motion capture and EMG data were recorded for minutes 2–4 and 5–7 for all trials. The order of wetsuit condition was randomized for each participant between their boardshorts only (no wetsuit), the TPE wetsuit, and neoprene wetsuit. Both the participants and the investigators were blinded to the specific wetsuit worn in each trial. Between each trial, EMG electrodes remained in place, but all motion capture markers were removed and replaced by the same researcher in their appropriate location.

2.5.3 Data analysis

Motion capture data were processed using the Qualisys Track Manager (version 2019.3) software. Custom routines in Matlab (R2020a) were used to filter the data (4th order

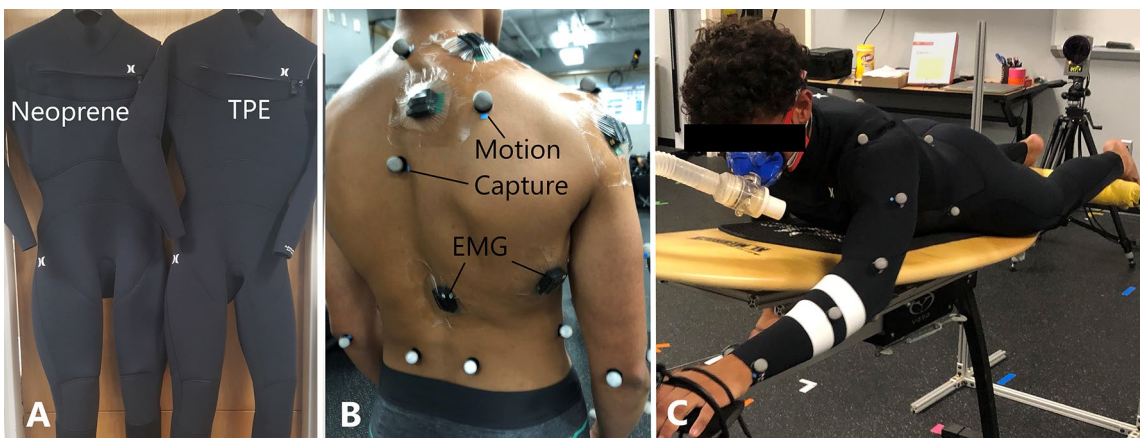


Fig. 3 All 7 EMG locations are represented by an "X" while the 21 reflective motion capture markers are represented by circles

Butterworth, cutoff frequency 10 Hz), and calculation of the following joint angles occurred in Visual 3D (v6 Professional 2016, C-Motion Inc., Germantown, MD, USA): shoulder flexion/extension, shoulder abduction/adduction, and elbow flexion/extension. The sagittal plane trajectory of the ulnar styloid process of the right wrist was used to determine stroke duration, length, width, height, peak height, and minimum height. Each complete stroke began when the wrist reached the furthest anterior (cranial) point in the sagittal plane trajectory and ended when the wrist returned to the same point. The stroke was further divided into the propulsive phase, defined as the beginning of the stroke until the wrist reached the furthest posterior (caudal) point, and the return phase, defined from the end of the propulsive phase until the stroke was completed. Motion capture data were then averaged across all complete strokes, and then compared between trials.

EMG data were full wave rectified and filtered using a 4th order Butterworth filter with a cutoff frequency (20 Hz) consistent with previous studies of a similar nature [43]. EMG activity was then averaged across all complete strokes for each trial, and the mean area under the curve was calculated. In some cases, the wireless EMG signal was either lost or corrupted via excessive motion artifact. Each of these cases was identified based on upon visual inspection of data and omitted from statistical analysis. Extensive motion artifact was found often in the serratus anterior EMG data due to the chest and arm sliding against the rail of the surfboard. For this reason, all serratus anterior EMG data were excluded from the final analysis.

2.5.4 Statistical analysis

Separate 1 (Variable) × 3 (Trial) Repeated Measures ANOVA were performed using the data for each variable. Oxygen consumption was averaged for minutes 3–7 for all trials based upon previous studies that demonstrated that steady-state oxygen consumption began near the 2-min mark [46, 47]. All EMG and motion capture data from minutes 2–4 were used for final data analysis. A significance value of $\alpha = 0.05$ was used for all statistical comparisons and partial eta squared (η^2_{partial}) was used to estimate effect size where appropriate.

