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The Fluid Dynamics of Tech-Suits in Competitive Swimming

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Abstract

This research paper covered the current understanding of possible advantages the Speedo® LZR Racer and other tech-suits, or technical suits, have over other swimsuits. More specifically, it aimed to investigate the legitimacy of FINA's(Fédération internationale de natation) ban against tech-suits. Insight into this topic is necessary since Speedo and other companies faced considerable financial losses due to their swimsuits getting banned for technology doping by FINA, now known as World Aquatics. In other words, the tech-suits were banned due to their excessive advantages over other swimsuits. This research showed that the advantages of the Speedo® LZR Racer and other tech-suits were apparent as these full-body tech-suits showed decreased drag coefficients and higher velocity due to the compression of the swimmers' bodies. Moreover, the research also exposed that the Speedo® LZR Racer does not have fabrics that resemble sharkskin through microscopic images. The research also discussed the possibility of biological advantages of the Speedo® LZR Racer and other tech-suits such as the increase in ATP production and activation of fast-twitch fibers. In conclusion, this research concluded that tech-suits does offer a considerable advantage to athletes in competitive swimming, justifying the ban and the nullification of records broken with this suit. This conclusion and the justification behind it can be applied to various areas especially in future regulations on technology doping and future developments of high performance gear.

Keywords: Competitive swimming, Technology doping, Fluid dynamics, Tech suit, Olympics

1. Introduction

In 2008 the FINA, now known as World Aquatics, banned several swimsuits from being worn in competitive swimming. According to FINA, It was suspected that such swimsuits provided a competitive advantage to the wearer by"...aid[ing] [the swimmers'] speed, buoyancy or endurance during a competition"(FINA, 2023). Since 2009, several studies have been conducted to ascertain if this is the case, and how advantageous the swimsuits actually are.

The phenomena at play in swimsuit design and any enhancement, are largely driven by the underpinning physics of fluid dynamics. Therefore, in order to critically analyze the studies carried out on this topic, investigation into the fundamental theorem of swimming is necessary. This begins with the Navier Stokes Equations.

The Navier Stokes Equations help model the fluid dynamics involved in swimming in various ways. Most importantly, the Reynolds number, used in laboratory experiments on fluid dynamics, can be derived from these Navier Stokes equations.

1.1 Swimming

Swimming is defined as a body propelling itself through a body of liquid fluid. Competitive swimmers typically focus on 3 components of their movement to improve their time. Those are torque, buoyancy, and drag.

To start off, torque refers to the force that causes the swimmer's body to rotate in water. This is usually caused by the swimmer's position or body position and is detrimental when torque is positive (assuming that the swimmer is moving towards the left). This is because the rotation of the body connects to another component, drag.

Mainly, there are 2 types of drag in swimming. One being generated by the angles and shapes of the human body. Another being generated by the relatively miniscule features of the body such as hair, skin, and swimsuit. Although the latter is known to be negligible in records, the first drag force is not to be ignored.

Finally, buoyancy is often mistaken for torque, however, buoyancy is evidently different. Buoyancy in swimming often refers to the buoyancy force generated by the composition of a swimmer's body and swimsuit. To elaborate, fat composition in the body sways the buoyancy force along with the materials used in a swimsuit.

1.2 Swimsuits

Swimsuits in swimming have advanced tremendously over the last century. From wearing fabric boxers in the early 20th century to Tech-suits made with high-end technology in the 21st century, it is safe to say that swimsuits' advancement played a big role in competitive swimming.

Modern swimsuits are well known to enhance a swimmer's record in contrast to how swimsuits in the past slowed swimmers down. In the past, the focus was on minimizing the effect swimsuits had on records. Nowadays, the benefits of swimsuits are maximized. Some scholars even raise the question: "[Is it] the suit or the swimmer in the suit?" (Stefani, 2012).

The swimsuit in the spotlight in this study is the Speedo® LZR Racer. This swimsuit was banned in 2008 by FINA, now known as World Aquatics, as it went against the rule of "No swimmer shall be permitted to use or wear any device or swimsuit that may aid his/her speed, buoyancy or endurance during a competition" (FINA, 2023).

