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INVITED PAPER

Surfing equipment and design: a scoping review

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Abstract

Growth in the surfing equipment industry has led to increased scientific interest in this area, yet no current paper has reviewed and synthesized the effects of equipment design on surfing. Therefore, the aims of this study were to: (1) assess the volume and type of scientific literature that is available to the authors specific to surfing equipment and design, (2) summarise all surfing equipment and design studies completed to date specific to outcome measures and key findings and (3) identify knowledge gaps in the topic of surfing equipment design. This review was conducted in accordance with the PRISMA scoping review guidelines. A total of seven electronic databases were searched (PubMed, Embase, CINAHL, SPORTDiscus, Web of Science, SCOPUS, and Ovid). Google Scholar was also searched for grey literature. Inclusion criteria were mention of surfing equipment and relevant surfing outcome measures (physiological and mechanical). Exclusion criteria were no full text availability and works not available in English. Results from these articles were then extracted, summarised and presented. A total of 17 articles were selected for review and organized by theme of board, wetsuit and fin. Fin and wetsuit design were the most prominent themes (seven studies each respectively). Most were written within the past 5 years and written in the USA. Fin design studies were largely computational, whereas board and wetsuit design were mostly field and laboratory based. Within each study theme there were consistencies in outcome measures and measuring devices. Board design studies focused on paddling efficiency (VO_2 and HR). Wetsuit design studies primarily assessed thermoregulation, and less so muscle activation and paddling biomechanics. Fin design studies focused on fin shape and configuration to assess lift and drag properties. Three key themes of board, wetsuit and fin design were noted; from this the authors were able to identify several knowledge gaps such as a lack of standardisation in equipment controls and study design procedures. Alongside improving standardisation, the use of wave pools presents as an area of interest in future research.

Keywords Action sports · Wetsuit design · Fin design · Surfboard design · Wave riding

1 Introduction

Surfing is a sport with rapidly growing participation rates which encourages innovation within the surf equipment industry, leading to the growth of surfing as a sport and a multinational industry [1, 2]. The inclusion of surfing as an Olympic sport will likely further enhanced this growth.

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Surfing equipment innovation aims to increase accessibility to the sport and enhance performance. Surfboards and apparel are the two primary pieces of equipment most often associated with surfing. Over the past century these pieces of equipment have undergone significant changes in design and function.

Specifically, early surfboards were recorded up to five or more metres in length [3], a stark contrast to boards commonly seen today, with surfers riding boards as short as one to two meters [4, 5]. Adding fins to the underside of the board changed the dynamics of surfing, giving surfers greater control and manoeuvrability whilst wave riding [2]. Alongside the advances seen in surfboard design, surf apparel has progressed markedly. Since its inception in the 1970s, the surfing wetsuit has continued to develop, allowing athletes to surf for longer durations, in cold weather climates, and with less effort due to its buoyancy and thermoregulatory properties [3, 6, 7]. Modern surfing equipment innovation combined with the increase in surfing popularity has attracted increased scientific interest into the human physiology and mechanics of surfing [8].

Over time, surfboards have become shorter, lighter and more durable [9]. Advances in materials have seen boards transition from solid wood to fiberglass and on to carbon fibre-reinforced polymer [3, 10]. Board shape has evolved to introduce angular noses and board rocker (upwards nose curvature) [3, 11]. Combined, these innovations allow surfers to more easily paddle and ride waves. This can be further enhanced by changes in fin design and positioning [12, 13].

Lift and drag are important characteristics of fins, in surfing lift is the turning force produced perpendicular to the direction of water flow, and drag is the friction-like force produced in the direction of water flow [14]. Modern fins seek to optimise lift to drag ratios, giving maximum speed and manoeuvrability [2–4, 14]. Fin shape, angle and placement are areas of interest with researchers now looking to modern computing solutions [15, 16]. Computer Assisted Design (CAD) and Computational Fluid Dynamics (CFD) allow rapid progression as novel fin shapes and placements can be simulated. Advances in 3D printing technology allow for rapid production and trial of complex fin shapes and profiles [17–19].

Whilst board and fin design are typically assessed regarding fluid dynamics, the wetsuit is typically assessed regarding human physiology. Surfing is a sport with a dynamic physiological demand, with high-intensity bursts of paddling followed by sustained low-intensity paddling and prolonged periods of rest [20–22]. Physiological outcome measures such as oxygen uptake (VO_2), heart rate (HR) and energy expenditure are well documented in surfing [21, 23, 24]. Advances in wetsuit materials seek to improve thermoregulation, without compromising the biomechanics of paddling. Unlike swimming and triathlon where substantial research into the physiological and biomechanical effect of wetsuit design has been explored [25–32], in surfing this remains limited. Current research looks to biomechanics [6], thermoregulation [33–35] and physical wetsuit properties [36].

To the authors knowledge, there is no current publication that has reviewed the effect of equipment design on surfing. Therefore, the aims of this study were to (1) assess the volume and type of scientific literature that is available to the authors specific to surfing equipment and design, (2) summarise all surfing equipment and design studies completed to date specific to outcome measures and key findings and (3) identify knowledge gaps in the topic of surfing equipment design.

2 Methods

2.1 Protocol and registration

The aims of the current study were addressed using a Scoping Review design. An initial protocol was developed based on the Preferred Reporting Items for Systematic Reviews and Meta-analysis (PRISMA) Extension for Scoping Reviews [37]. The finalised protocol was submitted to Open Science Framework (OSF)[1] on 04/11/2020.

