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Comparison of Design Characteristics and Customization Protocols for Swimming Goggles

Jangwoon Park [1], Mehrube Mehrubeoglu [1], Jungyoon Kim [2] and Jaehyun Park [3,*]

[1] Department of Engineering, Texas A&M University-Corpus Christi, Corpus Christi, TX 78412, USA; jangwoon.park@tamucc.edu (J.P.); ruby.mehrubeoglu@tamucc.edu (M.M.)
[2] Department of Computer Science, Kent State University, Kent, OH 44240, USA; jkim78@kent.edu
[3] Department of Industrial & Management Engineering, Incheon National University, Incheon 22012, Korea
* Correspondence: jaehpark@inu.ac.kr; Tel.: +82-32-835-8867

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Abstract: Swimming goggles are important tools for swimmers; however, most of the commercialized swimming goggles are designed as one-size-fits-all, which may cause improper fit to a wearer's facial shape. The present study is intended to review and compare the design characteristics of the existing swimming goggles and the published customization protocols of swimming goggles. The detailed design characteristics of lens, strap, gasket, and nose bridge of 26 commercialized swimming goggles were reviewed, and the dimensions (length, width, and depth) of five swimming goggles are summarized in this paper. Next, the customization protocols of swimming goggles were investigated, which consisted of three major steps: first step involves collecting a wearer's 2D or 3D facial shape including eye and nasal root areas by using a hand-held scanner, and then using this scanned data to create a 3D contour shape of customized swimming goggles in a computer-aided design (CAD) environment. Second step requires the fabrication of the designed 3D CAD model of the customized swimming goggles by using a 3D printer using transparent and flexible materials. Third step includes conducting validation tests to evaluate the performance of the customized swimming goggles in terms of waterproofness and wearing comfort by comparing with the other existing goggles. To the best of our knowledge, this is the first paper that reviews the design characteristics of swimming goggles. The review results presented in this paper are particularly useful to develop not only swimming goggles, but also other types of wearable products such as safety goggles, military goggles, and any sort of sports goggles.

Keywords: ergonomic design; swimming goggles; 3D facial scan; wearable device; fit

1. Introduction

Swimming goggles are designed to be worn on a swimmer's face to not only improve visibility but also protect the eyes from harmful chemicals in swimming pools; however, swimming goggles that are not properly fitted at the contact points between the goggles and the wearer's skin can cause water leakage. Water leaking into the goggles would result in chemical irritants reaching the wearer's eyes, possibly causing eye irritation and other damage in the long term [1,2]. Similarly, water leakage causes the swimmer to lose visibility and requires the swimmer to adjust the swimming goggles while swimming [3]. Furthermore, wearing swimming goggles by fastening the strap with too much tension may compress orbital vasculature, which causes an elevation in intraocular pressure (IOP) [4]. Note that the continuously elevated IOP is a significant factor affecting glaucoma development and progression [5]. Ma et al. [6] suggested that swimmers should wear properly fitted swimming goggles with straps that are not overly tightened.

A few studies have been conducted to design swimming goggles to improve wearing fit by customizing the shape of the contacting surface using a swimmer's facial data. For the first time, Coleman et al. [7] introduced the design protocol of customized swimming goggles using a wearer's 3D facial scan. In addition, Coleman conducted a human subject experiment to evaluate the customized swimming goggles in terms of waterproofness and wearing comfort compared to existing one-size-fits-all swimming goggles. Park et al. [8,9] conducted a similar study, but they used a typical mobile camera, such as GoPro, to capture the wearer's 2D facial images without using an expansive 3D scanner. Scanning was followed by digital facial reconstruction using a commercial software tool (Agisoft Photoscan, Agisoft LLC, St. Petersburg, Russia), producing the wearer's 3D facial image based on the multiple 2D facial images taken at various angles. Park et al. reported that although the reconstruction process of the 3D facial image required at least one hundred 2D selfie images, the quality of the reconstructed 3D facial image, composed of point cloud data, was good enough to design the goggles to fit to the wearer's skin contours.

The previous studies showed potential ergonomic advantages and cost-effective production process of customized swimming goggles. However, research is still limited on the review of detailed design characteristics of the existing swimming goggles, such as shapes, materials, and dimensions. To the best of our knowledge, no research articles exist that compare design characteristics of swimming goggles. The objectives of this study include providing an extensive review and comparison of design features of the existing swimming goggles and the design protocol of customized swimming goggles. The results of this comparative study would be useful to designers, researchers, and manufacturers of swimming goggles.

2. Design Characteristics of Swimming Goggles

This section introduces the design characteristics of existing swimming goggles based on the review of the existing swimming goggles [10–35] as well as patents [36–38]. To understand design characteristics of the existing swimming goggles, 26 commercialized swimming goggles were analyzed in terms of their design features and dimensions (see Table 1). All the goggles were searched via Amazon.com, and their price range was from $3 to $75 USD (Mean = $21.54; SD = $17.62; min = $2.95; max = $75.00) which would cover typical swimming goggles for exercise as well as sports purposes. The selection of the compared swimming goggles was determined based on the availability of various commercial swimming goggles that users can easily access and purchase without any financial burden. Therefore, the price range of the compared swimming goggles was also chosen to cover various existing swimming goggles. We believe that these 26 swimming goggles are representative of most design characteristics of the existing commercial swimming goggles and formed a strong basis for comparison. The authors specifically analyzed design features, material characteristics of straps, lenses, and nose bridge designs of the goggles.

Figure 1a shows the summary of results of overall goggle design features. Out of the 26 swimming goggles analyzed, 21 goggles (81%) possess an anti-fog feature and 18 goggles (69%) have ultraviolet (UV) protection. On the other hand, only a few of the goggles include the anti-scratch (3 out of 26, 12%), hypo-allergenic (4 out of 26, 15%), and hydrodynamic design features (8 out of 26, 31%). More specifically, 75% of those eight hydrodynamic goggles possess flat lenses, 50% are designed with symmetric lenses, and 75% have double head straps. Figure 1b shows the review results regarding design characteristics and materials of head straps. Based on the review on the 26 existing goggles, all the head straps were designed to be adjustable; 69% of the goggles used double straps, and 31% of the straps were made of silicone. Silicone is being used to replace rubber which contains latex material that might cause allergic reaction in the skin. Figure 1c shows the review results regarding the lens of analyzed swimming goggles. 73% of the goggle lenses were designed in an asymmetric shape, 62% of the lenses were designed flat, while 38% of the lens were designed as curved shape. Finally, Figure 1d shows the design characteristics of nose bridges. 50% of the goggles have an exchangeable nose bridge. Most of the exchangeable nose bridges (12 out of 13) were made of plastic that do not allow any adjustments while the only one sample is made of a rubber which can provide better flexibility for a user's preference.

