A Parametric Method to Customize Surfboard and Stand Up Paddle Board Fins for Additive Manufacturing

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Abstract. At all levels of sporting competition, from recreational to elite, athletes desire products that improve their performance, comfort, safety, or enjoyment. Additive manufacturing, also known as 3D printing, provides a new method of producing sporting equipment that can be customized to the unique needs of an individual. This study examines the opportunity to produce surfboard and stand up paddle (SUP) board fins through 3D printing and details a parametric computer-aided design (CAD) system for surfers to modify the geometry of a surf fin in real-time. Specifically, the fin system, fin position on the board, cant, fin depth, sweep, base length, base foil profile, tip sharpness, tip thickness, as well as the overall dimensions can be modified using simple interactive controls that do not require any CAD experience. Indicative cost data was collected for ten virtual fins designed through this system intended for fused filament fabrication (FFF), selective laser sintering (SLS) and multi jet fusion (MJF) technologies. Two designs were 3D printed and trialled on a SUP board. The method of creating the parametric system is sufficiently detailed in order to be replicable and built upon by designers, with future research directions outlined in order to improve surfing performance and extend the well-established culture of experimentation within the sport.

Keywords: 3D printing, Grasshopper, Human-computer interaction, Personalization, Rhinoceros 3D, Sport technology, Surfing, Visual programming language.
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1 INTRODUCTION

Surfing is both a recreational and professional water sport that encompasses several different disciplines with different hardware requirements, including shortboard and longboard surfing performed on coastal waves, as well as stand up paddling (SUP) which can be performed on both wave and flat-water conditions. The iconic surfboard is the principle piece of equipment required for surfing, and it was only in the 1930's that fins were added to surfboards [9, 13], increasing stability and control in the water. Initially fixed to the board, surfboard fins today are typically removable and can be configured for different conditions or rider preferences. For shortboards this includes twin (2 fins), thruster (3 fins) and quad (4 fins) configurations, while many longboards and SUP boards may use a single central fin, although numerous configurations with smaller fins are also popular.

The shape of surfboard fins have largely been bio-inspired, assimilating proportions from the dorsal fins of fish and mammals such as the dolphin [9, 13]. There are several common manufacturing methods employed including injection molding, layered fiberglass and various composite techniques. Injection molding of a resin with fiberglass is the most common due to the ability to be mass produced [6, 9], providing affordable and durable fins. However, this means that there are limitations on the range of geometries for a rider to choose from due to the expensive tooling costs associated with injection molding [23]. Composite fins follow a similar process with the addition of a different core material that is then molded around. This core provides opportunities to modify fin performance through the use of different materials and honeycomb structures, without the need to create a new mold, although the fins will all have the same external form. In contrast, fiberglass fins provide much more design freedom as each must be made by hand using layers of fiberglass cloth and resin. However, this can make them expensive, with performance and durability directly related to the skill of the maker.

For these reasons, Additive Manufacturing (AM), known popularly as 3D printing, is receiving attention as a new means of fin production due to the ability for each print to be different, yet produced through a largely automated machine process. Academic research on this application is newly emerging, for example Gately et al. [9] conducted experiments using a range of 3D printers and materials to prototype surf fins, which were compared in both lab and real-world surf conditions to commercially available surf fins. Their findings revealed similar performance between those 3D printed using carbon fiber composite or ULTEM (polyetherimide) materials and traditional manufacturing techniques, although 3D printed Acrylonitrile Butadiene Styrene (ABS), which is a common material used in desktop Fused Filament Fabrication (FFF) 3D printers, was found not to be durable for surfboard fins. A similar weakness was found in less academic studies of desktop 3D printed surf fins, for example kitesurfing fins and a SUP fin [15], which suffered from delamination issues between layers, or weakness around fasteners to the board. Carbon fiber composite instead appears to be the most popular choice, with several examples published online [4, 10], including a company called Westkust [24] which leveraged a service bureau to 3D print fins on-demand for customers in carbon fiber composite, as well as freely supplying digital files for others to download, 3D print and experiment with. Most recently in 2020, a team of undergraduate students from Embry-Riddle Aeronautical University experimented with 3D printed surf fins in a wind tunnel, optimising a fin design for local surf conditions, although fibreglass was manually applied to the exterior in order to improve strength [8].