Tukey's Boxplot Method was used to determine outliers for participant age, weight, years surfed, and competency [48]. While some outliers were identified, they did not affect the results of the statistical analysis and were therefore included in the final analysis. Two participants ($n = 2$) had incomplete biomechanical data sets due to lost markers and EMG motion artifact. These participants were excluded, resulting in a total of 15 participants for the final analysis. Further, some of the remaining participants were excluded from the analysis of specific variables if they were missing data for any of the three trials due to loss of EMG signal or lost markers during data collection.

3 Results

3.1 Experiment 1: skin temperature

3.1.1 Environmental conditions and surface skin temperatures

The ambient air and water temperatures were 23 ± 5.08 °C and 16.01 ± 0.20 °C, respectively. The relative humidity was 51.72 ± 18.34%.

There was a significant main effect for time for skin temperature in the upper chest, the upper back, the upper arm, the lower abdomen, the lower back, the lower arm, the upper leg, and the lower leg (Table 2). There was also a significant main effect for wetsuit material for skin temperature in the upper chest, the lower abdomen, the lower back, the lower arm, the upper leg, and the lower leg (Table 3).

Finally, there was a significant interaction effect for the upper chest, the upper arm, lower arm, lower abdomen, the upper leg, lower leg (Table 2). Benjamini–Hochberg analysis of paired *t* test comparisons at each time point indicated skin temperatures were significantly warmer under the neoprene

Table 3 Statistical results for surface skin temperature under neoprene vs TPE

Sensor location	Main effect: time		Main effect: material		Interaction	
	p	η^2_{partial}	p	η^2_{partial}	p	η^2_{partial}
Upper chest	< 0.001	0.595	< 0.01	0.291	< 0.01	0.192
Upper back	< 0.005	0.284	0.472	0.033	0.644	0.034
Upper arm	< 0.001	0.460	0.309	0.065	< 0.005	0.312
Lower arm	< 0.001	0.640	< 0.001	0.537	< 0.005	0.362
Lower back	< 0.001	0.711	< 0.005	0.416	0.264	0.078
Lower abdomen	< 0.001	0.872	< 0.001	0.527	< 0.01	0.257
Upper leg	< 0.001	0.889	< 0.001	0.717	< 0.01	0.355
Lower leg	< 0.001	0.942	< 0.001	0.802	< 0.005	0.408

material at the upper chest for all time points beyond minute 25. Skin temperature under neoprene was significantly warmer at the lower abdomen and lower arm for all time points beyond minute 5, and at the lower back and upper leg for time points beyond minute 10. Skin temperatures were significantly warmer under the neoprene at the lower leg for all time points (Fig. 4).

3.1.2 Perceptual data

Three participants (19%) reported they perceived the TPE side of the wetsuit provided more effective insulation while five participants (31%) perceived the neoprene side provided more effective insulation. Eight participants (50%) perceived no thermal differences bilaterally. Perceptual data on flexibility were also obtained. Four participants (25%) reported they perceived the TPE side of the wetsuit was more flexible than the neoprene side. Five participants (31%) reported they perceived the neoprene side of the wetsuit was more flexible than the TPE side. Seven participants (44%) perceived no differences in flexibility between the TPE and the neoprene. All perceptual data are reported in Table 4.

Number of participants who gave each response when asked which wetsuit felt more flexible and which felt warmer.