Table 1. Design characteristics of the 26 commercialized swimming goggles.

No	Model	Features	Strap/Material	Lens	Frame/Gaskets	Nose Bridge	Image
1	Sporti Antifog Swedish Goggle + Bungee Strap ($2.95)	- Pre-assembled with latex strap - Addition black bungee strap with goggle - Ant- fog - UV Protection	- Replaceable latex bungee strap (through the holes next to the eyepiece) - adjustable in the back to customize fit	- Clear - Flat	- Mounted to lens - No gasket	- Exchangeable	
2	Sporti Antifog Optical Pro II Mirrored Goggle ($8.95)	N/A	- Rubber - Adjustable	- Curved - Revo mirror	Mounted to lens, with rubber gasket	- Fixed and unexchangeable	
3	Speedo Adult 3PK Goggles ($16.87)	- G.O. Fit System: - Outer eye fit - Anti-fog - UV protection - Latex-free	- Silicone head strap	- Clear - Flat	- Gasket shape offers universal fit outside the eye socket with found in other Speedo goggles - Comfortable flex frame that moves with the face for a watertight fit	- Fixed and unexchangeable	
4	Amanzi Axion Mirrored Goggle ($20.00)	- Anti-fog - UV protection - Hydrodynamic design with sleek lens profile and minimal drag - Silicone/Plastic	- Dual head strap secures goggle firmly on head, for swimming or diving - Easy strap adjustment with dual hook clip to tighten or loosen.	- Multi-colored mirrored lens for outdoor swimming, or well-lit indoor pools	Soft silicone seal - for comfort around the eye socket - prevents leakage	- Interchange-able nose clip - Nose clip comes in three sizes for a customized fit: small, medium, large	
5	Sporti Antifog Cabo Mirrored Goggle ($6.95)	- Anti-fog	- Plastic/rubber - Adjustable - Double strap	- Clear- Blue in irregular shape	- Made of rubber connected to strap	- Fixed and unexchangeable	

Table 1. *Cont.*

No	Model	Features	Strap/Material	Lens	Frame/Gaskets	Nose Bridge	Image
6	Arena The One Jr. Goggle ($18.00)	- Anti-fog - Orbit-Proof Technology provides watertight fit around the eye socket - Seals avoid zones on any face that compromise suction	- Anti-fog - 50% Polycarbonate, 30% Thermoplastic Rubber, 20% Silicone	- Wide poly-carbonate lenses shaped for forward and peripheral visibility - Clear - pink	- Smart one-piece construction - embedded lenses and clips	- Fixed and unexchangeable	
7	Sporti Antifog Swedish Mirrored Goggle + Bungee Strap ($3.95)	- Anti-fog - UV Protection	- Comes pre-assembled with Latex strap - Additional black bungee strap with toggle - Easily adjustable to customize fit	- Mirrored lenses to further reduce glare - Flat	- One piece	- Fixed and unexchangeable	
8	Speedo Vanquisher EV Goggle ($21.99)	- G.O. Fit system offers a precision fit with the sleek, low-profile inner eye fit. - 20% more functional optical surface than its predecessor	- Rubber double strap - Adjustable	- Black - Flat	- Soft silicone gaskets	- Four (4) interchangeable nose pieces	
9	Sporti Antifog S3 Mirrored Goggle ($7.95)	- Anti-fog - Enhanced peripheral vision - UV Shield - Low-profile design - Hypo-allergenic (Latex and PVC Free) - Dynamic cuts to help slice through water	- Straps/Gasket: 100% Silicone - Double Silicone thin straps - Back buckle distributes pressure evenly for a comfortable fit	- Rubbing inside lens will damage the antifog performance - Shatter-resistant, poly-carbonate lenses - Lens: 100% Poly-carbonate	- Easy 90 degree locking system, for a secure andreliable fit - Lightly Softeril® gasket than S2 goggle for improved extended comfort	- Includes 2 sizes of interchange-able nose pieces for custom fit - Improved nose bridge design, to prevent contact with user's nose	

Table 1. *Cont.*

No	Model	Features	Strap/Material	Lens	Frame/Gaskets	Nose Bridge	Image
10	Zone 3 Vapour Polarized Revo Goggles ($45.00)	- Anti-fog - Extremely soft and flexible - 100% UVA/UVB protection	- Adjustable straps with twin piece head straps for a supportive fit	- Petrol colored polarized lenses curved to ensure superior vision in both light and dark conditions	- Ultra-soft eye pieces with flexible silicone.	- Fixed and unexchangeable	
11	Speedo Speed Socket 2.0 Mirrored Goggle ($31.99)	- Anti-fog - Retains classic Speedo Socket fit, but also offers increase peripheral vision - Hypo-allergenic comfort seals - UV protection	- Double head strap ensures a secure fit - Latex-free	- Mirrored lens reduces glare and brightness	- Wide panoramic vision - Inner Eye: - Provides a precision fit - The gasket rests snugly and securely on the eye socket.	- Fixed and unexchangeable	
12	Huub Brownlee Goggle ($48.95)	- Unparalleled clarity - Comes in a protective Brownlee casewith two additional straps as a tribute to the brother 2016 Olympic victories	- Three interchangeable split straps for comfort and facial pressure reduction	- Mirrored lens	- N/A	- Triple interchange-able nose bridge for optimum fit	
13	Speedo Futura Biofuse Flexiseal Mirrored Goggle ($27.99)	- Anti-fog - Biofuse technology - UV protected lenses block the sun's harmful UVA and UVB rays	- Speedo Fit clips for easy, precise adjustment - Soft silicone head strap - Latex-free	- Curved lens for optimal peripheral vision - Mirrored lens	- Flexible gaskets for added comfort and reduced pressure around eyes - Soft unibody frame - Outer eye fit	- Fixed and unexchangeable	