While empirical evidence supporting the production of surfboard fins using AM is not comprehensive, given the rapid developments of the technology and associated materials in recent years, it is likely that research within academia and industry will increase due to the small size of the fins, making them easy to 3D print on most 3D printers, as well as providing opportunities for customization. This is supported by the high profile and competitive nature of the sport which had been scheduled as an Olympic sport for the first time in Tokyo 2020, despite the games being postponed due to the COVID-19 pandemic [11]. Such competition creates a high level of performance-driven research and development for sporting equipment to gain competitive advantage, and with minimal equipment needs in surfing, the fins provide a significant opportunity to improve performance, which has been estimated to account for up to 40% of surfing performance [5].

Despite several Computational Fluid Dynamics (CFD) studies into surfboard fin performance providing knowledge into the relationship between geometry, positioning on the board and performance [2, 12, 13, 20], factors affecting surfer performance are multidimensional and complicated by environmental inconsistencies that cannot be efficiently simulated. Surf conditions change from day-to-day, and location-to-location, and different fins will be suitable to ride different waves. Furthermore, qualitative factors are a critical factor not considered in studies to date and are a combination of personal preference (e.g. brand association), experience, knowledge passed from one surfer to another, and personal surfing style. A surfer may perform better with a fin they believe works best for them even if another would have better performance characteristics. As a result, there is a strong culture of experimentation and personalization in surfing [5, 13], whether modifying existing fins, or sculpting them from materials like bamboo/wood, resins and composites. This is different to industries like automotive or aviation where optimization strategies can more directly contribute to performance through light-weighting or increased strength [14], and conditions more readily simulated.

Therefore, this study builds upon the opportunity for 3D printing to allow almost limitless customization and experimentation for surfers, digitizing a largely analogue process. Popular 3D computer-aided design (CAD) software *Rhinoceros 3D* with the *Grasshopper* plug-in was used to prototype an interactive, parametric system which could be used by any surfer to customize the geometry of surfboard or SUP fins, without the need for CAD skills. Following a similar method to one used to interactively customize knit geometry [17], simple control mechanisms linked to common fin terminology and geometry conditions allowed for rapid and real-time manipulation, visualized in 3D before being exported as a file suitable for 3D printing. The expertise of a surfer and desire for freeform experimentation was combined with geometric data as a feedback mechanism, creating new opportunities to manufacture fin geometries that may not be available commercially, or may require significant skill to shape by hand, prohibiting many from experimenting.

Cost data for a range of different fin geometries was also compared across fused filament fabrication (FFF), selective laser sintering (SLS) and multi jet fusion (MJF) technologies, providing surfers with data on the manufacturing costs associated with 3D printed surf fins as opposed to those that are commercially available, or the costs of custom manufacturing fins through different means. Embracing opportunities offered by 3D printing may provide both professional and recreational surfers with improved knowledge of the relationship between fin geometry and their personal performance and enjoyment of the sport, but only if accompanied by systems that empower them to design surfboard fins without the years of CAD and manufacturing training of a designer.

2 GEOMETRY OF SURF FINS

Surfboard fin geometry can be complex with many designs featuring organic shapes that are difficult to accurately define using parametric CAD tools [2]. At a fundamental level, several key features are commonly described by surfers and fin manufacturers, shown in Figure 1. The *fin system* is the block of material that sits at the base of a fin and slots into a surfboard or SUP board. There are several common systems on the market, with 'FCS' and 'Futures' being two of the most popular [9], while longboards and SUP boards often utilize an adjustable position single fin as pictured in Figure 1. Fin systems are proprietary and switching between systems requires aftermarket adapters, so many surfers will only use surf fins manufactured with the fin system that fits their board.

