Biomimetic Shark Skin Textile Design for Enhanced Hydrodynamic Drag Reduction.

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I. INTRODUCTION

Hydrodynamic drag force is the resistance that fluid exerts against an object moving in the opposite direction. It comprises form drag, wave drag, and friction drag [1], with form drag accounting for 70–90% of the total drag and up to 90% of the energy expenditure in competitive swimming. Shark skin has a microstructure known as dermal denticles, which offers a promising solution, as their riblet-like patterns generate streamwise vortices, delay flow separation, and reduce drag by up to 10% [2]. Despite advances in sharkskin biomimicry, its applications in textiles remain limited. In particular, there is a lack of systematic investigations into denticle design and the optimization of their parameters through numerical simulation. This specific research domain has not yet been adequately explored, even though it holds strong potential to enhance drag reduction in textile applications. In this study, the applicable criteria derived from such investigations will be identified and used to fabricate prototypes, which will then be validated for performance.

II. LITERATURE REVIEW

Drag is influenced by factors such as velocity, size, fluid density, viscosity, and flow conditions. The Reynolds number characterizes flow regimes by comparing inertial to viscous forces, where high values, typical of fast swimmers, induce turbulent flow and vortices that increase drag [1][3][4]. Additionally, surface roughness affects boundary layer dynamics and turbulence, impacting both frictional and pressure drag[3]. Minimizing drag is critical for competitive swimming performance, the optimization of fabric design for drag reduction remains a complex challenge due to the intricate interactions between fabric properties and fluid dynamics.

A. Current Advancements in Drag-Reduction Textiles

Advancements in drag reduction technologies for athletic fabrics have significantly enhanced performance in swimming and triathlon sports. Optimized surface structures, such as those in TYR Sayonara and Speedo LZR suits, have demonstrated drag reductions up to 15%, with full-body suits achieving 6.9–12% reductions depending on fabric type and bodysuit design [5]. Shark skin-inspired technologies like Speedo's Fastskin contribute to drag decreases between 6.2% and over 10%, improving swimmer velocity and efficiency [6]. Additionally, triathlon wetsuits and speed suits reduce drag by 5.2–14% contingent on swimming speed, while advanced nanoparticle coatings and hydrophobic finishes further enhance fabric performance by lowering surface energy and friction, achieving up to 1.5% drag reduction and measurable improvements in race times [7]. Speedo's Fastskin™ swimwear, introduced in 2000, utilizes advanced weaving techniques to produce riblet-like surface structures with fine grooves that dynamically adjust under stretch, effectively reducing water flow friction. The LZR Racer full-body suit features a patented design that provides extensive body coverage, trapping air to enhance buoyancy when worn loosely, although the fabric itself does not inherently increase buoyancy. Therefore, Speedo's drag reduction results from both fabrication methods and innovative suit design.

B. Biomimicry of Shark Skin for Drag Reduction

Shark skin reduces drag through specialized dermal denticles featuring riblet-like microstructures called miniscule placoid scales or denticles that generate streamwise vortices, stabilize near-wall flow, and delay flow separation, thereby enhancing hydrodynamic efficiency and lowering friction drag [4] [5]. Additionally, the tooth-like surfaces of the denticles create dynamic micro-roughness that stabilizes the near-wall flow field, increasing the viscous sublayer's thickness, dampening velocity fluctuations, and lowering Reynolds shear stress. This results in lower friction coefficients compared to smooth surfaces. Therefore, the synergy of vortex generaenhancecro-roughness, optimal denticle size, and advanced structures enhances fluid flow on shark skin, reducing drag.[9][10]

Denticle patterns show remarkable variation across the same shark's body regions, impacting hydrodynamic efficiency. Studies on a shortfin mako (*Isurus oxyrinchus*) from Pacific waters near Taiwan examined four regions: flank abdomen, tail abdomen, pectoral fin, and caudal fin, to evaluate denticle differences. Denticles on the tail abdomen measure about 164.5 µm in length and 85.7 µm in width, with a high density of 118.8 denticles/mm², while flank abdomen

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denticles are around 17.11 µm in length and 98.88 µm in width, with a density of 125.35 denticles/mm². Roughness in these areas shows that larger abdomen denticles and almost double the roughness of those on the fins, enhancing hydrodynamic properties. While fin areas have smaller denticles and thus lower surface roughness, they experience relatively higher drag due to denticle density and other influencing factors. Overall, the abdomen regions of the shark skin, with their larger, rougher denticles, serve as the primary zones for drag reduction.