Table 1. *Cont.*

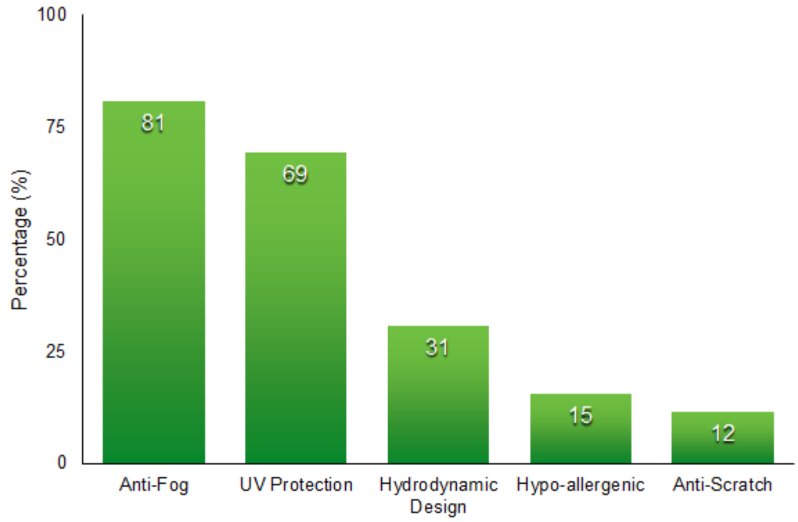
No	Model	Features	Strap/Material	Lens	Frame/Gaskets	Nose Bridge	Image
14	Speedo Fastskin Elite Mirrored Goggle ($75.00)	- Anti-fog - Developed as part of the world's first Racing System, engineering cap, goggles, and suit to work in harmony - Speedo's first true 3D goggle seal designed for real head and face contours - Improved seal leak resistance	- IQ Fit goggle strap is fully integrated one piece strap which eliminates dangling strap ends - Latex-free	- Hydroscopic Lens is a uniquelens shape offering an increased field of vision - Mirrored lens	- N/A	- Fixed and unexchangeable	
15	MP Michael Phelps Xceed Goggle ($16.87)	- Anti-fog & anti scratch - Exo-Core technology, combining two materials for maximum performance - Developed with Michael Phelps andBob Bowman - Expanded field of vision allows the swimmer to sight walls and the competition without altering head position	- Quick-adjusting, hydrophobic, and low-profile head buckle - Silicone, low-profile strap: For ideal grip and easy adjust	- Curved lens techno-logy: Wide, peripheral vision - Poly-carbonate lenses	- Anatomical gaskets: For comfort and feel - Semi-rigid exoskeleton maximizes the structure, strength, and stability of the goggle - Ultra-soft Softeril® gasket: For a water-tight seal and comfort	- Ergonomic, interchangeable nose bridge	
16	TYR Nest Pro Swim Goggle ($13.59)	- Anti-fog - Tight fit - Nest Frame Technology	- Head strap features Glide Clip system which allows easy on-head adjustment - Double VTS (Varied Tensile Strength) silicone head strap conforms to side of head while flat back straps allow for secure fit	- Wide peripheral Cellulose Propionate (CP) lenses feature embedded antifog properties and are UV protected	- TPR frame/gasket features dual injected system with over-molded nose bridge - Polypropylene over-mold nest frame provides unique high-tech structure design - Soft TPR gaskets for comfortable, water-tight fit	- Over-molded nose bridge	

Table 1. *Cont.*

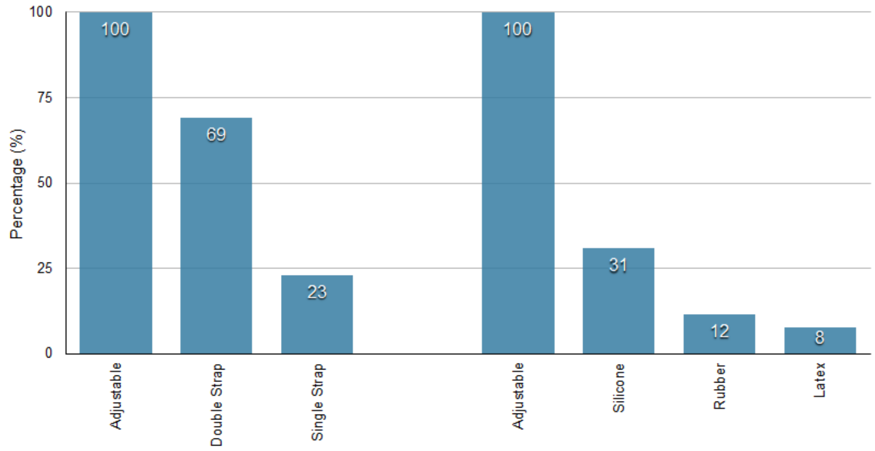
No	Model	Features	Strap/Material	Lens	Frame/Gaskets	Nose Bridge	Image
17	Speedo Vanquisher Optical Goggle ($21.99)	- Anti-fog - UV protection - Available in negative diopters −1.5 to −8	- N/A	- Polycarbonate lens	- N/A	- Interchangeable nosepiece	
18	TYR Tracer Racing Metallized Goggle ($10.69)	- Anti-fog - Sleek, low-profile design reduces drag - Improved light absorption and peripheral vision - UV protection	- Adjustable head strap with glide clip system	- PC lens - Spherical shape	- Soft TPR gaskets	- Includes five nose bridges for custom fit	
19	Speedo Speed Socket Mirrored Goggle ($17.57)	- Hypo-allergenic comfort fit - Low-profile design with great peripheral vision - Shatter resistant, polycarbonate lens with UV protection & anti-fog protection	- Silicone double length head strap for a more secure fit.	- Mirrored lenses to further reduce glare	- N/A	- High nose bridge with three sizes included for a custom fit	
20	Aqua Sphere Kayenne Goggle Smoke Lens ($21.95)	- 100% UV protection - Anti-fog - Scratch resistant lens	- One-touch, Quick-Fit Buckle for simple adjustments	- Oversizedultra-durable Plexisol® lens for 4-point expanded and 180-degree visibility	- Hypoallergenic Softeril® one-piece, hydrodynamic micro frame	- Stabilizing nose bridge keeps fit secure and comfortable	
21	Aqua Sphere Kaiman Goggle Clear Lens ($17.94)	- Anti-fog coating - Ultra violet (UV) protection	- Adjustable strap for custom fit	- N/A	- Fits adult faces - for small and medium faces, fits around the outside of eye socket - Super soft skirt engineered for comfort and watertight seal	- N/A	