The main instigation of this spotlight was the 2008 Beijing Summer Olympics. In this event, 98% of the medalists wore the LZR Racer in their race, catching the attention of the swimming federation, FINA. Furthermore, NASA, a partner of Speedo in the makings of the LZR Racer, publicly stated that the novel swimsuit reduced skin friction drag by 24% compared to preceding swimsuits, escalating concerns from FINA. NASA also claims that the suit not only reduces the drag through material and novel types of seams but also the orientation of the swimmer. They claim that the compression on the swimmer orients their body to experience less drag, increasing their efficiency by 5% (NASA). Furthermore, there are claims that the grooves on the LZR Racer resemble shark skin and that these features make the suit more dynamic underwater (Tang, 2008). In later parts of this paper, discussions regarding the validity of these claims and further applicability will be discussed.

1.3 Navier Stokes Equations

The Navier-Stokes equations are a group of mathematical expressions that describe the flow of any fluid. Developed over several decades, firstly between 1820-1830 by Claud-Louis Navier, and then by George Gabriel Stokes, they form a set of partial differential equations achieved through applying Newton's law of conservation of momentum, and the continuity theorem to fluid.

The Navier-Stokes equations are based on two fundamental principles in physics: the continuity principle and Newton's Second law of motion.

Derivation of the Continuity Equation

Since mass input and mass output in fluid systems are

$$m_{in} = \rho_1 u_1 A_1$$
$$m_{out} = \rho_2 u_2 A_2$$

According to the conservation of mass,
Accumulation) = (input) - (output)

To derive the Continuity equation, an infinitesimal cube as shown in the diagram below should be imagined.

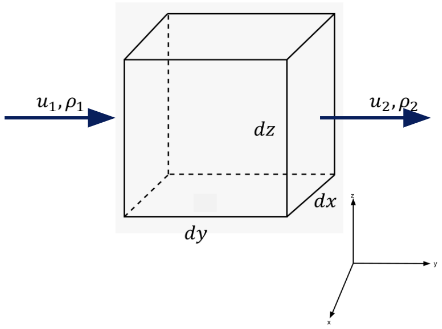

Figure 1. diagram showing a infinitesimal cube

Considering the movement towards the y-direction,

Input mass is $u_1\rho_1 dzdx$

Output mass is $u_2\rho_2 dzdx$

Accumulation mass is

$$\frac{dm}{dt} = \frac{d(\rho \cdot dV)}{dt} = dV\frac{d\rho}{dt}$$

(Accumulation mass) = (Input mass) - (Output mass)

Therefore,

$$dV\frac{d\rho}{dt} = u_1\rho_1 dzdx - u_2\rho_2 dzdx$$

$$(dx \cdot dy \cdot dz)\frac{d\rho}{dt} = u_1\rho_1 dzdx - u_2\rho_2 dzdx$$

$$dy\frac{d\rho}{dt} = u_1\rho_1 - u_2\rho_2$$

Since the cube is infinitesimal, across dy, change in density and velocity is also infinitesimal. Therefore, $[u_1\rho_1 - u_2\rho_2]$ can be simplified as $[d(u\rho)]$

$$\therefore \frac{d\rho}{dt} = -\frac{d(u\rho)}{dy}$$

$$\frac{d\rho}{dt} + \frac{d(u\rho)}{dy} = 0$$

For both the x and z direction the same is true.

$\therefore$

$\frac{d\rho}{dt} + \frac{d(u\rho)}{dx} = 0$ (x - direction)

$\frac{d\rho}{dt} + \frac{d(u\rho)}{dy} = 0$ (y - direction)

$\frac{d\rho}{dt} + \frac{d(u\rho)}{dz} = 0$ (z - direction)

$\therefore$

$$\frac{d\rho}{dt} + \nabla \cdot (\rho u) = 0$$

※ If fluid is incompressible, ρ is constant. In other words, , $\frac{d\rho}{dt} = 0$

$\therefore$

$$\nabla \cdot (\rho u) = 0$$

$$\begin{aligned} \nabla \cdot (\rho u) &= \rho\nabla \cdot (u) + u \cdot \nabla\rho \\ &= \rho\nabla \cdot (u) \\ &= 0 \end{aligned}$$

$\therefore \rho\nabla \cdot (u) = 0$ $\therefore \nabla \cdot (u) = 0$ ($\because \rho$ is a non-zero constant)

The following continuity equation is derived, $\nabla \cdot (u) = 0$ (1)

<u>Newton's second law of motion / Conservation of mass</u>

The second part of the Navier-stokes equations can be derived from either Newton's second law of motion or the law of conservation of momentum. Due to the simplicity of the former option, Newton's second law of motion will be used to derive the Navier-stokes equations.