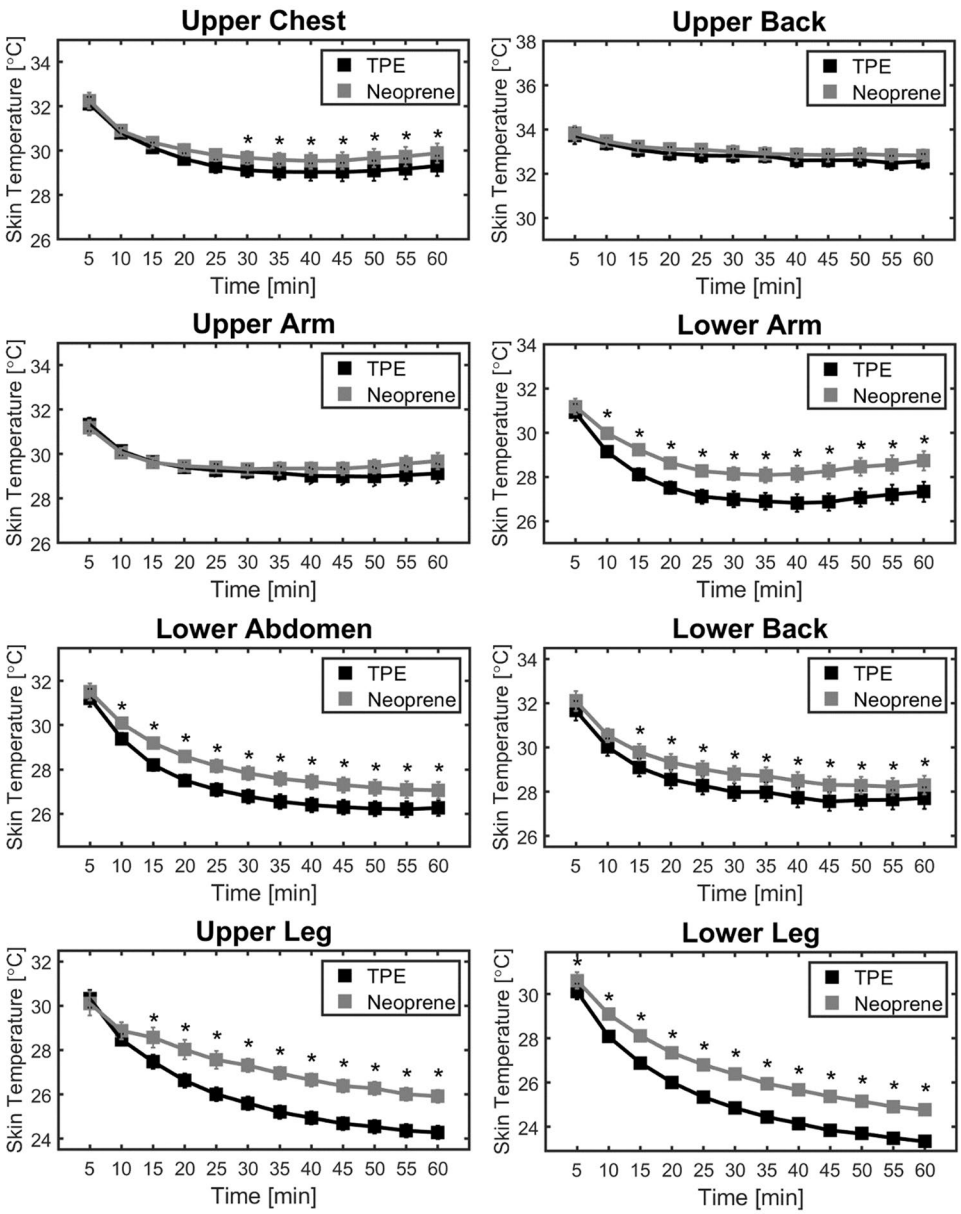


Fig. 4 Comparisons of skin temperature under the neoprene and the TPE wetsuit materials over time (12 epochs) at the 8 indicated locations. All graphs were scaled between 22 and 38 °C. Bars represent the standard error. Asterisks show areas of statistical significance ($p < 0.05$)

Table 4 Perceptual data

	Flexibility perception ($n=16$)	Thermal perception ($n=16$)
TPE	4	3
Neoprene	5	5
Equal	7	8

3.2 Experiment 2: paddling biomechanics

3.2.1 Trial characteristics

There were no significant differences between the three trials based on paddling cadence ($p=0.859$) or right arm power ($p=0.786$, Table 4) (Table 5).