Table 1. *Cont.*

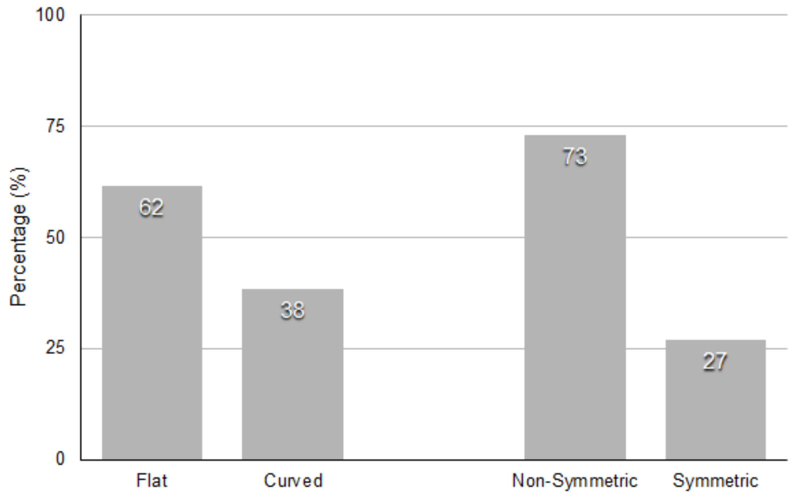
No	Model	Features	Strap/Material	Lens	Frame/Gaskets	Nose Bridge	Image
22	Arena Cobra Ultra Mirror Goggle ($60.00)	- Anti-fog - UV protection - Hydrodynamic design	- Dual strap - Silicone	- Hard lenses - Mirrored - Polycarbonate	- Extra-wide vision - Forward vision - TPE	- Interchangeable nose bridge	
23	Nike Swim Chrome ($7.20)	- Universal fit - Anti-fog - UV protection - Ideal for training	- Latex split strap	- Polished PC lens	- TPE gasket	- Six-way adjustable nose piece	
24	FINIS Energy Goggle (11.99)	- Great for all face shapes - "So More Can Swim"	- Silicone strap	- Curved lens for reduced distortion and optimal viewing	- Soft TPR frame	- N/A	
25	Zoggs Racepex Goggle ($9.75)	- Anti-fog solution for clear vision	- Quick adjust strap	- N/A	- flared silicone seals for comfort - Adjustable frame	- Four different nose bridge sizes	
26	MP Michael Phelps K-180 Goggle SmokeLens ($14.06)	- K 180 version goggles: 180 degrees of panoramic vision - 100% UV protection	- Integrated strap loop to help it stay hydrodynamic - Head strap is easy to adjust for the right fit.	- Curved Smoke lens - Anatomic lens shape for a comfortable and water-tight fit	- Ultra-soft gasket: 100% Softeril® material for a leak resistant and comfortable seal	- Three interchange-able nose bridge pieces for the right fit	



(**a**) Design features

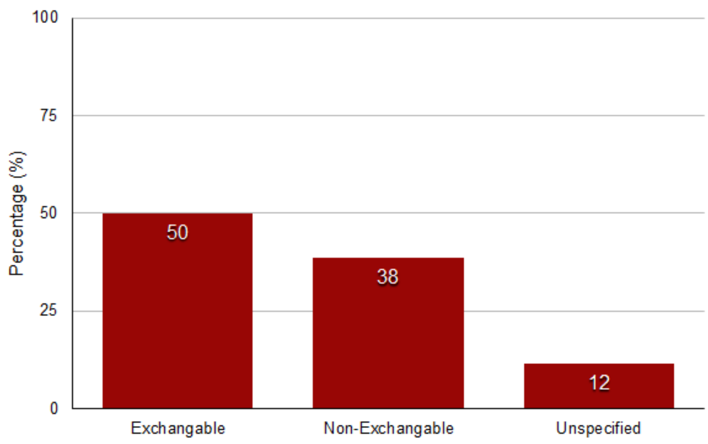


(**b**) Design characteristics of the head straps



(**c**) Design characteristics of the lens

Figure 1. *Cont.*



(**d**) Design characteristics of the nose-bridges

Figure 1. Comparative results on 26 existing swimming goggles.

To understand the range of dimensions of existing swimming goggles, we purchased five swimming goggles among the 26 swimming goggles reviewed. The dimensions (length, width, and depth) for each component (nose bridge, frame, and gasket) were measured by a caliper in each of the axes of the XYZ coordinate systems as shown in Figure 2. The measurements are summarized in Table 2. The vertical average width of the lens measured from top to bottom in y-direction was 31.6 mm (standard deviation (SD) = 4.4). The horizontal average length measured from left to right of the lens in x-direction was 50.3 mm (SD = 7.9). Similarly, to the dimension of frame, the average width was 143.2 mm (SD = 11.2), and the average length of the frame was 40.1 mm (SD = 2.7). The nose bridge was measured for its length and width as shown in Figure 2. The average of the nose bridge was 26.5 mm (SD = 3.6) for length, and 7.9 mm (SD = 2.5) for width. The gasket was measured for its depth and its average was found as 10.0 mm (SD = 3.6). These dimensional information (Table 2) was used to design new swimming goggles in a CAD software.

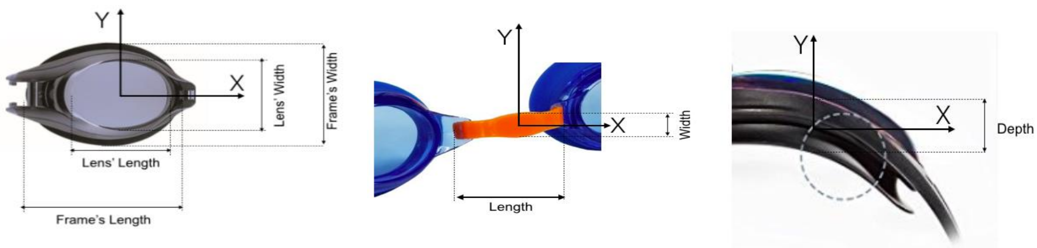


Figure 2. Dimensions of lens, nose-bridge, and gasket of swimming goggles [9].

Table 2. Dimensional measurements of the existing swimming goggles (W: width; L: length; D: depth; unit in mm).

Existing Swimming Goggles (Model Names)	Lens		Nose Bridge		Frame		Gasket
	W	L	W	L	W	L	D
Model #1	27.0	40.1	26.0	7.9	135.6	38.7	5.8
Model #2	35.8	56.8	25.0	7.0	147.2	43.0	13.8
Model #3	36.4	57.5	28.0	6.8	137.7	43.0	13.8
Model #4	27.5	53.1	31.6	12.2	161.0	37.2	9.0
Model #5	31.4	43.8	22.0	5.7	134.3	38.6	7.8
Mean	31.6	50.3	26.5	7.9	143.2	40.1	10.0
Standard deviation	4.4	7.9	3.6	2.5	11.2	2.7	3.6

Shau [36] patented a light reflector for the user to see any obstacles, such as the edge of the swimming pool, during a backstroke without having to turn the head from its normal position. The light reflecting function is offered by backstroke viewing windows at the top side of each eye socket. The backstroke viewing window stands vertically while the user faces the water surface. The windows can be disposed of and switched into a regular forward viewing window. The design of this patent comprises two eye sockets connected by a single head strap. The eye sockets are mounted to the suction socket which is made of rubber and has water leakage. Both eye sockets are connected by a single head strap and inserted by viewing windows which are made of transparent plastic.