2.2 Eligibility criteria

The eligibility criteria for this study was informed by the Population, Context, Concept framework recommended by the Joanna Briggs Institute Reviewers Manual [38].

Population A population criterion was set to ensure that this scoping review only selected studies involving the sport of surfing. People of all age and genders were eligible for inclusion in this study.

Concept The concept of this scoping review was to obtain and analyse the scientific literature relevant to the impact of surfing equipment design on surfing-related physiological and mechanical outcome measures (surfing outcome measures)

Context: Publication types and study designs This review was inclusive of all research settings (laboratory, field, computational), across all periods of time. Publication types included were journal articles, theses, conference abstracts and books, provided they were written in English and could be fully accessed via information sources listed below. Periodicals such as magazine articles and newspaper articles were excluded. All study designs were included.

2.3 Information sources

Following a restricted search of PubMed for key literature relevant to the topic, an initial key terms list was formed through screening of titles and abstracts. Following further correspondence with the author SN, additional key terms were added to the search as per their recommendation. Commercial websites in surfing equipment were also searched for key terms for the search strategy (O'Neil, Billabong, Ozmosis, Quicksilver, Sideways Surf Shop, Needessentials, Island Surfboards, Trigger Bros Surfboards, Ripcurl). This search strategy was then edited and refined by a Bond University librarian skilled in advanced search strategies. Utilising the final search strategy on 29/09/2020, PubMed, Embase, CINAHL, SPORTDiscus, Web of Science, SCOPUS, and

[1] https://doi.org/10.17605/OSF.IO/BAJDH.

Table 1 Exemplar search strategies for both PubMed and Google Scholar

PubMed	Google scholar
(("surfing population"[tiab] OR Surfer*[tiab] OR surfboard*[tiab])) AND (("equipment design"[tiab] OR "board design"[tiab] OR "wetsuit design"[tiab] OR "board shape"[tiab] OR "board length"[tiab] OR (board[tiab] AND volume[tiab]) OR "board thickness"[tiab] OR wetsuit[tiab] OR (rash[tiab] AND vest*[tiab]) OR "thermal jacket"[tiab] OR neoprene[tiab] OR jersey[tiab] OR slick[tiab] OR fin[tiab] OR skeg[tiab] OR "leg rope"[tiab] OR "surf leash"[tiab] OR "surf rope"[tiab] OR wax[tiab] OR grip[tiab] OR “tail pads”[tiab] OR “surf suit”[tiab] OR “deck grip”[tiab] OR hardware[tiab] OR steamer[tiab] OR “spring suit”[tiab] OR boots[tiab] OR “toe boot”[tiab] OR “short board*”[tiab] OR “long board*”[tiab] OR “foam board*”[tiab] OR “single fin”[tiab] OR “multi fin”[tiab] OR “leg rope”[tiab] OR seal[tiab] OR Hydrophobic[tiab] OR “thermal conductivity”[tiab] OR dimensions[tiab] OR foil[tiab] OR shape[tiab] OR Polychloroprine[tiab] OR thruster[tiab] OR leash[tiab] OR Tri-fin[tiab] OR “tri fin”[tiab] OR rocker[tiab] OR Booties[tiab] OR Epoxy[tiab] OR Polyurethane[tiab] OR blanks[tiab] OR shapers[tiab] OR “CNC Machines”[tiab] OR "Sports Equipment"[Mesh]))	surfing population OR Surfer OR surfboard* AND equipment design OR board design OR wetsuit design OR board shape OR board length OR board volume OR board thickness OR wetsuit OR rash vest OR thermal jacket OR neoprene OR jersey OR slick OR fin OR skeg OR leg rope OR surf leash OR surf rope OR wax OR grip OR tail pads OR surf suit OR deck grip OR hardware OR steamer OR spring suit OR boots OR toe boot OR short board OR long board OR foam board OR single fin OR multi fin OR leg rope OR seal OR Hydrophobic OR thermal conductivity OR dimensions OR foil OR shape OR Polychloroprine OR thruster OR leash OR Tri-fin OR tri fin OR rocker OR Booties OR Epoxy OR Polyurethane OR blanks OR shapers OR CNC Machines OR Sports Equipment

Ovid were all searched with results imported to Endnote X9 (Clarivate Analytics, version 9.3.3). Systematic Review Accelerator [39] was used to give database-specific search terms. A source of grey literature was obtained through a search of Google Scholar. In this search patents were excluded, and the first ten pages of results were screened as per CADTH Grey Matters: A practical search tool for evidence-based medicine [40]. Further articles were hand selected by two of the authors (AR and SE) after screening reference lists of selected articles.

2.4 Search

The final search strategy for all database searches can be viewed in Online Resource 1. A filter was used for the SPORTDiscus database as it returned a high yield of magazine-based results; the researchers then refined the SPORTDiscus search to only include journal articles, theses and conference abstracts. Table 1 presents the search strategy for PubMed and Google Scholar as an example.

2.5 Selection of sources of evidence

Following the database search, duplicate articles were automatically removed using Endnote X9 (Clarivate Analytics, version 9.3.3). Authors (AR and SE) independently screened articles by title and abstract, and a consensus was then formed on articles to be assessed for full text screening. Any discrepancies were resolved via the inclusion of a third author (JF). Authors (AR and SE) then independently screened full text articles against established inclusion and exclusion criteria. Any discrepancies were resolved via the inclusion of a third author (JF), with the remaining articles being selected for use within the scoping review.