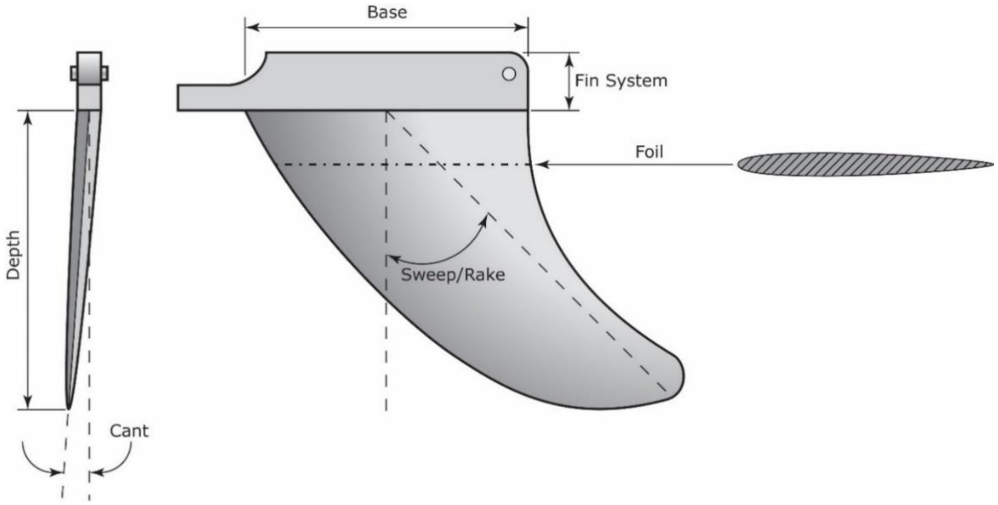

Figure 1: Diagram of surf fin with key geometries.

The *base* of the fin is the length connected to the fin system and sits flush with the base of the surfboard. The base length is linked to acceleration [13] and turning ability on a wave [5]. The *fin depth* is the vertical length of the fin from the fin base, with a longer depth providing increased stability [5, 13]. The *sweep/rake* can be measured as an angle, or a length from the back of the base to the tip of the fin, with a lower sweep angle believed to allow tighter pivot turns, while a larger sweep angle creates more drawn out turns [5, 13]. The *foil* is the cross-section through the fin and much like an aerodynamic aircraft wing, is directly responsible for generating lift, with a poor hydrodynamic shape increasing drag through the water [2, 5]. A center fin will have a symmetrical double convex foil (as pictured in Figure 1), while outside fins may have a single convex foil on the outer edge, and a flat or concave foil on the inside [2, 12]. Similarly, outside fins may have a *cant* angle to increase turning speed [5], while a center fin will not.

3 METHOD

In order to provide a fully customizable surf fin, three separate elements were required: Firstly, a fin system which was based on those commercially available and suitable for fitting to a surfboard. Secondly, the parametric model of the main fin body to be customized below the fin system. This was based upon the core geometry of surf fins outlined previously. Lastly, a simple means for modifying the parameters of the fin in real-time. These are detailed in the following sections to enable reproducibility by designers and engineers.

3.1 Fin System

Several fin systems, including the FCS, Futures and adjustable longboard/SUP system, were manually measured with Vernier calipers and reverse engineered within Solidworks. This was necessary in order to accurately replicate the standardized geometry of each system. These systems were then exported as .IGS files and imported into Rhinoceros 5.0, as shown in Figure 2. Each model was aligned in relation to the origin, ready to connect to the lower fin geometry, and swap between as desired.

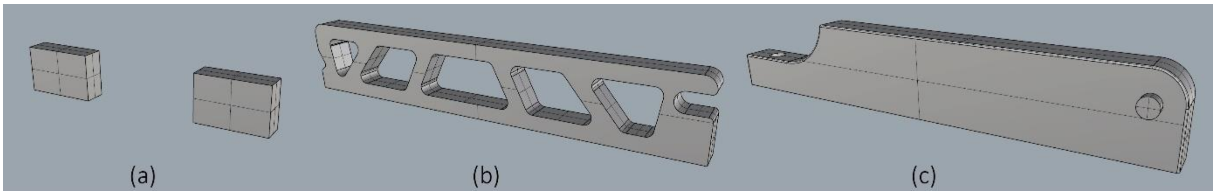

Figure 2. Fin systems (a) FCS, (b) Futures, (c) adjustable longboard/SUP.

3.2 Fin Geometry

The remaining fin geometry was created completely within Grasshopper, allowing full parametric control. The foundation of the fin was described by the base length, fin depth and sweep described in Figure 1. The *Line SDL* function was used to form the base, extending from the origin in the x-axis. A *Number Slider* was used for the length, allowing an interactive method of modifying the base length as shown in Figure 3. From the center of the fin base an arc was formed with another *Number Slider* to control the radius. This relates to the fin depth, although further measurements were calculated later to show an accurate fin depth to the user. Lastly, the *Evaluate Length* function was used to control a point along the arc, which was connected back to the center of the fin base with a line to control the sweep angle of the fin.

From this foundation, a 2D profile of the fin could be constructed as shown in Figure 4. Equidistant lines were extended perpendicular to the lower end of the sweep line, controlling how sharp the tip of the fin would be. *Arc SED* was used to connect the endpoints of these lines to the appropriate endpoint of the base length line.