Starting from Newton's 2nd law of motion, or

$$F = ma$$

a, or acceleration, can be expressed as

$$a = \frac{du}{dt}$$
$$= \frac{\partial u}{\partial t} + u_x \frac{\partial u}{\partial x} + u_y \frac{\partial u}{\partial y} + u_z \frac{\partial u}{\partial z}$$
$$= \frac{\partial u}{\partial t} + u \cdot \nabla u$$

∴

$$F = dm(\frac{\partial u}{\partial t} + u \cdot \nabla u)$$

Since the force per unit volume(f) is the key, and $\frac{F}{dV} = f$

$f = \rho(\frac{\partial u}{\partial t} + u \cdot \nabla u)$

Identifying the forces acting upon the infinitesimal cube, there are 3 main forces.

- Pressure force
- Shear force
- Gravitational force

Since $\nabla \cdot \sigma$ represents the divergence of stress on the block externally,

And gravitational force can be represented as

$$f_{grav} = \frac{mg}{dV} = \frac{\rho dV g}{dV} = \rho g$$

$$F = ma$$

Can be turned into

$$\nabla \cdot \sigma - \rho g = \rho(\frac{\partial u}{\partial t} + u \cdot \nabla u)$$

Or,

$\frac{\partial u}{\partial t} + u \cdot \nabla u = \frac{1}{\rho} \nabla \cdot \sigma - g \quad (2)$

<u>Derivation of the Navier-Stokes equations</u>

Combining (1) and (2), the following equation can be derived.

$\frac{\partial u}{\partial t} + u \cdot \nabla u = \frac{1}{\rho}(-\nabla p + \mu \nabla^2 u) - g$ (3)

$\nabla \cdot (u) = 0$ (1)

These equations are the final form of the Navier-Stokes equation for Newtonian fluids.

The derivation of the Navier-Stokes equations allows us to understand the derivation of the Reynolds Number. Upon the writing of the dimensionless Navier-Stokes equation, a set of differential equations is achieved with only one factor that may be adjusted. This is termed the Reynolds number and has a large impact on the understanding of fluid flow.

1.4 Reynolds Number

The Reynolds number is a dimensionless quantity that characterizes fluid flow patterns. This concept was first introduced by George Stokes in 1851 and was named by Arnold Sommerfield in 1908. The name was derived from Osborne Reynolds who popularized the use of this dimensionless quantity in 1883.

The derivation of the Reynolds number can be conducted through the use of the dimensionless version of the Navier-Stokes equations.

By introducing the characteristic scales:

Reference velocity U
Reference length L
Reference time scale L/U
Reference pressure scale ρU^2

The following dimensionless variables are defined:

$$u' = u/U$$
$$x' = x/L$$
$$t' = tU/L$$
$$p' = p/(\rho U^2)$$

Substituting these dimensionless variables into the Navier-Stokes equations (1),(3)
The dimensionless Navier-Stokes equation is derived.

$$\frac{\partial u'}{\partial t'} + u' \cdot \nabla' u' = -\nabla' p' + \frac{1}{Re} \nabla'^2 u'$$
$$\nabla' \cdot u' = 0$$

Where

$$Re = \frac{\rho \cdot V \cdot L}{\mu}$$

In conclusion, Reynold's Number, or Re, is defined as

$$Re = \frac{\rho \cdot V \cdot L}{\mu} \quad (4)$$

When

- ρ is the density of the fluid (kg/m³)
- V is the velocity of the fluid (m/s)
- L is a characteristic length or linear dimension (m) of the flow
- μ is the dynamic viscosity of the fluid (Pa·s or kg/(m·s))

Reynolds number is a dimensionless number that represents the characteristic of a flow with a value that indicates whether the flow is laminar or turbulent.

1.5 Drag Coefficient

Drag is the resistive force exerted by a fluid moving relative to a solid body. Drag has two components, these are the normal forces due to motion perpendicular to the surface, and shear forces due to motion of the fluid tangentially to the surface.

The drag force can be expressed by the following equation,

$$F_d = C_d \frac{1}{2} \rho U^2 A$$

Where

F_d is the drag force
C_d is the drag coefficient

The drag coefficient is a dimensionless quantity that quantifies the drag or resistance experienced by an object in a fluid environment. It is obvious then that the drag coefficient has a large role in swimming.

1.6 Anticipated findings

This research expected to find the extent to which tech suits, especially the LZR Racer, aided the athletes in terms of record in competitive swimming. This result was expected to be in the form of drag coefficients and cross sectional area of the body.