2.6 Data extraction

Extraction of the data was conducted by two authors (AR and SE). A pilot data extraction process was undertaken, whereby the data were collaboratively extracted and refined by authors (AR and SE). The authors divided the articles equally, extracted the data independently and cross-checked each other’s results to finalise.

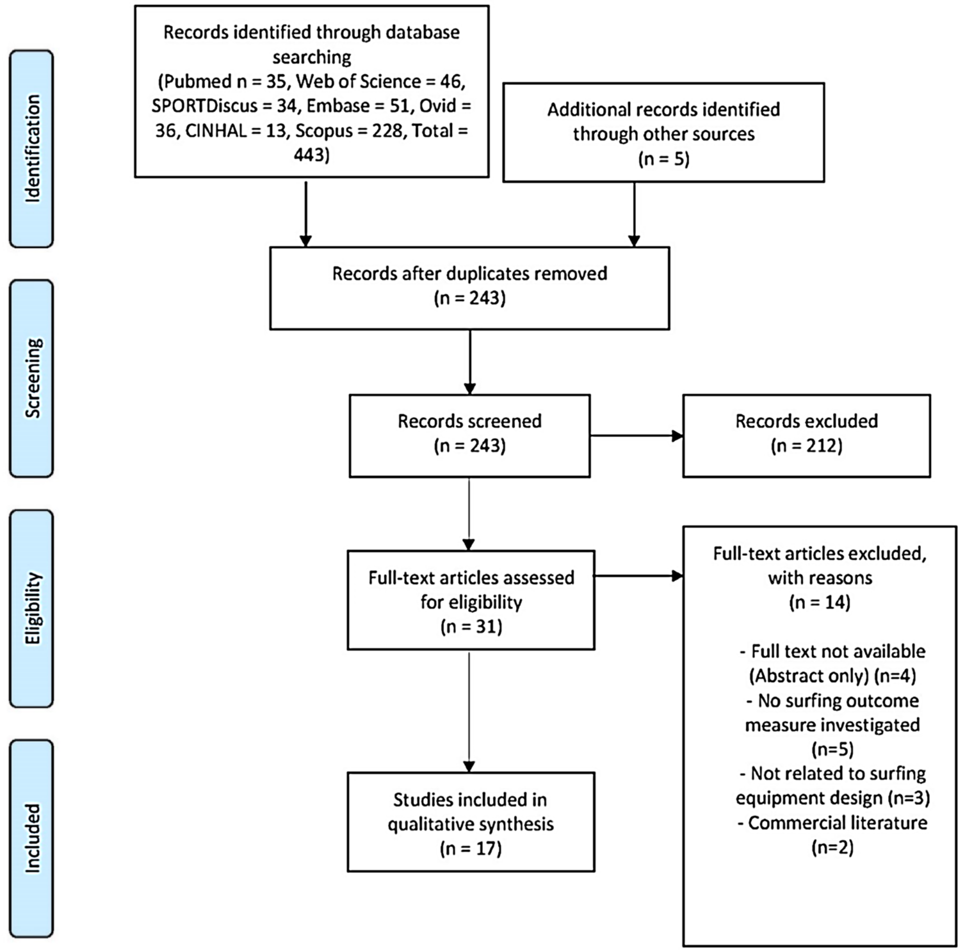
The researchers’ initial data extraction table was formed through discussion within the research team (AR, SE, JF, and KKS). Variables of study characteristics (aim, study design, recruitment procedure, setting), participant characteristics (sample size, age, gender, ethnicity, experience level, inclusion and exclusion criteria) and data characteristics (intervention, outcome, control, result, type of surfing, dependent variable) were recorded. As the authors began to extract data, the table was further modified as key data points became more apparent. Following recommendations from JF, data extraction was limited to mean values and summarised conclusions of each article.

3 Results

3.1 Selection of sources of evidence

Following database searching and additional inclusions, 448 articles were found. Duplicate removal resulted in 243 articles remaining. Upon completion of title and abstract screening 212 articles were excluded, leaving 31 articles

Fig. 1 PRISMA flow diagram



remaining for full text screening. When screening via full text, 14 articles were excluded leaving 17 articles remaining for selection in the scoping review. Exclusions were made on the grounds of not measuring surfing outcomes, full text unavailable to authors, not surfing equipment design-specific and being commercial in nature. This process is illustrated in the PRISMA flow diagram found below in Fig. 1, as is recommended by the PRISMA Scoping Review guidelines [37].

3.2 Study characteristics

Of the 17 studies included in this review, general study characteristics including period of publication and country of origin are presented in Table 2. Although not all selected studies provided the details of equipment used during testing, those that did are grouped by theme and presented in Table 2.

Analysis was conducted by graphically presenting each of the research themes against their years of publication as illustrated in Fig. 2. This highlights the overall increase of surfing equipment research from 2015 onwards.

Further analysis was conducted by presenting research themes against study setting as defined by the location in which data was collected, this is presented in Fig. 3. Study settings were grouped as uncontrolled field environments, laboratory or controlled environments and digital computer simulations. There are clear preferences of study setting between the equipment themes, with fin design preferencing computer simulations, and wetsuit design preferencing field and laboratory studies.