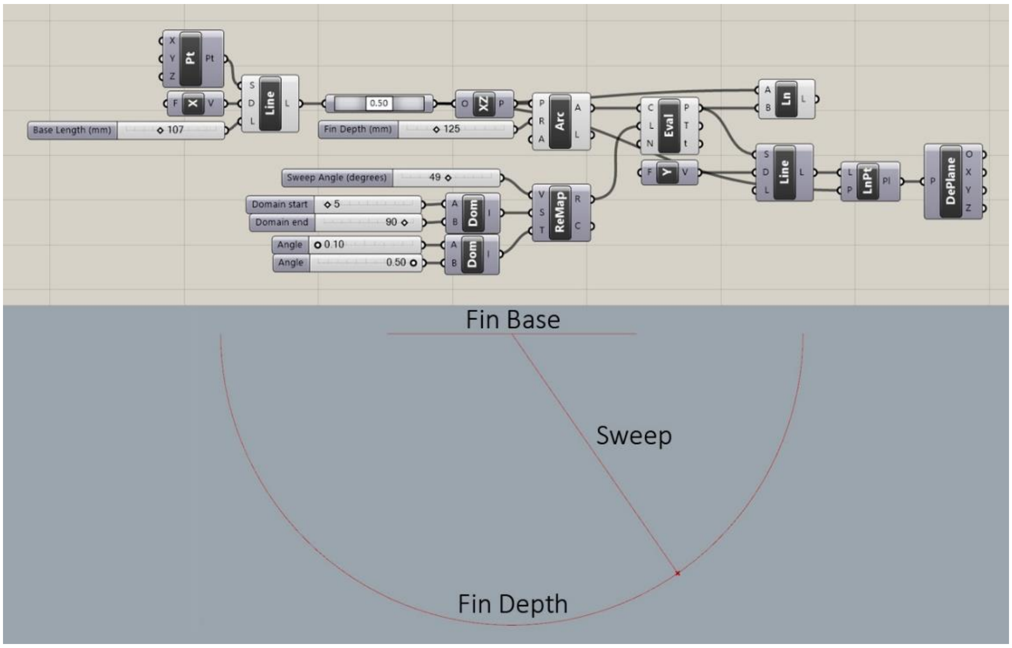

Figure 3. Grasshopper code and resulting geometry defining the fin foundation (side view).

For the front arc, construction lines were used so that the top of the arc would be tangent to a line at an angle midway between vertical and the angle of the sweep line. For the rear arc, the top of the arc was tangent to a vertical line. The final tip profile used a *Blend Curve* feature to tangentially connect both arcs. From this profile geometry, two *Linear Dimensions* were added in the *x* and *y* planes so that the Rhinoceros 3D model would always display the overall length and depth of the fin to the user.

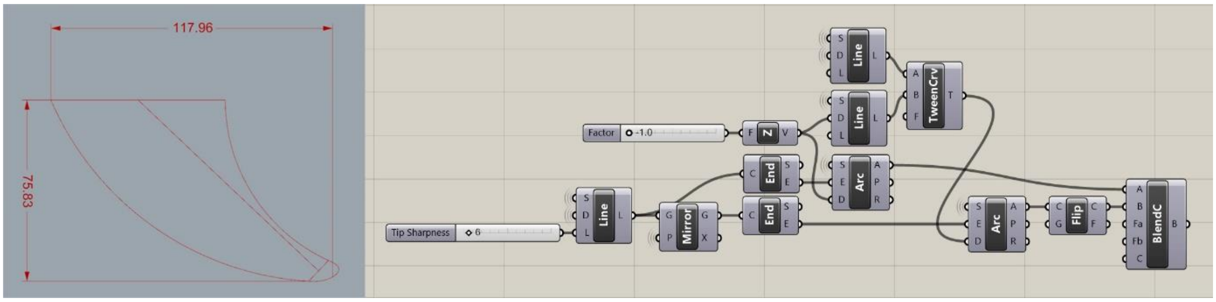

Figure 4. Grasshopper code and resulting geometry defining the 2D fin profile (side view).