3.2.2 Physiology

The mean heart rate (BPM) for participants was 103.6 ± 12.8 BPM ($n=8$), 112.3 ± 12.5 BPM ($n=8$), and 107.9 ± 10.7 BPM ($n=8$) for control, TPE, and neoprene, respectively (Fig. 5). The relative steady-state oxygen consumption for all participants was 12.6 ± 1.6 mL/kg/min for control, 12.9 ± 1.7 mL/kg/min for neoprene, and 13.1 ± 1.6 mL/kg/min for TPE (Fig. 5). There were no significant differences between trials for mean heart rate ($p=0.376$) or relative steady-state oxygen consumption ($p=0.794$).

3.2.3 Electromyography

There were no significant differences between any trials for the middle deltoid ($p=0.964$), posterior deltoid ($p=0.554$), latissimus dorsi ($p=0.960$), upper trapezius ($p=0.732$), middle trapezius ($p=0.963$), nor erector spinae ($p=0.667$, Fig. 6, Table 6).

3.2.4 Kinematics

There were no significant differences between any trials for stroke height ($p=0.625$), stroke length ($p=0.592$), stroke width ($p=0.725$), peak height ($p=0.680$), or minimum height ($p=0.954$, Table 7). Mean sagittal plane wrist trajectories are depicted in Fig. 7.

There were no significant differences between any trials for shoulder flexion range of motion ($p=0.690$), shoulder peak flexion ($p=0.921$), shoulder peak extension ($p=0.772$), shoulder abduction range of motion ($p=0.673$), shoulder peak abduction ($p=0.933$), shoulder peak

Table 5 Mean paddling cadence and power output ($n=11$ for each condition)

Condition	Control	Neoprene	TPE	Combined
Paddling cadence (strokes per minute)	20.51 ± 1.53	20.49 ± 1.26	20.26 ± 1.39	20.42 ± 1.36
Right arm power (W)	9.65 ± 1.34	9.69 ± 1.46	9.89 ± 1.09	9.75 ± 1.27

Data are expressed as mean ± SD

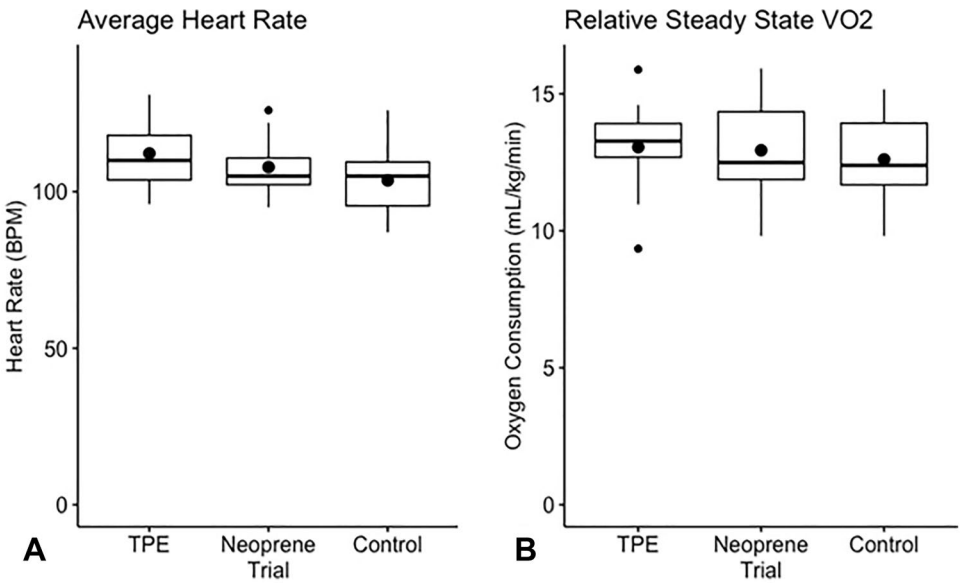


Fig. 5 Relative steady state oxygen consumption ($n=15$) and average heart rate ($n=8$) per trial. In the Interquartile Range (IQR) box, the horizontal line represents the median and the large dot represents the mean. The whiskers of this figure represent the minimum (Q1 − 1.5*IQR) and maximum (Q3 + 1.5*IQR). Any dots outside the whiskers represent outliers