3.3 Summary of outcome measures and findings across study themes

Board design Across the board design studies, eight different outcome measures were assessed, with seven measuring devices utilised as seen in Table 3. Included in these outcome measures, HR and VO_2 were measured in two of the three studies using the same measuring device; however, these outcome measures were assessed in separate aspects of board design, board volume and surfboard foil, respectively [23, 41]. Increasing board volume showed significant decreases in HR, VO_2 and pitch and roll angle; however

Table 2 Key study characteristics

	Number of studies	References
Period of publication		
2005–2009	1	[15]
2010–2014	1	[36]
2015–2019	10	[6, 14, 17, 19, 23, 33, 35, 41–43]
2020–30/03/2021	5	[16, 18, 34, 44, 45]
Country of origin		
USA	11	[6, 16, 18, 19, 23, 33–35, 41, 42, 44]
Australia	2	[15, 36]
Germany	2	[43, 45]
United Kingdom	1	[14]
Norway	1	[17]
Research setting[a,b]		
Quasi experimental no control	9	[6, 18, 23, 33–35, 41, 42, 44]
Observational	2	[19, 36]
Simulated observational	7	[14–17, 19, 43, 45]
Publication type		
Journal article	12	[6, 15, 18, 23, 33–35, 41–45]
Conference proceeding	4	[14, 16, 17, 36]
Thesis	1	[19]
Specified equipment board		
Custom board shaped by Todd McFarland	1	[23]
Firewire dominator	1	[41]
Not specified	1	[17]
Wetsuit		
Hurley 2 mm full-length wetsuit	3	[33–35]
Paddleair™ Ergo Vest	1	[42]
Gadget beyond velcro cuff	1	[44]
Not specified	2	[6, 36]
Fin		
FCS accelerator fins	2	[43, 45]
Custom designed bio-inspired fins	3	[16, 18, 19]
Future fins USA dolphin style fins	1	[18]
Not specified	2	[14, 15]

[a]MacNeill [19] performed simulation and laboratory tests

[b]The authors defined any study which took place in computer software such as CFD to be simulated. Studies were differentiated as either experimental or observational based on established literature [46, 47]

changing board foil (thickness profile) had no significant effect on these parameters. One study found that decreasing surfboard rocker increased lift and drag force [17].

Online Resource 2 presents further summary of the study design, sample size, experience level of participants and inclusion criteria of each included study, as well as a narrative summary of key findings.

Wetsuit design Skin temperature was the most frequently observed outcome measure of wetsuit design (86% of included studies). Less frequently observed outcome measures included muscle activation, paddling biomechanics and heart rate. There was minor variability in the measuring devices used, with iButton wireless thermal sensors and Polar heart rate monitors commonly used across studies. A detailed summary of the outcome measures and measuring devices utilised is outlined in Table 4.

Important thermoregulatory key findings were noted across included wetsuit design studies. Anatomically region-specific differences in skin temperature were noted, with the lower limb experiencing the greatest thermoregulatory losses; further differences were identified between males and females, with females demonstrating a greater mean temperature loss across all regions combined [33, 35]. An outer layer of slick material provided a significantly higher mean

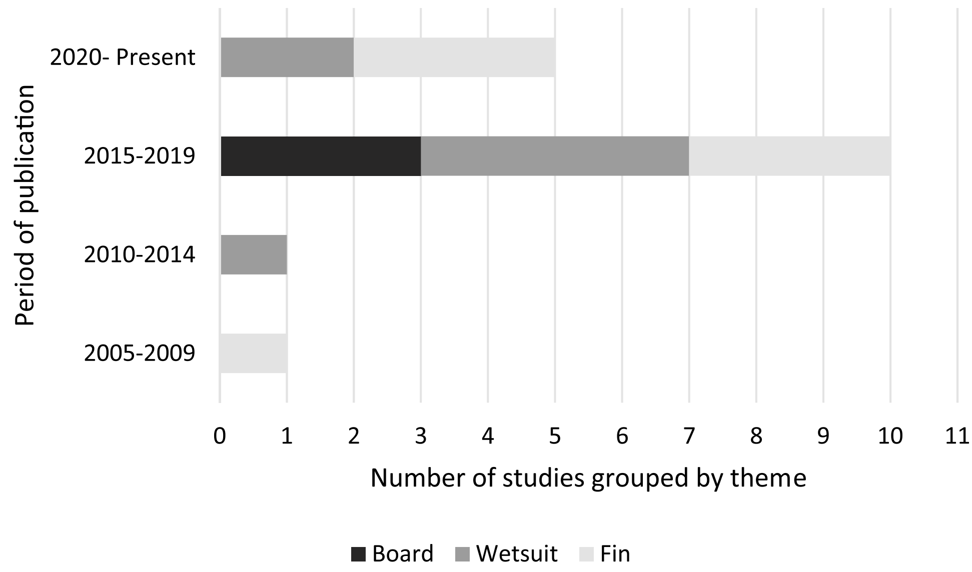


Fig. 2 Bar graph presenting the number of publications over 5-year intervals, colour coded by equipment theme (board, wetsuit and fin)