The foil was the next 2D geometry required to describe the surf fin. The first component of the foil was the shape around the base length. This required an initial *Circle CNR* feature that was centered along the base length and intersecting with the origin. The radius was controlled with a *Number Slider*, allowing the size of the leading edge to be easily manipulated. The circle was split using *Evaluate Length*, with this point mirrored around the base length, allowing a new *Arc 3Pt* to be constructed, forming the leading edge. By using the *Evaluate Curve* feature for the endpoint of this arc, an additional *Arc SED* could be used to tangentially connect the leading edge of the foil to the end of the base length as shown in Figure 5. The three curves were used to create an *Edge Surface*, with the *Dimensions* feature added to automatically calculate the maximum thickness through the center of the foil, which when multiplied by two, gave the overall thickness of the fin for display with the interactive controls of this system.

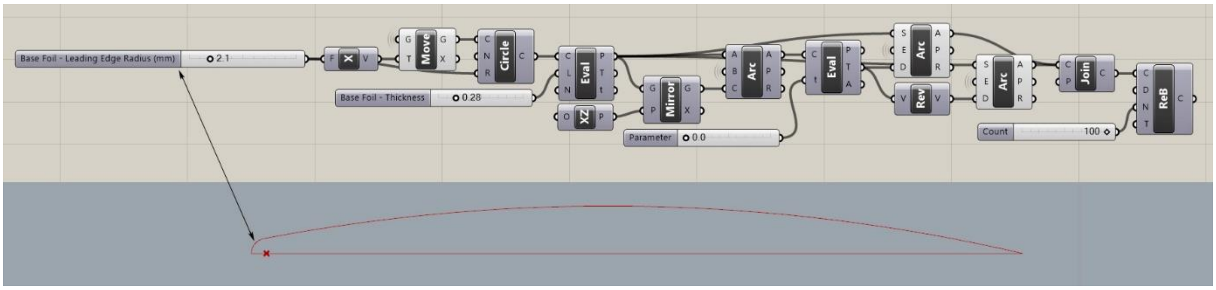

Figure 5. Grasshopper code and resulting geometry to define the base foil profile (top view).

The second component of the foil was the profile towards the tip of the fin, in line with the end of the sweep line. A copy of the end point of the sweep line was moved in the *y* direction, with a *Number Slider* controlling the thickness of the foil profile. An *Arc 3Pt* was then used to connect the end points of the perpendicular lines at the endpoint of the sweep, and the newly created point.

From this collection of profiles, the 3D geometry of the fin was defined. The *Edge Surface* feature allowed the collection of lines defining the main body of the fin, as well as the lower tip, to be turned into separate surfaces as shown in Figure 6. The two arcs defining the base foil in Figure 5 were also extruded vertically by 10mm in order to allow for a future trimming process. These three surfaces were mirrored around the central axis and all surfaces joined together.

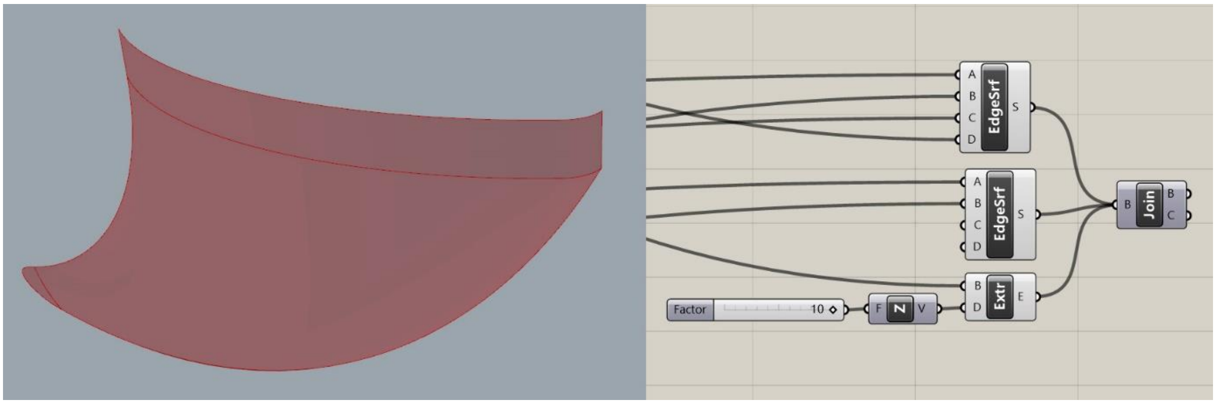

Figure 6. Grasshopper code and resulting 3D surface geometry for half the fin.