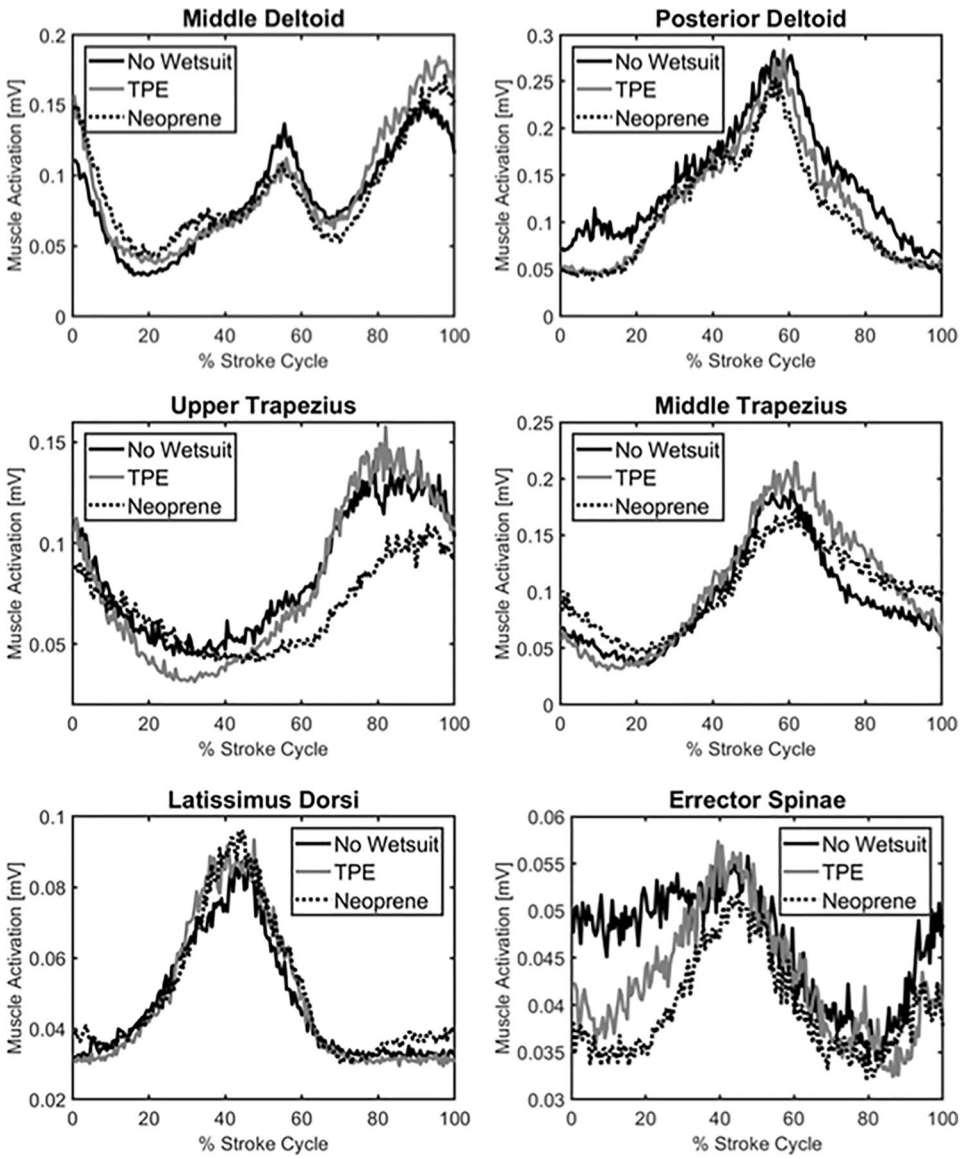


Fig. 6 Muscle activation per location measured in millivolts, averaged across strokes. 0% represents the hand in the most forward position and 100% is the return of the hand to the most forward position, completing the stroke. Averaged across all participants