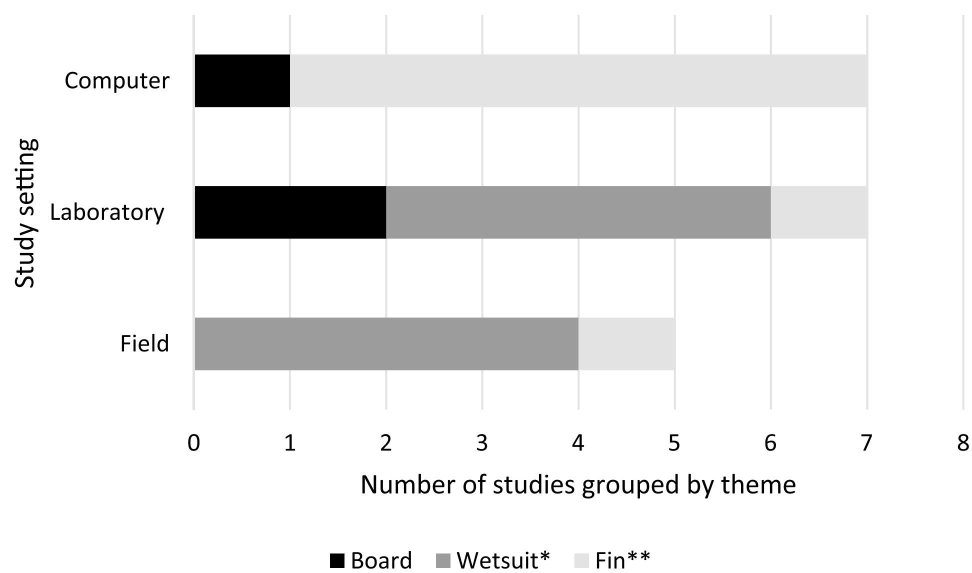


Fig. 3 Bar graph presenting the number of publications conducted in different study settings (Computer, Laboratory, and Field), colour coded by equipment theme (Board, Wetsuit and Fin). *Smith et al. [34] was conducted in both field and laboratory settings. **MacNeill [19] was conducted in both laboratory and computer based settings

Table 3 Frequency of board design outcome measures and their associated measuring devices

Measuring device	Outcome measure							
	VO_2	Heart rate	Board motion	Drag force	Paddling cadence	Pitch and roll angles	Body position	Lift force
TrueOne 2400 Metabolic Cart	[23, 41]							
Polar RCX5 heartrate monitor		[23, 41]						
GoPro 4 Digital camera			[41]		[23]	[23]	[41]	
MaxTraq biomechanics and motion analysis software					[23]	[23]	[41]	
Wireless accelerometer			[41]					
Load Cell Model SBO-200				[41]				
Simcenter STAR-CCM+CFD Software				[17]			[17]	

Table 4 Frequency of wetsuit design outcome measures and their associated measuring devices

Thermoregulation	Outcome measure		
	Skin temperature	Region-specific skin temperature	Wetsuit thermal properties
Measuring device			
iButton wireless thermal sensor type DS1921L (Maxim/Dallas Semiconductor Corp., USA)	[34]	[34]	
iButton wireless thermal sensor type DS1921G (Maxim/Dallas Semiconductor Corp., USA)	[6, 33–35]	[33–35, 44]	
Kawabata Evaluation System F7 ThermoLabo II (Kato Tech, Japan)			[36]

Non-thermoregulation	Outcome measure					
	Paddling biomechanics	Muscle activation	Energy consumption	Heart rate	Comfort	Wetsuit mechanical properties
Measuring device						
TrueOne 2400 Metabolic cart (Parvo Medics, USA)			[6]			
Polar RCX5 Heart rate receiver (Polar Electro Inc., Finland)				[6, 33–35]		
Polar T31 Heart rate recorder (Polar Electro Inc., Finland)				[6, 33–35]		
Polar FT1 Heart rate receiver (Polar Electro Inc., Finland)				[34]		
8 Camera motion capture (Vicon, UK)	[6]					
Trigno wireless EMG movement data (Delsys Inc., USA)	[42]	[6, 42]				
"Precision balance to measure mass"						[36]
Thickness Lab 1880 thickness gauge (Mesdan, Italy)						[36]
LR 30 K Tensile tester (Lloyd, UK)						[36]
CAM 200 contact angle meter (KSV Instruments Ltd., Finland)						[36]
"Wool Comfort Meter"					[36]	
DP70 camera (Olympus, Japan)						[36]
SZX12 optical microscope (Olympus, Japan)						[36]

skin temperature in both field and laboratory conditions when compared to a jersey material [34]. Adding a Velcro cuff to a 2-mm wetsuit decreased mean skin temperature at the wrist, but had no significant change when used with a 3-mm wetsuit [44]. Commercially available wetsuits were categorised as either high or low end according to recommended retail price (RRP) and seam type (stitched or fluid sealed) [36]. High end wetsuits with fluid-sealed seams demonstrated better thermoregulatory properties and seal strength but low end wetsuits with stitched seams rated as more comfortable on a Wool Comfort Meter scale [36].

Electromyography (EMG) analysis was used to compare muscle activation between wetsuit and non-wetsuit trials, and with and without the use of an inflatable vest. Wetsuit use increased Middle Deltoid activation, and resulted in less organized, more varied vertical trajectory of the wrist [6], whereas inflatable vest use decreased Middle Trapezius and Erector Spinae activation as well as mean trunk angle [42].

Online Resource 3 further summarizes the wetsuit design studies, presenting study design, sample size, experience level of participants and inclusion criteria, as well as a narrative summary of key findings.

Fin design All selected studies investigated a combination of lift, drag and lift to drag ratio, and six of seven studies investigated stall angle. STAR CCM + CFD software was commonly used throughout selected studies, with three of seven studies making use of the software. A full summary of all outcome measures and measuring devices utilised in fin design studies is presented in Table 5.