Chiang, in his invention [37], aimed to improve the structure of swimming goggles, especially the nose bridge. The inventor enhances the comfort of wearing the swimming goggles by attaching a soft protective pad onto the nose bridge. The soft pad could be made of a rubber sponge, plastic, or thermoplastic rubber. The soft pad under a nose bridge behaves as support and it can be a single piece or fastened to the frame. The design comprises two frames, two lenses, a nose bridge combined with a soft protective pad and joined to frames, and a double head strap. The soft protective pad is assembled with a connecting unit or nose bridge by accommodating a groove.

Van invented a patented design to reduce hydrodynamic drag and optical distortion in swimming goggles by eliminating the connection unit and head strap [38]. The inventor attempts to keep the lens flat to prevent distortion that might occur due to water pressure, even though this can cause an increase in hydrodynamic drag. The purpose of decreasing drag force is to maintain the swimmers' speed without having the drag force against the lens. For further improvement, the inventor minimizes the anterior-posterior depth of the eyepiece's profile which allows water to flow over easily. Minimizing the profile depth means moving the eyepieces closer to the user's eyes, which typically enhances the user's vision under water. The patent design specifies that the eyepieces must have depth less than or equal to 8 mm. The design comprises a transparent material with a peripheral frame for each eyepiece. Each frame has a posterior surface for attaching the eyepiece onto the user's skin. The design has no nose bridge or head strap, but relies on the adhesive surface or tape.

Apex compared the weight of goggles that are made of two different materials, polycarbonate (PC) and polyamine-66 (PA-66) [39]. Apex reported that light weight swimming goggles are important especially among competitive swimmers. For example, Apex mentioned that the swimming goggles, New Carbon Race™, was made of PA-66, instead of PC, and the goggles showed 12–15% less weight compared to other common swimming goggles that were made of polycarbonate.

When goggles are worn, there develops a pressure inside the goggle based on the surface area. Morgan et al. [3] developed a method to measure the amount of pressure that forms around the eye, known as intraocular pressure. This pressure can cause biological damage if it gets too high. The article forms a predictive model that determines an expected IOP on the wearer's face. IOP is a significant contributor to glaucoma and people who are at risk of glaucoma are advised to avoid smaller eye goggles, which, in the article's findings, exhibited the highest change in IOP among all the goggles. Considering the amount of pressure any new design will create, it was important to make sure that the goggles we designed also did not cause injury.

Between the suction and pressure, there are a list of adverse side effects. Diplopia, or double vision, is one said side effect. A human's eye movement is controlled by six muscles; four rectus muscles that allow the eyes to move up and down, as well as side to side, two oblique muscles which give added support to the rectus muscles, and the superior oblique which "ties" to a tendon called the trochlea located near the nose. This pulley-like tendon serves to aid the attached muscle in stability of the eye's movement. Improperly fitted swimming goggles can put undue pressure on this tendon, causing the user to experience severe double vision and pain [40]. The padding serves to seal the eyes from the environment of the pool, however seals are known to fail over time and can sometimes lead to high pressures on the eyes, making the wearer uncomfortable. The proposed design seeks to eliminate the need for a padding between the eye and goggles by designing the swimming goggles with the wearer's facial contours.

3. Design Protocols of Customized Swimming Goggles

This section introduces the design protocols of customized swimming goggles based on the detailed review of recently published papers [7–9]. The papers were based on the authors' previous bodies of work conducted from 2017 through 2019. The customization protocols of swimming goggles in the published papers consist of the following five steps (see Figure 3): first, ergonomic issues and limitations of the existing swimming goggles were identified. Second, design concepts were generated by brainstorming or benchmarking to resolve the identified ergonomic issues of the existing swimming goggles. Third, watertight swimming goggles were designed based on the wearer's 3D facial scan data to incorporate the generated ideas. Fourth, a working prototype was fabricated using a 3D printer. Finally, fifth, the fabricated swimming goggles were validated in terms of ergonomic performance compared to other swimming goggles. The following paragraphs provides more details and insights for each of the design steps.

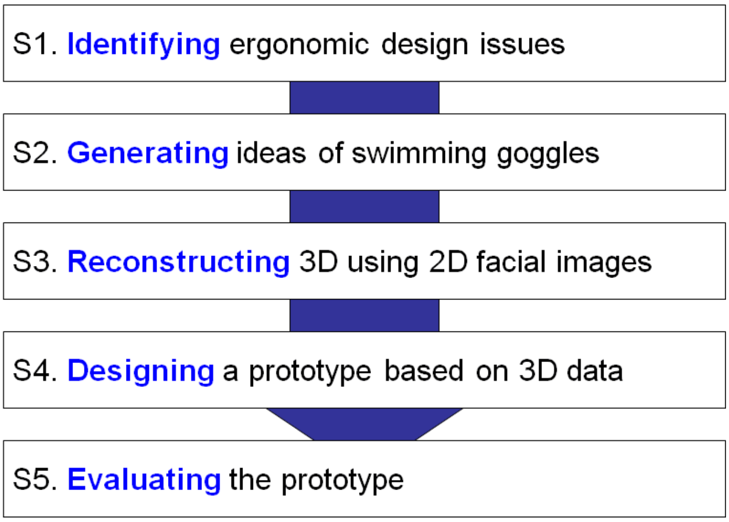


Figure 3. The five-step design protocol of customized swimming goggles.

In the first step, the ergonomic problems or design issues of the existing swimming goggles were identified. Coleman et al. conducted benchmarking as well as a questionnaire-based survey with professional swimmers in the local area to collect feedback on the existing swimming goggles worn and issues encountered [7]. Park et al. conducted a literature review to understand the current research status of swimming goggles, relevant patents, and the materials and design features of swimming goggles [8,9]. The group reported six ergonomic issues of the existing swimming goggles: (1) improper fit, (2) high pressure on eyes, (3) leaking water, (4) reduced visibility due to fog, (5) poor customization and adjustability of the strap, and (6) uncomfortable to wear.

In the second step, design ideas were generated by brainstorming or benchmarking based on the existing products. The design requirements included fitting the goggles to the dimensions of a wearer's facial scan, not having any leaks in the frame, as well as having a drag coefficient lower than or comparable to the existing swimming goggles. In addition, the design included a flexible nose bridge for better adjustability and fit as shown in Figure 4.