Table 6 EMG data for 6 shoulder muscles

	Control	Neoprene	TPE	Combined
Middle deltoid (mV ms) ($n=12$)	17.23 ± 12.82	18.07 ± 12.13	18.55 ± 11.09	17.95 ± 11.7
Posterior deltoid (mV ms) ($n=9$)	25.36 ± 12.51	20.17 ± 8.92	23.62 ± 8.65	23.05 ± 10.03
Latissimus dorsi (mV ms) ($n=11$)	6.92 ± 3.78	7.35 ± 3.86	7.25 ± 3.3	7.17 ± 3.54
Upper trapezius (mV ms) ($n=11$)	14.85 ± 10.93	12.15 ± 7.96	14.93 ± 8.97	13.99 ± 9.16
Middle trapezius (mV ms) ($n=11$)	20.52 ± 12.02	21.82 ± 14.44	21.98 ± 14.49	21.44 ± 13.28
Erector spinae (mV ms) ($n=11$)	10.49 ± 5.41	9.01 ± 4.59	8.86 ± 3.86	9.46 ± 4.58

Data are expressed as mean ± SD

adduction ($p=0.271$), elbow range of motion ($p=0.980$), elbow peak flexion ($p=0.858$), elbow peak extension ($p=0.802$, Table 8).

4 Discussion

The purpose of this study was to determine if experienced surfers exhibit differences in skin temperature

Table 7 Kinematic data ($n = 15$ for each condition)

	Control	Neoprene	TPE	Combined
Stroke height (mm)	403.035 ± 110.926	384.894 ± 102.894	421.672 ± 95.654	403.200 ± 102.106
Stroke length (mm)	913.526 ± 115.356	845.833 ± 235.866	863.371 ± 189.165	874.243 ± 184.831
Stroke width (mm)	168.274 ± 80.243	150.212 ± 58.640	168.994 ± 76.422	162.494 ± 71.263
Peak height (mm)	986.112 ± 89.741	980.302 ± 115.109	1009.495 ± 79.523	991.970 ± 94.622
Minimum height (mm)	583.077 ± 74.151	595.409 ± 133.402	587.824 ± 118.350	588.770 ± 109.064

Data are expressed as mean ± SD

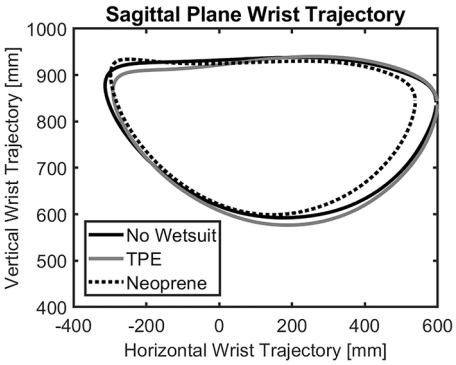


Fig. 7 Trajectory of the ulnar styloid process of the right wrist averaged across all participants, sagittal view. To aide visualization, the right edge of the figure (600 mm) represents the hand in the most forward position (cranial), or the beginning of the stroke. The left side of the figure demonstrates the halfway point of a stroke (caudal), where the hand would exit the water and begin to return back towards the nose of the surfboard

and paddling performance while wearing a traditional neoprene wetsuit and a comparable wetsuit made of an alternative material (TPE). The data indicate that skin temperatures were significantly warmer under neoprene at multiple anatomical locations. However, there were no significant differences in oxygen consumption, HR, upper extremity kinematics, and muscle activation observed during simulated paddling in a neoprene wetsuit, TPE wetsuit, or boardshorts (no wetsuit). These data did not support the hypothesis that there would be no differences in skin temperature, but do support the hypothesis that upper extremity range of motion, muscle activation, heart rate, and oxygen use would not be different between wetsuits.

A surfer's upper chest, lower abdomen, lower back, lower arm, upper leg, and lower leg are exposed to cold water longer than the upper back and the upper arm during a typical surf session [9, 10]. In the current data, there were no significant differences in skin temperatures in the upper back or the upper arm, indicating TPE and neoprene have a similar thermal impact in situations of reduced cold-water exposure. However, the current findings suggest that TPE is a less effective insulator than neoprene as cold-water exposure increases over time. Therefore, neoprene is likely a better insulator than TPE in conditions where prolonged submersion in cold water occurs frequently. The mechanisms underlying reduced insulation of TPE in anatomical sites exposed to cold water are unclear. Potential insulation differences between materials may be attributed to variations in production that result in differences in closed cell size and structure. Future studies should examine if altering closed cell size and structure of TPE can impact thermal insulation. If alterations in closed cell size and structure fail to improve insulation, then TPE wetsuit thickness would need to increase to mimic the insulation characteristics of thinner neoprene.