The final fin geometry commonly customized is the cant angle. In order to achieve this, the *Rotate Axis* feature was used to rotate the surfaces around the original base length line in both the negative and positive direction (for left or right sided fins). A large *box* was added in Rhinoceros with its' bottom face sitting on the origin, aligned with the fin systems. A *Solid Difference* feature was then used to subtract the material from the fin that intersected with the *box*. This left a perfectly aligned fin sitting below a fin system, and the two pieces could be joined together.

3.3 Customization Controls

Given the visual complexity of this parametric system in its entirety, shown in Figure 7, it would be unrealistic to expect someone without significant experience with Grasshopper to customize the surf fin. In order to make this system interactive for a surfer without any CAD experience, key sections of the algorithm were moved and arranged into a logical format, shown in Figure 8.

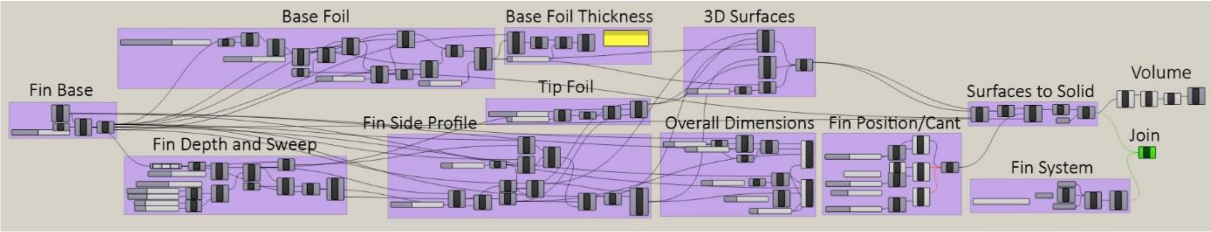

Figure 7. Complete Grasshopper code for the parametric surf fin.

Figure 8. User interface for customizing the surf fin.

A user is guided through a step-by-step process to customize the fin, beginning with the choice of fin system from a drop-down menu. This is linked to a *List Item* feature that allows only one of the fin system 3D models to be active at a time. The user can then select the position of the fin they want to design, whether it is in the center, on the left of the board, or the right. The selections are linked to a series of Boolean expressions that control whether the cant *Number Slider* activates, following the logic below:

if Fin Position = Left **then** Dispatch rotation: Number Slider "Cant (deg)"
else if
Fin Position = Right **then** Dispatch rotation: [Negative] Number Slider "Cant (deg)"
else
Dispatch rotation 0°

The number slider is constrained to a range of 0-20° to ensure the user only produces functional geometry, and when the center fin is chosen, a cant angle cannot be described as it must be vertical.

The third step allows the user to control the overall profile of the fin, as describe by Figure 3 and 4. This begins by defining the base length with a *Number Slider* constrained to a range of 50-200mm, followed by a fin depth range of 50-300mm, and a sweep angle of 5-90°. The overall *x* and *y* dimensions visualized within the 3D Rhinoceros workspace allow a surfer to gauge the scale of their design and compare to fins they use already, or modify from a previous design based on their requirements.

Lastly, the user can modify the fin foil at the base and tip. Two controls are used to define the base foil profile, being the radius of the leading edge, and overall curvature of the profile. An accurate measurement of the maximum thickness through the base foil is provided. Two more controls define the geometry of the foil towards the tip, including a *Number Slider* controlling how sharp it is, as well as the thickness which is constrained from 1-10mm. By limiting the number of controls to ten in this interface, surfers are encouraged to experiment and play with the design, with the complex code hidden from view. The constraints limit the possible geometry to those that are both functional as a surf fin, and practical to produce via 3D printing, removing the opportunities for errors such as self-intersecting geometry or non-manifold designs. At the end of the interactive space is a calculation of the volume of the fin, which does not include the fin system. This data can further assist in iteration and an understanding of the overall geometry, as well as being directly related to the amount of material required for 3D printing, and therefore cost. Future testing with surfers will evaluate the effectiveness of the chosen parameters, and the interactive mechanisms used to control them.

3.4 3D Printing Simulation

In order to provide surfers with an understanding of costs of 3D printed surf fins, geometrically different designs were exported as Stereolithography (STL, also known as Standard Triangle Language) files and pre-processed for FFF 3D printing. Cura (v4.6.1), a popular slicing software for many FFF 3D printers, was used to gather indicative data related to print times and material use using the settings outlined in Table 1. All fins were oriented laying parallel to the build plate as shown in Figure 9, optimizing the layer orientation for strength perpendicular to the forces of water [15]. This meant that support material was required using the settings shown in Table 1, and data included this material that would be removed as a waste product. Fin costs were calculated in Australian dollars ($AUD) based on the material used, assuming a cost for PETG filament of $50/Kg.