Key fin design findings centred around lift and drag forces produced by the fins. Maximal lift force was shown to occur between 20 and 25 degrees angle of attack [19, 43]. However, maximum lift to drag ratio occurred at around 10 degrees angle of attack [14]. When comparing between three and four-fin configurations, three-fin setups produced peak lift at a smaller angle of attack, while fou-fin configurations produced peak lift at a larger angle of attack [14, 45]. Moving the rear fins outwards (transverse) on a four-fin configuration resulted in delayed lift stall in a turn, but moving the rear fins rearward (longitudinally) did not affect the stall

Table 5 Frequency of fin design outcome measures and their associated measuring devices

	Outcome measure				
	Lift force	Drag force	Lift to drag ratio	Stall angle	Turn rotation rate
Measuring device					
Acoustic Doppler velocimeter flow measurement tool (Nortek, Norway)	[19]				
"Spring loaded force gauges"		[19]			
TraceUp GPS tracking system (TraceUp, USA)		[18]			[18]
NX 9.0 CFD Flow solver (Siemens PLM software Inc., USA)	[19]	[19]	[19]	[19]	
Simcenter STAR-CCM + CFD Software (Siemens PLM Software Inc., USA)	[43, 45]	[16, 43, 45]	[43, 45]	[16, 43, 45]	
FLUENT solver CFD software (Ansys, USA)	[14, 15]	[14, 15]	[14, 15]	[14]	
Unspecified CFD Software	[18]	[18]	[18]	[18]	
iPhone 6 camera (Apple, USA)	[19]	[19]			

angle [45]. Lift to drag ratio was not significantly affected by the longitudinal positioning of the rear fins, but the lift to drag ratio did increase when rear fins were moved inward in the transverse plane [45].

The performance of nine different animal-inspired fins was assessed, identifying the short-finned pilot whale fin as performing best in lift to drag ratio and lift force due to its large surface area [19]. A humpback whale fin design demonstrated enhanced rotation rate in comparison to a straight edged fin and to a partially grooved and serrated fin [16, 18]. This whale fin also produced the lowest amount of resultant force during turning manoeuvres (force of water pushing against the rider's movement, often referred to as hold) [16, 18].

Online Resource 4 further summarizes the fin design studies, presenting study design, setting, intervention, outcome measure and a narrative summary of key findings.

4 Discussion

4.1 Principal findings

Following duplicate removal, 243 articles were included for screening, and of these 17 were selected for inclusion in the study (6.9%). The percentage of studies included was lower than expected. This can be attributed to the homogeny in equipment nomenclature between surfing and other water-based sports, for example studies into surfing and triathlon both use the term wetsuit [6, 25, 30, 31, 33–36, 44]. Additionally, there was a large volume of results investigating the business and marketing of surfing and associated apparel which did not meet the inclusion criteria for this review [48–51]. A possible explanation for the many irrelevant studies was due to a wide range of search terms being used to ensure the large variety of surfing equipment available was searched.

During the screening process, three key themes of surfing equipment were identified: board, wetsuit and fin. The most frequently identified themes were wetsuit and fin design, contributing seven articles each, respectively, whilst board design contributed three. Of these themes, journal articles were the prominent study design (12/17), followed by conference proceedings (4/17) and theses (1/17). A trend in the publication frequency of all surfing equipment studies was noted, increasing rapidly since 2015, depicting surfing equipment as an emerging area of research. This is consistent with the growth of all research into surfing, with 57% of all surfing literature published after 2010 [52].

Of the assessed literature in the field of surfing equipment, 65% had a primary affiliation based in the USA, this is of note as previous studies have identified Australia as the country with the greatest output of research into surfing [52]. However, this scientific output is primarily in the area of physiology and performance, while the study of surfing equipment design seems to be primarily occurring within the USA [52]. Of these publications, the majority investigated either board or wetsuit design. One research laboratory based out of California State University San Marcos conducted 80% of research into board and wetsuit design [6, 23, 33–35, 41, 42, 44]. The concentration of this research demonstrates the benefits of having an established surfing research department with technology to manipulate equipment design variables and monitor outcome measures. This availability of equipment may be a limiting factor in surfing research, with many different research groups looking into physiological aspects of surfing, independent of equipment variables [20, 22, 53–56].

The capacity of CAD technology to manipulate fin design may have contributed to a broader global interest in fin research. While used in 86% of fin studies (6/7), CFD technologies were only utilised as an outcome measure in 1/3 board design studies. This software can be further utilised as the validity of CFD to measure the effect of surfboard rocker was demonstrated by Oggiano [17]. A suitable progression following CFD simulation would be to compare those findings with real-world laboratory experiments using equipment such as fluid tanks or flumes, but this may be currently limited by availability of these resources. From there further studies into surfboard rocker may benefit from research completed in an ocean-based field setting. Similarly, with the large variety of board volumes and tail shapes that are commercially available, this review found no field-based studies that investigated these areas of equipment design.