In the third step, customized swimming goggles were designed in a CAD environment based on the measured 3D facial scan data and the generated design concepts. When capturing a wearer's 3D facial scan, Coleman et al. [7] used a hand-held 3D scanner (Sense 3D scanner, 3D SYSTEMS INC., Rock Hill, SC, USA; see Figure 5a). The 3D hand-held scanner allows efficient measurement of high-resolution 3D facial scan data. The measurement time was less than 10 s, the resolution of the 3D facial scan file was 69K vertices, and the type of the scan file was in Polygon file (PLY) format. However, the cost of the 3D hand-held scanner varies and the price is relatively high compared to a

2D camera (the range of 3D hand held scanner price can range from $500 to $20,000 USD depending on its measurement quality), and the 3D scanner is not easily accessible to the general public, nor it is portable. For these reasons, Park et al. [8] used a typical mobile camera to measure a wearer's 3D facial data (Figure 5b). Park et al. used a GoPro 2D camera, which can capture several 2D selfie images at different angles, and then reconstruct a 3D facial features with the 2D images using a 3D image reconstruction software (Agisoft Photoscan, Agisoft LLC, St. Petersburg, Russia) by aligning the 2D images appropriately. Note that before conducting any human subject research including surveying and measuring facial scan, an experimental protocol must be approved by Institutional Review Board (IRB). The work conducted by Park et al. [8] was approved by the IRB at Texas A&M University-Corpus Christi prior to the start of the work (IRB ID: NHS 19-19).

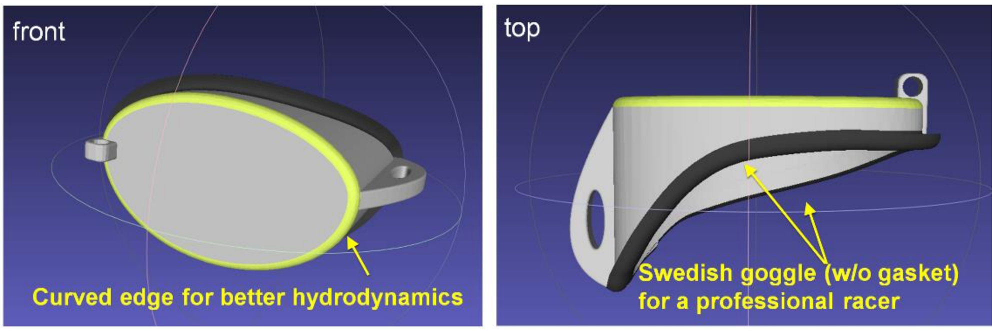
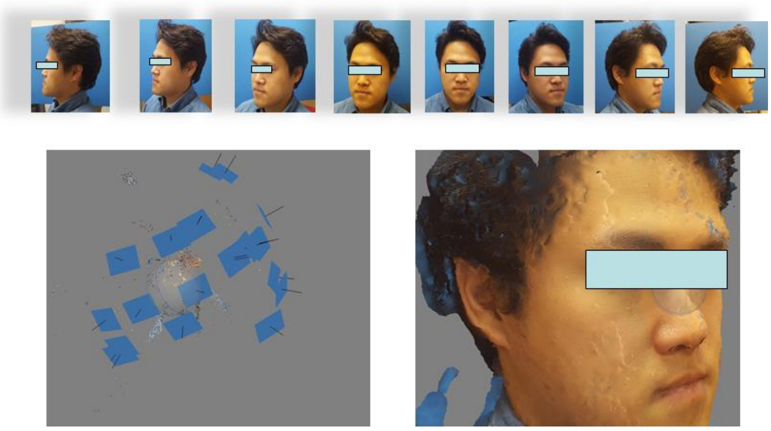


Figure 4. The generated ideas for the customized swimming goggles based on the brainstorming [9].

(**a**) Capturing 3D facial scan using a hand-held 3D scanner [7]



(**b**) Reconstructing a 3D facial image based on multiple 2D images captured by GoPro [8]

Figure 5. Measurement and reconstruction of a wearer's 3D facial images.

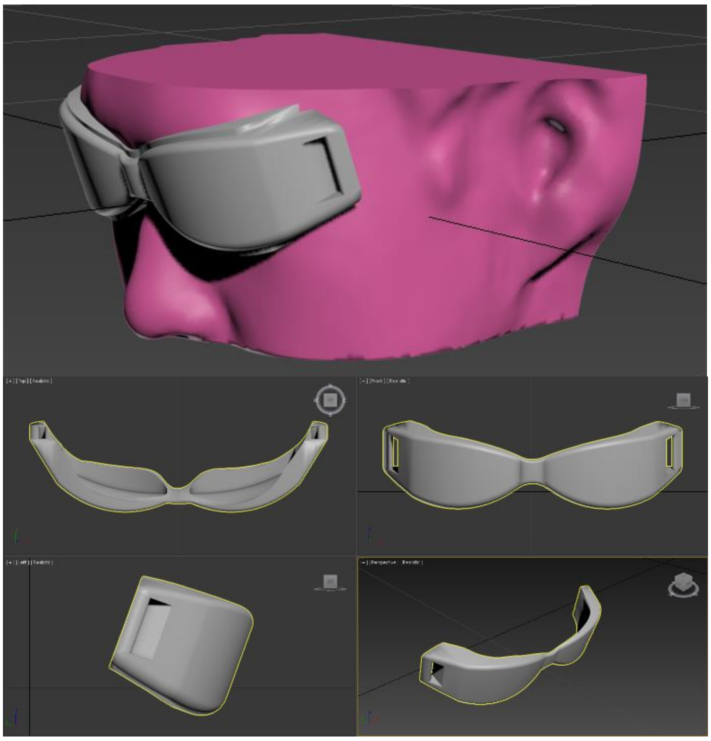
The requirements for the designed swimming goggles are listed as follows: the design must use the 3D facial scan data. In addition, the goggles must prevent water leakage when the swimmer is wearing them. The material used to create the swimming goggles must be comfortable to the user and must have a stable construction (if the swimming goggles are not stable there can be water leakage, or the goggles may crack from the pressure of the water). The goggles' lenses must be clear and visible for the wear while maintaining safety standards. The overall design must improve the quality of the swimming goggles for the wearer.