Layer height	0.25mm
Line width	0.4mm
Wall thickness	1.2mm
Top/bottom thickness	0.75mm
Infill density	20%
Infill pattern	Zig Zag
Print temperature	235°C (PETG)
Build plate temperature	75°C
Top/bottom print speed	30mm/s
Print speed	50mm/s
Travel speed	100mm/s
Build plate adhesion	None
Support Settings	
Placement	Touching build plate
Overhang angle	45°
Pattern	Zig Zag
Density	15%

Table 1. Cura settings used for slicing.

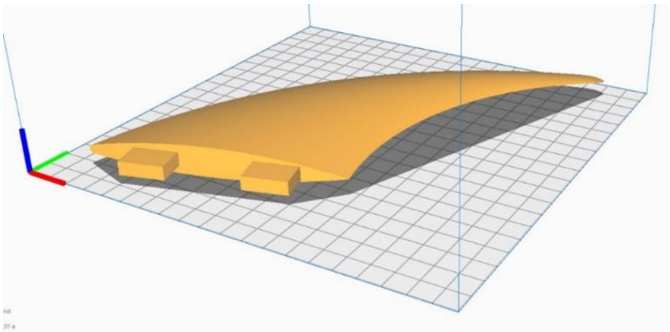

Figure 9. Print orientation of fins within Cura.

For comparison, the same fins were also uploaded to the service bureau i.Materialise to compare costs using Selective Laser Sintering (SLS) and Multi Jet Fusion (MJF), with one fin manufactured using SLS for physical test fitting alongside a FFF fin.

4 RESULTS

To evaluate the results produced by the system, and the validity of the 3D models, a range of ten virtual models were produced as shown in Figure 10. The results of slicing in Cura, as well as cost data for SLS and MJF 3D printing from i.Materialise, is shown in Table 2.

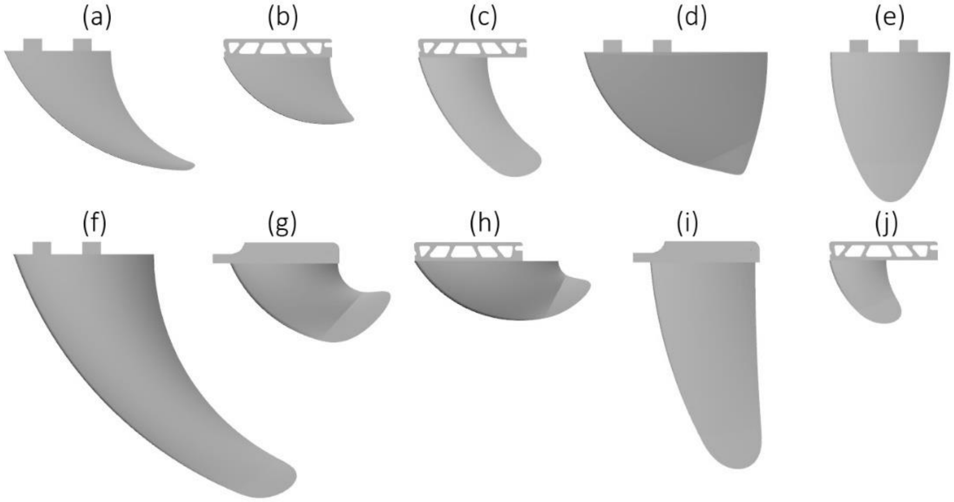

Figure 10. Several variations of surf fins.

Fin	Volume (mm^3)	FFF			SLS	MJF
		Print time (mins)	Material (g)	Cost ($AUD)	Cost ($AUD)	Cost ($AUD)
a	79731	191	56	2.80	37.53	60.39
b	54383	144	42	2.10	22.52	37.19
c	58027	200	60	3.00	33.13	57.82
d	257870	468	148	7.40	177.63	159.02
e	153218	321	98	4.90	95.14	95.59
f	627938	1026	347	17.35	319.76	399.30
g	150712	327	106	5.30	95.54	98.35
h	182760	371	121	6.05	106.80	107.88
i	168301	385	118	5.90	121.19	108.04
j	29716	92	25	1.25	20.78	27.65
Average	**176266**	**353**	**112**	**5.61**	**103.00**	**115.12**

Table 2. Comparative volume and costs of ten surf fins from Figure 10.