C. *Optimized Parameters for Biomimetic Sharkskin Drag Reduction*

Optimizing biomimetic sharkskin parameters is critical for effective drag reduction in engineered surfaces. Studies show that natural shark denticle sizes range between 157.3 µm and 899.3 µm, while biomimetic denticles larger than 2.1 mm have been found ineffective in reducing drag. Research has primarily focused on denticle shapes featuring either three or five ridges, both of which exhibit significant potential for hydrodynamic improvement. Among orientation patterns, the staggered overlapped design has demonstrated superior performance, achieving speed increases of up to 38.5% compared to linear overlapped and non-overlapped configurations. Moreover, the relationship between denticle height and spacing plays a pivotal role, with optimal drag reduction observed when denticle height is approximately half the spacing between ridges. In terms of riblet shapes, the scalloped riblet offers the best compromise between drag reduction (6.5%) and durability, outperforming sawtooth and blade designs, although the blade riblet achieves the highest drag reduction at 9.9% but lacks long-term durability [8].

D. *Previous CFD Analysis*

To investigate the hydrodynamic effects of sharkskin-inspired surfaces, research has primarily focused on numerical simulations of ship hulls rather than textiles. The implementation of a newly designed blade-type riblet structure achieved a 3.75% reduction in drag coefficient and a 3.89% decrease in total drag force acting on the vessel [11]. Another study employing a discontinuous trapezoidal riblet configuration reported a maximum drag reduction of 7.88%. Additionally, it was found that riblet arrangements with smaller spacing provided better drag-reduction performance by more effectively suppressing the penetration of streamwise vortices into the riblet channels [12].

III. METHODOLOGY

Determination of best ridge configuration: Denticle models were proportionally derived from real measurements, using a 0.5 mm ridge length in SolidWorks as the base for a 151 µm real scale. A staggered configuration of 15 denticles was applied to simulate flow patterns by using ANSYS software. Due to computational limitations, a simplified flat surface model was used instead of a denticle-wrapped mannequin. Denticle models with 3, 5, and 7 ridges were developed with a ridge height of 0.5 mm, and the 7-ridge configuration was selected based on the results because it showed consistently aligned flow vectors with minimal disturbance compared to the other two configurations.

Determination of best size: Size variations of the 7-ridge configuration were rescaled to 0.5 mm, 1.0 mm, 1.5 mm, and 2.0 mm. The 1.0 mm denticle size was selected as the optimal base configuration, as it exhibited the most stable and laminar flow patterns compared to the two larger sizes, while also being more feasible for manufacturing than the 0.5 mm size.

Determination of best ridge pattern: To evaluate the riblet pattern, denticles with ridge lengths of 0.8 mm, 1.0 mm, and 1.2 mm were applied to a cylindrical surface in a staggered configuration, testing both aligned and non-aligned ridge arrangements. Based on the simulation results, the non-aligned 1.0 mm size was selected as the optimal configuration, considering both fluid flow behavior and manufacturing feasibility.

Analyze the effect of denticle density: The final aspect investigated was the spacing between denticles (denticle density). Using the optimal 1.0 mm denticle size, three spacing values, 0.1 mm, 0.2 mm, and 0.3 mm, were tested to understand how density influences flow. Based on the simulation results, a spacing of 0.1 mm was selected as the optimal configuration.

Physical Sample Development: Using appropriate technologies, textile samples were developed and evaluated through a hydrodynamic drag testing setup to validate the simulation results.

IV. RESULTS AND DISCUSSION

Fig 1. Exhibits the flow pattern between 3,5, and 7 ridges. The 3-ridge and 5-ridge designs exhibited clear signs of disrupted flow in the form of wake regions and absent flow vectors in the downstream areas. In contrast, the 7-ridge configuration showed consistently aligned flow vectors with minimal disturbance. The continuity of the fluid paths suggests that the 7-ridge structure effectively guides the water along the surface, minimizing resistance.