Forty-seven per cent of studies included commercially available products in their study designs. Of these studies only one compared between commercial surfing equipment products, and this study did not specify the make and model of the products, branding them as high vs low end in retail value [36]. Prominent surfing equipment brands such as Hurley and Firewire were selected in several other studies, but were utilised as controlled variables (e.g., Hurley wetsuit used to determine regional skin temperature difference). Within the theme of wetsuit design, 43% of studies (3/7) utilised a standardised wetsuit to test a variety of surfing equipment such as Velcro cuffs and wetsuit materials. However, the themes of board and fin design largely lacked any standardised equipment in their study designs. For example, one fin design study allowed participants to use their own boards, as opposed to self-selecting a size of board from a control board make and model [18].

When considering the summarised key findings within all three study themes, the authors noted a distinct heterogeneity between study designs. As a result, this did not allow for a systematic comparison between studies. The consistency in outcome measures and measuring devices within each theme highlights common areas of interest in surfing research, and a potential to compare like findings with appropriate study design standardisation. Additionally, the quantity of findings within the assessed research highlights the ability of equipment design to impact surfing and demonstrates the need for further research. This continuation of research into the field, especially with controlled variables, for example, standardising fin configurations in board design studies, will allow future researchers to produce stronger comparative analysis and, therefore, higher quality evidence. When attempting to compare the study's findings to previous literature, the authors found no research which assessed the effectiveness of surfing equipment variation. The focus of surfing reviews completed to date centres on injuries [12, 57, 58] and quantifying the physiological characteristics of surfers [20].

Broadening into other related sports, an article by Burtscher et al. [59] investigated the effect of skiing equipment design; however, only used injury rates as an outcome measure, an area which was out of the scope of this review. Similarly, a review by Shuman and Meyers [60] investigated injury rates in skateboarders with varying equipment, but only investigated safety equipment, not the core equipment necessary to skateboarding itself.

4.2 Knowledge gaps

Despite the diversity of surfing equipment included within the search strategy, only studies relating to board, fin and wetsuit design were found. Other equipment, such as leashes, wax, boots and tail pads were all included within the search strategy, but did not yield results. The authors believe these pieces of equipment to be relevant for the safety and ease of access to surfing and, therefore, a valid area for future research. A possible explanation for this lack of research is the novel nature of surfing equipment design research, with only larger scale equipment being investigated at this time.

Within the theme of board design, there was a lower-than-expected number of studies, leading to numerous areas of interest remaining uninvestigated. No identified study investigated the effect of tail shape on physiological outcome measures such as energy consumption. Furthermore, no study investigated the effect of board construction material (Fibreglass or Epoxy outer shells, Expanded Polystyrene or Polyurethane foam cores), nose shape, or rail shape, which are important elements of surfing equipment design. Finally, all identified studies assessed board design in either a simulation, or in a paddling setting, with no research conducted assessing wave riding. Board design can impact on board velocity and cutback turn performance [17]. Assessing the properties of board volume, construction material and nose/rail shape through wave riding may provide a more accurate representation of these outcome measures due to the unpredictability of environmental conditions. Shormann and in het Panhuis' [18] fin study demonstrated the effectiveness of investigating board velocity and cutback turn variables in a field setting. Such field setting measurement may also lead to progression in board design if applied in a similar study.

Within the theme of wetsuit design, knowledge gaps existed in the comparison between available lengths and thicknesses of wetsuits, with only one study comparing thermoregulation in wetsuit thicknesses [44], and no studies comparing the biomechanics or thermoregulation of differing lengths of wetsuits. The authors also identify wetsuit surface material as having important implications for thermoregulation, and as such further comparisons between commercially available surface materials should be conducted. When assessing styles of wetsuits, no research comparing front closure and back closure suits exists, no literature compares the comfort of inner linings and no research looks to the effect of wetsuit additives such as boots on wave riding.

Wetsuit construction material also provides a further gap within the available literature, with materials such as plant-based rubbers uninvestigated. Due to Neoprene being petroleum based its manufacturing is environmentally damaging and the end product is not biodegradable, research should look to the effectiveness of plant based alternatives to neoprene [61]. To the authors' knowledge no research was identified which assessed the properties of wetsuits constructed from these materials.

Within the theme of fin design, many of the included studies examined the hydrodynamics of fins, but only one of these assessed the impact of fin design on wave riding. This study only assessed four participants and as such further research is needed in the area. A mixed methods study design may provide better insight into this area due to the subjective nature of surfing culture and decision making. For example, combining GPS data with numerical ratings of perceived surfing performance is a potential method using which researchers can draw further conclusions on the effectiveness of their fin designs.

Methodological standardisation in surfing equipment design research presents a number of challenges. Current measuring device technologies limit the ability to make valuable measurements in a field-based setting, due to a trade-off between the measurement complexity and accuracy, and the fragility of devices. For example complex paddling analysis requires cameras for motion analysis, which cannot easily be used in water, especially in a field setting. Similarly, studies occurring in field environments require measuring devices which are waterproof and capable of logging data, as data streaming connection cannot be maintained in the event of sensor submersion (loss of wifi or Bluetooth connection).

Few studies utilised multiple settings, or repeated trials within the same setting in their study design. Future research may benefit from the use of multiple settings as comparison between study settings serves to validate the transferability of findings in lab or computer settings with field-based settings. Utilising multiple settings may also allow for validation of the consistency of human participants' performance such as repeated trial paddling efficiency. Furthermore, the authors note the distinct increase in environmental variability between laboratory and ocean settings. Benefit may be found in repeating trials within the same field setting to validate the findings in a variety of weather and surf conditions. Alternately, the capacity for waves to be controlled in a wave pool eliminates the unpredictability of wave size, force and other environmental conditions [62], as such wave pools may provide an intermediary link between the controlled laboratory environment and the uncontrolled ocean environment.