Table 8 Shoulder and elbow angles ($n = 12$ for each condition)

	Control	Neoprene	TPE	Combined
Shoulder flexion ROM (°)	137.784 ± 15.532	132.964 ± 13.458	135.240 ± 11.671	135.329 ± 13.399
Shoulder peak flexion (°)	131.525 ± 6.213	130.499 ± 5.877	131.101 ± 6.538	131.042 ± 6.050
Shoulder peak extension (°)	− 6.210 ± 14.862	− 2.456 ± 10.666	− 4.033 ± 12.431	− 4.233 ± 12.497
Shoulder abduction ROM (°)	33.446 ± 7.735	30.784 ± 8.432	31.258 ± 7.082	31.829 ± 7.635
Shoulder peak abduction (°)	60.377 ± 7.008	61.278 ± 7.948	61.380 ± 6.716	61.011 ± 7.048
Shoulder peak adduction (°)	26.992 ± 5.557	30.454 ± 5.823	30.111 ± 5.613	29.185 ± 5.724
Elbow ROM (°)	59.344 ± 9.991	60.196 ± 12.770	59.471 ± 10.527	59.671 ± 10.844
Elbow peak flexion (°)	75.652 ± 8.535	73.536 ± 9.046	74.749 ± 10.441	74.646 ± 9.146
Elbow peak extension (°)	16.291 ± 9.351	13.353 ± 11.941	15.293 ± 11.490	14.979 ± 10.739

Data are expressed as mean ± SD

ROM range of motion

Although there were significant differences in skin temperature between materials the data did not correspond with participants' perception of warmth. Specifically, eleven of the sixteen subjects (68.75%) reported that neoprene was not warmer than TPE. These findings are unexpected because lower extremity skin temperature differences were as high as 1.8 °C in the current data and previous research has reported that differences in skin temperatures of 1.5 °C in the upper back are perceivable between wetsuit materials [39]. These discrepancies may be related to the fact that the perceptual differences described previously [39] were isolated to anatomical locations with limited exposure to cold water, whereas the anatomical locations with the greatest differences in skin temperatures in the current study were in regions with constant exposure to cold water. Therefore, one can speculate that water exposure may hinder the ability to perceive differences in skin temperature.

The results for upper extremity kinematics support the hypothesis that there would be no statistically significant differences between any of the three trials compared here. These results are similar to those reported in [43], who reported no significant differences in stroke length and width, or shoulder range of motion during simulated surfboard paddling while wearing a wetsuit jacket vs. boardshorts only [43]. In addition, a previous study in swimmers reported no difference in stroke length while wearing a full wetsuit [49]. Combined, the results of these three studies suggest that wearing a wetsuit made of TPE or neoprene does not significantly impact mean stroke length or width.

While there were no statistically significant differences between paddling conditions in the current data, the variability in stroke length between conditions was relatively high when compared to results reported previously [43]. For example, the mean stroke length for the control condition was 913.5 ± 115.4 mm, and the average stroke length for the neoprene condition was 845.8 ± 235.9 mm (mean difference of 78 mm). In a previous study, the mean stroke lengths were 971.6 ± 76.9 mm and 970.0 ± 64.2 mm (for control and neoprene, respectively) [43]. Comparing the standard deviations between studies suggests that the current results may have been influenced by excessive variability among participants (coefficient of variance = 28 vs 7%). Artificial movement variability is a concern when simulating surfboard paddling on an ergometer, because there is no spatial reference for motion such as the surface of the water. However, since the same ergometer was used for all conditions (and the previous study), it is likely that the additional variability observed in the current data is due to other factors, such as differences in skill level or physical conditioning of the participants. It is also possible that these data were impacted by the type of wetsuit garment worn; in the current study the participants wore a full wetsuit, while in the previous study only a neoprene top was worn. A full body wetsuit may add resistance to shoulder abduction and flexion through stretch of the entire suit because it is one continuous piece of material. Conversely, a wetsuit jacket or top does not generate this type of tension in the abdomen and lower limbs, and the garment can "ride up" when the arms are lifted above the head. Future studies that examine upper body kinematics while wearing a wetsuit should consider these differences among garment types.