The design specifications for the swimming goggles were constructed with the help of the following computer software programs: AutoCAD (Autodesk, Inc., San Rafael, CA, USA), Inventor 2016 (Autodesk, Inc., San Rafael, CA, USA), and 3Ds Max (Autodesk, Inc., San Rafael, CA, USA). Using the 3D facial scan data, the goggles were made to fit uniquely to the face of the scanned individual. The swimming goggle dimensions depended on the 3D facial scan data. The depth, height, and length also depended on the person's facial features. The material used to construct the custom swimming goggle design was VeroClear [41], and bungee material was used for the strap.

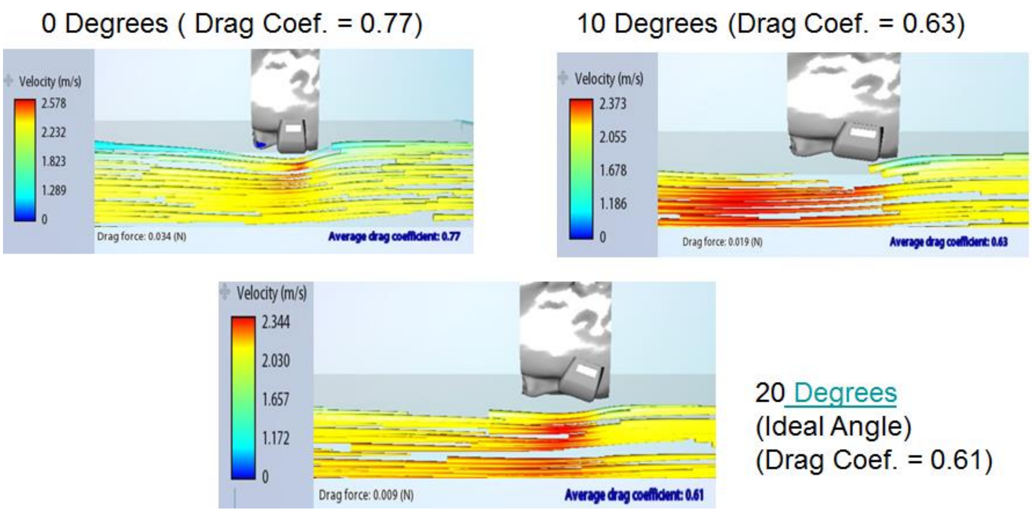
In this step, the inner shape of the swimming goggles was designed to match the contact surface of the wearer's facial scan, so that the inner shape of swimming goggles would fit perfectly to the wearer's skin. By considering the wearing positions of existing swimming goggles, the 3D shape of the wearer's eye region scan data was used to design the inner shape of customized goggles. Coleman et al. [7] used the 3D shape of the wearer's nasal root area to design the shape of nose bridge using Autodesk Inventor Professional 2016 (Autodesk Inc., San Rafael, CA, USA) and created the 3D model of the customized swimming goggles (see Figure 6a). The final design had a seal between the wearer's face and swimming goggles and leakage prevention was determined by the contact between the goggles and the wearer, and how well the contours of the swimming goggle matched the contours of the wearer's face. The custom swimming goggles were curved to increase the swimmer's visibility when swimming. In addition, the dimensions of the swimming goggles were determined based on brainstorming for design ideas as well as benchmarking results from existing swimming goggles (Table 2). The generated design by Park et al. [9] included 0.25 mm fillet radius that helps to reduce the drag force by spreading the distribution of pressure. The geometry included curve and edges. The design had a maximum diameter of 2.2 mm for the nose bridge holder and 5.4 mm for the head strap coupler. The thickness of the design was 2.0 mm for the eyecup and 1.6 mm for the coupler. The lowest depth was 7.6 mm while the tallest depth was 20.8 mm. The width of this design was 37.9 mm.

The shape of the lens was also designed to minimize the drag force while swimming (see the hydrodynamic simulation results in Figure 6b). The program, Flow Design (Autodesk, Inc., San Rafael, CA, USA) was used to determine the drag force and drag coefficient of water acting on the design by simulating water flowing across the design at various angles. By taking the average speed of a swimmer, the simulation shows the drag force and drag coefficient in real time. The angle at which the goggles are fixed on the user's face effects how large or small the drag force and coefficient is. By using this data, the authors can find the ideal angle the goggles should rest on the wearer's face in order to reduce the potential drag force and coefficient.

The program determined drag coefficient and drag forces acting on the goggles while swimming at 2.2 m/s. As shown in Figure 6 the ideal angle the goggles should be at is 20 degrees, because at 20 degrees the goggles provide the least amount of drag force and drag coefficient. This simulation provides insight on how much drag force will be applied while swimming, and the optimal angle to produce the least amount of drag force, reducing the likelihood of the goggles to fall off.



(**a**) Design of a 3D model of the customized swimming goggles with the wearer's 3D facial scan [7].



(**b**) Hydrodynamic simulations to minimize drag forces [7].

Figure 6. Design and evaluation of the 3D model of customized swimming goggles.

In the fourth step, the designed customized swimming goggles were fabricated by using a 3D printer. In this prototyping stage, either hard or soft materials can be used to create the prototype. Coleman et al. [7] used a hard material for fabricating the swimming goggles (see Figure 7a). The prototype was all one piece printed entirely from polycarbonate material. On the other hand, Park et al. [8] used soft material (see Figure 7b). Ninja Flex and polycarbonate materials were used for the goggle gasket and lenses, respectively. For the 3D printing, Park et al. [8] used LULZBOT TAZ 6 (Aleph Objects, Inc., USA), which enables printing with various materials including nylon and polycarbonate.

(**a**) One-peace prototype [7] (**b**) Two-peace prototype [8]

Figure 7. The fabricated working prototypes of the customized swimming goggles.

In the fifth step, the fabricated swimming goggles were evaluated by comparing with other swimming goggles. Coleman et al. [7] conducted a swimming pool test to compare the developed and existing swimming goggles in wearing comfort, leakage, visibility, in-water maneuvers, and fit with standing dive into water (see Figure 8). The subjective evaluations were completed using the 5-point Likert scale (1 = not satisfied, 5 = very satisfied). In addition, the water leakage was evaluated in the swimming pool by measuring the amount of leaked water. Even though the testing was done by one participant, it is an exploratory result, helping the authors focus on improvements in the next iteration of this protocol.