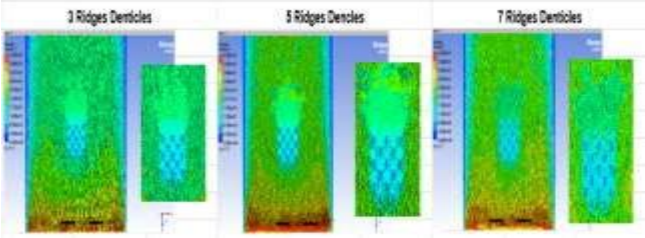

Fig 1: Ridge Configuration

Using the 7-ridge configuration, simulations were conducted with denticle heights of 0.5 mm, 1.0 mm, 1.5 mm, and 2.0 mm to assess the size impact on hydrodynamic performance. According to Fig. 2, velocity contours and flow vectors showed that 0.5 mm and 1.0 mm sizes produced the most stable, laminar flow with minimal vector deviation, indicating efficient surface guidance and reduced turbulence. The 1.5 mm size caused moderate disturbances, while the 2.0 mm height generated significant wake formation and disorganized vectors due to excessive protrusion into the flow. Considering both performance and manufacturability, the 1.0 mm denticle was selected as the optimal size, as the 0.5 mm design, though effective, posed durability and fabrication challenges.

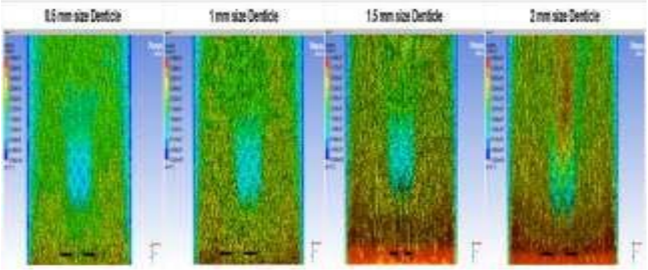

Figure 2: Size Analysis

Then evaluated the combined influence of ridge alignment, denticle size, and denticle density on drag reduction, using a smooth cylindrical surface (2.0628×10^{-1} N drag force) as the baseline. Comparing ridge orientations revealed that the non-aligned configuration outperformed the aligned design, achieving a drag force of 1.7773×10^{-1} N (13.83% reduction) versus 1.8930×10^{-1} N (8.25% reduction). This improvement was attributed to enhanced flow disruption and delayed separation, although it introduced greater meshing complexity.

Further analysis of denticle size of 0.8mm, 1.0mm, and 1.2mm in the non-aligned layout identified 1.0 mm as optimal, producing the same 1.7773×10^{-1} N drag force (13.83% reduction). Smaller (0.8 mm) denticles likely lacked sufficient flow influence, while larger (1.2 mm) sizes increased turbulence and pressure drag.

For denticle density, the narrowest spacing (0.1 mm) again yielded the lowest drag (13.83% reduction), outperforming 0.2 mm (12.23%) and 0.3 mm (12.05%). The higher density likely enhanced boundary layer control but posed significant manufacturing challenges, including nozzle clogging and material deformation in prototyping.

Overall, the optimal configuration of non-aligned ridges with 1.0 mm denticles spaced at 0.1 mm consistently delivered superior hydrodynamic performance, reducing drag by 13.83% relative to the smooth cylinder. Based on these findings, the developed samples with the same design achieved a 13.82% drag reduction under hydrodynamic testing, further reinforcing the potential of biomimetic surface structures to enhance the performance of competitive swimwear.

V. CONCLUSION

This study demonstrated that biomimetic sharkskin-inspired surface morphologies can achieve significant hydrodynamic drag reduction through systematic optimization of ridge configuration, denticle size, and denticle density. CFD simulations revealed that a 7-ridge, non-aligned configuration with 1.0 mm denticles spaced at 0.1 mm achieved optimal drag reduction (13.83%) while balancing manufacturability and durability, although fabrication constraints remain a consideration for real-world applications.

These findings enhance the understanding of sharkskin-inspired designs for drag reduction and provide valuable insights for the future development of high-performance swimwear.

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