There were also no differences in upper extremity muscle activation between the three wetsuit conditions examined here. This result differs from previous studies on surfboard paddling that have reported an increase in middle and posterior deltoid EMG activity while wearing a wetsuit [43, 50]. Both regions of the deltoid are most active during the return phase of the stroke, and it stands to reason that a wetsuit might impact deltoid activation during this phase by resisting shoulder abduction and flexion. Therefore, the difference between the current results for middle deltoid activation and those reported previously are noteworthy since the paddling protocols and intensities were similar between the two experiments. This disparity might be attributed to differences in participant age and conditioning. In the previous study, participants were older on average (33.1 ± 8.6 years) and exhibited a higher level of steady state oxygen consumption during the control trial (14.2 ± 1.8 ml/kg/min), suggesting that they were working harder even though the ergometer power output and cadence were the same. Participants in the current study were younger (25 ± 7.4 years) and exhibited lower steady state oxygen consumption (12.6 ± 1.6 ml/kg/min), suggesting that this paddling intensity may not have been sufficient to impact middle deltoid activation as it did in the older sample. This idea is supported by data from a previous study that reported that the level of middle deltoid activation is related to paddling intensity [42]. Taken together, data suggest that age and cardiovascular conditioning of the surfer may be a factor in determining the impact of wearing a wetsuit and should be considered in future study designs.

Future studies on wetsuit materials should also include comparisons of durability. Anecdotal observation from the current investigation suggests that TPE wetsuits in their current form may be less durable than the standard neoprene wetsuit. All wetsuits used in this study were comprised of three layers of material, including an innermost layer that is in contact with the skin, a middle layer of closed cell foam (neoprene or TPE), and an outer layer of jersey-lined material. In the TPE wetsuit used in the current study, the three layers of material exhibited separation in the neck, and a few holes appeared in the stitched seams. This factor should also be considered when determining whether TPE can be a viable replacement for neoprene, and the durability and wear of TPE should be examined more systematically in the future.

The current results should be interpreted in view of the primary limitations of this study. Current technology is limited in its ability to capture detailed and precise kinematic and biomechanical data in the water during surfboard paddling. Therefore, a dry-land ergometer was used to simulate paddling in an aquatic environment for kinematic data collection. It is likely that paddling kinematics and wetsuit behavior would be different while paddling in water. For example, a previous study has reported that this ergometer underestimates aerobic demand of paddling at a comparable workload in water [51]. In addition, this study was limited to surfers of a particular size due to the limited number of experimental wetsuits available, and limited to males to ensure that differences in physiology between sexes did not impact measures of skin temperature. Future studies of wetsuit material should include female surfers and account for differences in size and cut of wetsuits between sexes. Further, detailed information regarding the material properties of the neoprene and TPE foam were not included here due to the proprietary nature of the TPE. Future analysis of TPE as a wetsuit material should include measures such as foam density, cell size and distribution, strength, and stiffness. Finally, fifteen surfers were included in the biomechanical analysis, and portions of the data were lost or not acquired in a few cases, which further limits the generalizability of these findings.

5 Conclusion

The findings of this study suggest that skin temperatures were significantly warmer under neoprene in anatomical locations that interacted with the water during a 60-min simulated surfing session in flume. However, only 31.25% of participants were able to accurately perceive these differences in skin temperatures between neoprene and TPE wetsuit materials. Additionally, there were no significant differences in oxygen consumption, heart rate, upper extremity muscle activation, or kinematics during paddling on an ergometer in a dry TPE wetsuit compared to a neoprene wetsuit. These data suggest that TPE may be a viable and sustainable alternative to neoprene in wetsuit design if insulation properties of TPE are improved through modifications to closed cell size and structure or increased material thickness. While additional work is needed to optimize foam structure, use of alternative materials such as TPE in wetsuit design might help to reduce demand for neoprene, leading to a more sustainable wetsuit product.

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Code availability Code available upon request.

Declarations

Conflict of interest The authors state no conflicts of interest.

Ethical approval Experimental procedures were approved by the California State University-San Marcos Institutional Review Board (IRB#1478043).

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

Consent for publication All authors approve submission of this manuscript.

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