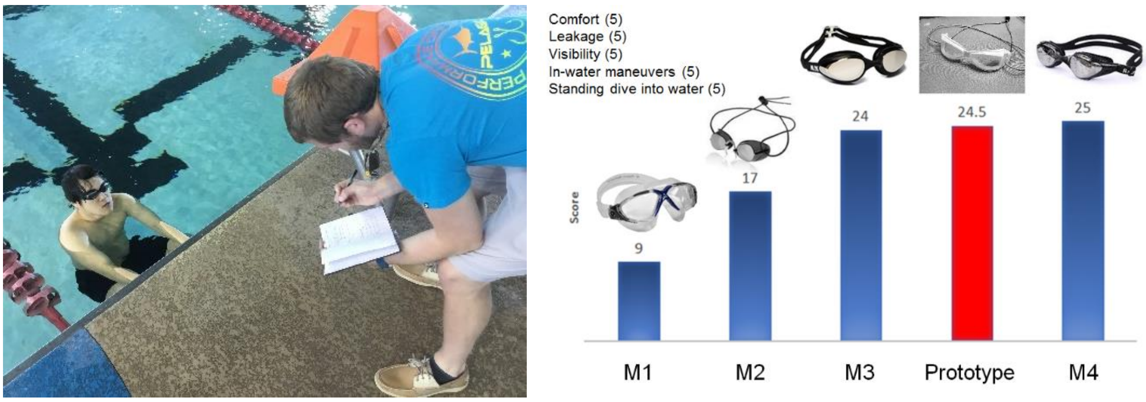


Figure 8. Evaluation of the customized swimming goggles compared to the existing swimming goggles. The bar chart shows total subjective ratings of each of the goggles across all subjective evaluation criteria.

4. Discussion

In the present study, an extensive review was conducted on existing swimming goggles in terms of design, materials, and dimensions. The identified design features of the existing swimming goggles will be useful when designing customized swimming goggles and optimizing parameters for usability and minimal eye pressure.

The price of commercial swimming goggles varies based on the design, physical properties, and the ability of the goggles to provide comfort. The price range is typically from USD $3 to $75. However, there is only one company which provides customized 3D printed swimming goggles based on a wearer's facial data, TheMagic5™ Inc. (North Carolina, USA) [42] is accessible online though a phone application for both Android and iOS systems. TheMagic5 produces individual swimming goggles using 2D facial scan. The lowest price offered by TheMagic5 is $54.

The customized design protocol was intended to improve the user's comfort during swimming and reduce drag. Coleman et al. [7] measured a wearer's 3D facial data using a 3D scanner. However, in general, 3D scanners are not easily accessible because of the high cost and additional software installation required on a computer to visualize the captured 3D facial features. The main outcome of the work by Park et al. [8] was a protocol for designing custom-made swimming goggles using multiple self-captured photos from any off-the-shelf camera or a camera on a smart device to create 3D facial scan data. A typical 2D camera used by Park et al. is more easily accessible than a 3D scanner; therefore, the data collection process has been made more user-accessible and easier than what was presented in the Coleman et al. Even with the reduced cost of 2D facial scan data collection, data analysis and 3D facial data reconstruction still requires a licensed software tool (Photoscan), and is not free; therefore, as part of the future work, the team plans to develop a free mobile application that can construct 3D facial data from a number of 2D selfie images. The simulation results in Coleman et al. showed that 20 degrees with respect to horizontal can provide reduced drag force and drag coefficient compared to other angles (0° and 10°; see Figure 5). The simulations provide an insight into how much drag force will be applied while swimming; the angle with the least amount of drag force will make the goggles less likely to fall off and more efficient during swimming.

Although the one-piece style prototype created in Coleman et al. was functional, it did not have seals potentially creating user discomfort over long-term use in the water despite perfectly fitting to the contours of the user's face. Another major shortfall was the less-than-optimal comfort experienced by the user in the nose area, because the nose bridge of the goggles was rigid. The final major challenge of the one-piece design involved the polycarbonate being printed on a surface that was not ideal for printing clear material. Since the entire design was one solid piece printed entirely of polycarbonate, it was not very cost-effective, as polycarbonate is more expensive than most other printing filaments. To address these issues, the design in Park et al. [8] was improved by converting the goggles into a two-piece design, where the lenses and frame form separate parts with different materials. The protocol required a seal to be created, followed by a nose bridge that was made of a more flexible material to allow the goggles to have some flexibility to decrease applicable stress and increase user comfort.

The prototyping protocol created for the soft material has two improvements compared to the hard material protocol: first, in the case of the hard material, it is difficult to secure the wearer's comfort at the points of contact because of limited flexibility of the hard material. By using the soft material, it is possible to increase the wearer's comfort in the area of contact with the goggles because of better flexibility of the soft material. Second, hard material does not accommodate skin movements and deformations around eyes, whereas the soft material has the advantage of being able to accommodate skin movements around the eyes more effectively.

We conducted the experiment with one participant. The participant chosen was an accomplished swimmer who would be available over the three years of iterations of this study and who would be able to provide feedback on the improvements of the goggles. The opinion of this competitive swimmer was used as a standard for comparing multiple goggles. It should be noted here that there are two main reasons for recruiting one participant, one of which included budget constraints for the pilot studies to develop a working prototype. Generally, prototyping one unique goggle costs around 300–500 USD in materials, and around 900 h in labor (5 individuals × 5 h per week × 9 months). The second main reason was based on the developers' project timeline that required each iteration of the prototype including development and testing to be completed within one year. With more budget and time, the number of participants could be increased for statistical analyses. However, we believe that by keeping the tester the same, we were able to validate the functionality of the developed prototype through improvements over three-year iterations.

The present study advances the scientific merit in designing swimming goggles by incorporating the virtual design and validation protocols. First, to the best of our knowledge, this study is the first research that uses an individual's 3D facial anthropometric data to design swimming goggles by matching the 3D shape of nasal bridge and eye regions with the inner shape of the custom-made swimming goggles. Second, the presented hydrodynamic simulations for the swimming goggles have never been published elsewhere. The proposed validation protocol combines software simulations as well as physical tests to find an optimal design as well as quantitatively evaluate the hydrodynamics of the swimming goggles. In addition, this simulation protocol is a safe way to validate goggles compared to a typical human subject experiment. Apparently, it would be impractical to ask any participant to test goggles' hydrodynamics in the water. In conclusion, by effectively designing goggles using the individual's 3D anthropometric data and using the simulation tool, the authors qualitatively and quantitatively validated the goggles. The presented work could be used as a reference for further studies to develop any kinds of custom-made goggles, not just swimming goggles, that include other types of eye wear and devices.

5. Conclusions

The developed design protocol can be applied to improve the fit of other types of wearable products, such as hats, snorkeling gear, suits, and industrial safety goggles. By applying the proposed protocol, custom designed swimming goggles that match the contours of an individual's face can be created by mass-customization production protocol, which is expected to reduce the production cost for customized goggles. The identified features from existing goggles provide an insight of preferred features that can be exploited in new ergonomic designs for facial wearable products.

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