4.3 Future recommendations

The growing recognition of surfing as an international sport can be partly attributed to its inclusion into the 2021 Tokyo Olympic games [52] and to the growth of adventure tourism [63]. Looking to the future of surfing research in an expanding industry, Saulino et al. [62] suggest the development and increasing availability of commercial wave pools as a space for further growth, demonstrating the efficacy of wave pools to produce consistent and measurable waves.

As previously stated, the work by Saulino et al. [62] not only highlights the ability of wave pools to produce consistent surf breaks, but also the efficacy of physiological measuring devices to produce useable data when measuring subjects whilst wave riding. Potential for future research now lies within using these pools and measuring devices to compare physiological outcomes in surfers when comparing between surfing equipment.

Similarly, research by Shormann and in het Panhuis [18] demonstrated the use of GPS and accelerometry tracking equipment to measure wave riding variables such as speed and rotation rate in an ocean setting. This ability to measure wave riding data in an ocean setting allows study participants greater freedom to perform a full wave riding cycle from paddling to complex surfing manoeuvres. These actions are more closely related to the intended end consumer use of surfing equipment and, therefore, should be measured, rather than isolated aspects of surfing. Technological advances in these measuring devices and telemetry allow for ever increasing accuracy of measurement when assessing the sport. These advances mean that television broadcasters are now able to display surfers' statistics such as speed and distance travelled in real time [64]. Personal devices are now capable of making similar measurements, with sensors now able to track wave height and aerial manoeuvre height and duration, either via mounting a sensor to the board [65], or by built in sensors within the board [66]. Devices such as these may further enhance researchers' capacity to assess biomechanics and surfing performance in the field.

A limitation to field based studies identified by Shormann and in het Panhuis [18] was the uncontrolled nature of ocean wave breaks, preventing researchers from controlling variables such as wave size and rest periods, leading to inconsistent measurement environments between trials. Use of a controlled surf break within a wave pool may solve this inconsistency in wave dynamics, allowing for more direct comparison between equipment.

It should also be noted that wave pools are not without their own unique limitations and difficulties. As previously stated measuring devices limit a study's ability to capture meaningful data in a field setting, this limit is still present in wave pools. Further issues arise in the decreased consistency of human participants to perform repeated turning manoeuvres on different pieces of equipment when compared to a CFD simulation or controlled laboratory experiment, such as fluid tank. Although the use of human participants to assess equipment is overall beneficial, researchers should note the human error which may be present when attempting to produce identical repeated actions. Finally, the authors acknowledge the differences in findings which may exist between ocean and wave pool-based studies due to the discrepancies of buoyancy between salt and freshwater environments and the impacts this may have on paddling efficiency and wave riding. Due to this discrepancy in buoyancy comparison between these study settings may be limited.

Alongside increasing research within wave pool settings, further development of measuring devices would prove beneficial within surfing equipment design research. Current measuring devices limit researchers' ability to measure complex outcomes such as motion analysis and EMG in a field-based setting. As such, advances in motion capture and EMG technologies would allow for research to capture complex outcomes in an ocean environment without issues of water damage and sensor submersion causing streaming disconnection.

4.4 Limitations

This review was limited by a lack of both total studies and comparable studies included for review. As alluded to previously, research into the area of surf equipment design is an emerging area and as such only 17 studies from a few research groups met the inclusion criteria for this scoping review. Additionally, the review was limited to publications in English, which may have excluded key surfing equipment design studies published in other languages.

Although extensive database searching was performed, the use of engineering-specific databases such as ProQuest Engineering, EBSCO Academic Search, and ProQuest Technology Collection may have further strengthened the review. Similarly, the use of thesis-specific databases such as Open Access Theses and Dissertations, EBSCO Open Dissertations, Bielefeld Academic Search Engine, or Global ETD Search would have also strengthened the review. The authors also note the searching of national databases of those countries where surfing is popular may have proved beneficial.

Due to the nature of this scoping review and its aims, no critical appraisal was performed; this may reduce the confidence the authors draw from these conclusions as the methodological quality of the included studies was not measured.

5 Conclusion

With the growing popularity of surfing as a global sport there have been significant advances in surfing equipment and design. This presents greater opportunity for surfers to access the sport and perform to the best of their ability.

This scoping review assessed and summarised the scientific body of literature pertaining to surfing equipment and design ($n = 17$). This study identified three distinct themes in the currently available literature: board, wetsuit and fin design. It was identified that board design impacted upon the paddling efficiency of the surfer and lift and drag forces acting on a surfboard. Wetsuit design impacted largely upon the thermoregulation of the surfer, with impacts also noted in muscle activation and biomechanics. Fin design was found to impact the lift and drag forces acting upon the surfboard dependent on fin configuration, placement, shape and angle.

The authors note a distinct lack of standardised study design and measurement procedures, leading to difficulty when comparing findings of similar studies. Further to this a lack of standardised surfing equipment control variables further decreases the ability to compare between studies. Addressing this lack of standardisation in surfing equipment research would allow for greater comparison between studies, yielding higher quality scientific conclusions, critical appraisal and systematic review.

Further research into the field of surfing equipment design would benefit from the use of wave pools as a semi-controlled field-based environment and from the publishing of all control equipment and measuring procedures/devices used to enhance replicability and comparability with future studies.

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