This indicative data shows that material costs for desktop FFF 3D printing range from $1.25-17.35 per fin, compared with $20.78-319.76 for SLS and $27.65-399.30 for MJF when sourced through a service bureau. The costs and material use will change depending on the specific process parameters chosen for each print technology, however, can be used as a guideline for surfers to compare to costs of commercial surf fins, or other methods of custom manufacturing.

Two fin designs were then 3D printed and mounted to a 2016 G-Whiz 9'4" SUP board from Slingshot Sports as shown in Figure 11, with one version produced on a desktop FFF machine (Wanhao Duplicator i3, Acrylonitrile Butadiene Styrene material), and another using SLS. Both fins were successfully used in flatwater ocean paddling conditions. Further testing is required to understand the material and mechanical properties of the fins produced via 3D printing, particularly under forces experienced in surf conditions, however, such testing was outside the scope of this parametric CAD study and will require extensive physical and simulation tests akin to those performed by Gately et al. [9].

Figure 11. Original 2016 G-Whiz Slingshot SUP center fin (left) compared with a similar version 3D printed using desktop FFF (2nd) and a version 3D printed using Selective Laser Sintering (3rd). Right image shows one of the fins fitted to the SUP board.

5 DISCUSSION

With evidence suggesting 3D printed fins are functional and comparable to commercially available fins [8, 9], what surfers will need in order to maximize this technology is a means to design and modify fins when they may not have the advanced CAD skills necessary to manually model the organic geometry of a fin. The indication from this study is that rapid iteration and customization of the 3D digital geometry necessary for 3D printing is possible using the parametric, algorithmic tools of Grasshopper within Rhinoceros. While the visual language of Grasshopper is rapidly learned by student product designers [16] and architects [3], further user testing is required to understand how surfers respond to the system described in this study. However, by linking the fin geometry to the principle features that surfers regularly use to describe and compare fins, and hiding all of the complex algorithms controlling the system, it is likely that surfers will engage through play and experimentation. Furthermore, online systems like Shapediver (https://www.shapediver.com) could be used to provide an experience more akin to online product customization platforms, removing the need to access Rhinoceros 3D and Grasshopper on a computer with reasonable processing hardware. This is part of the broader capacity for 3D printing to empower "prosumers" [1, 7, 18], a term used to describe people who both produce and consume products, bypassing traditional supply chains.

Combined with the need for materials testing mentioned previously, future development of the parametric design of surf fins could combine finite element analysis (FEA) and computational fluid dynamic (CFD) simulations to provide surfers with performance feedback about their 3D model as they make modifications. This may expedite the creation of desired surf fin properties without the time required for 3D printing and testing. However, it is likely that such feedback would not be provided in real-time due to the processing time required for computers to run such simulations, or require a much more advanced design system that utilizes pre-determined data for the range of possible designs from this system. It is also possible that any such data would not be advantageous, with surf fin arrangements, surfboard profiles, surf conditions and the unique surfing style of each individual highly variable, meaning that translating the data into valuable user-specific information would be extremely challenging. As previously discussed, surfers like to experiment with their equipment [5, 13] and typically rely on experience to inform their product choices, rather than data.

Finally, it is important to acknowledge that the range of possible surf geometries was constrained to those archetypal of surf fins, similar to the dorsal fin of a dolphin. While 3D printing provides opportunities for complex forms not manufacturable through traditional means [19, 21, 22], including lattice structures or geometries with undercuts, there is no evidence of such designs providing improved performance in watersport applications. However, this may be a limitation of both manufacturing capability and cost for conventional processes, and it is possible that the ability to 3D print surf fins opens a new era of experimental design in surf fin geometry, with designers building upon the parametric system described in this study to provide even more possibilities. This may be combined with machine learning capabilities.

6 CONCLUSION

This paper proposed a novel CAD system to customize the 3D geometry of surfboard and stand up paddle (SUP) board fins, featuring a simple interactive set of ten controls based on common features surfers use to describe fins. Specifically, the fin system, fin position on the board, cant, fin depth, sweep, base length, base foil profile, tip sharpness, tip thickness, as well as the overall dimensions can be customized within a constrained range of values that result in 3D printable geometry. The 3D visualization of the fin updates in real-time, and two results were 3D printed using fused filament fabrication and selective laser sintering technologies, and successfully fitted to a stand-up paddle board for initial functional testing.

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