To elaborate, drag coefficients were measured in environments simulating the racing environments, simulating controlling the Reynolds number. This measured value showed, as explained in (2.5), the resistive force exerted by the water moving relative to the athlete. Cross sectional area of the body was also measured since it is directly related to the hydrodynamic resistance applied to the athlete. A smaller cross sectional area allowed for less hydrodynamic resistance, giving an advantage to the swimmer.

2. Method

This research collected its information from various research done on swimming tech suits throughout the years. Before referencing these sources in this research, there were certain means of filtering the information so that it is relevant to this research.

Searching the keywords “competitive swimming”, “tech suit”, “LZR Racer”, “drag coefficient”, and “Reynolds number”, approximately 500 studies matched the key words. Of these studies, this research focused on those simulating the racing environment in the experiment setup. Through this process, approximately 5 studies were identified.

Data analysis of the referenced studies’ data was done based on the raw data without interpreting the conclusion of each research. This focused view on the data allowed this research to avoid errors made by preceding research, especially failing to simulate racing environments. By looking at the data itself, this research was able to analyze solely the data representative of the competitive swimming environment.

3. Main Review

3.1 Discussion of studies investigating drag and hydrodynamic properties of the LZR Racer

In 2010, scientists conducted an experiment measuring the aerodynamic properties of different advanced swimsuits at RMIT’s industrial Wind tunnel (Bundoora Campus of RMIT). Their research involved identifying the drag coefficient of different swimsuits in different fluid conditions. The research team wrapped pieces of different types of swimsuits around a metal cylinder of 110mm in diameter and recorded their drag coefficient at different reynold numbers. 2 types of swimsuits, the Speedo® FastSkin-II, and the Speedo® LZR Racer. According to this study’s results, at speeds higher than 1.7 m/s, the LZR Racer displayed lower drag coefficients compared to that of the FastSkin-II. This study also showed that the seams of the LZR Racer had negligible effects on the swimsuit’s drag (Moria et al., 2011). Normally, seams of swimsuits increase the net resistance the swimsuit experiences, posing as one of the main challenges in creating the optimal swimsuit.

The following year, an identical study was conducted by another team at the same facility with different sets of swimsuits. This study tested the drag coefficient of the Speedo® LZR Racer, TYR® Sayonara, and Blueseventy® Pointzero3. As mentioned earlier, the methodology of the study was identical to that of the study in 2010. The study’s results show that the LZR Racer had considerably lower drag coefficients compared to other swimsuits in speeds over 1.39 m/s (Moria, Chowdhury, and Alam, 2011).

Both aforementioned studies provide a comparison of the Speedo® LZR Racer and other swimsuits. However, the study of 2010 is more insightful as it compares the Speedo® LZR Racer with its predecessor, Speedo® FastSkin-II. Meanwhile the study in 2011 compares the Speedo® LZR Racer to other swimsuits that aren’t used in competitive swimming. Rather, the swimsuits discussed, the TYR® Sayonara and Blueseventy® Pointzero3, are designed for open-water swimming and triathlon.

There were apparent flaws in the 2010 study. The biggest being the velocity of the fluid experienced by the fabric wrapped cylinder. Professional swimmers, especially ones in the olympic level, swim at a speed of 2 to 2.5 m/s, sometimes reaching speeds up to 2.6 m/s. However, the maximum velocity of the fluid in the experiment is 120 km/h, equivalent to 2.08 m/s underwater. These fluid velocities were calculated using the Reynolds number of the fluid, and by keeping the Reynolds number constant, scientists were able to recreate the same fluid flow in different types of fluids (4). In conclusion, the effectiveness of the swimsuits can only be predicted using the trends of the data instead of being observed in the wind tunnel.

Despite the flaws of these studies, the results point to the obvious advantage of the LZR Racer at speeds of 1.7 m/s or higher. This study also shows that one of the reasons behind this result is the novel ultrasonic weld seams between the polyurethane panels, showing a consistent drag coefficient with or without the seams.

Regarding the Speedo® LZR Racer's resemblance to shark skin, a study conducted in 2011 at RMIT revealed that the LZR Racer's fabric looked nothing like a shark's skin on a microscopic level. While a shark's skin resembles the barks of trees with jagged points (figure 3), the LZR Racer's fabric showed none of these traits (figure 3). Rather, the predecessor of the LZR Racer, Speedo's Fastskin-II showed a higher degree of resemblance to shark skin (figure 4) (Moria, Chowdhury, and Alam, 2011). Adding on to this, the patent of Speedo's LZR Racer does not have any claims regarding grooves or patterns that resemble that of shark skin (Rance, Yeomans, and Simmons, 2008).

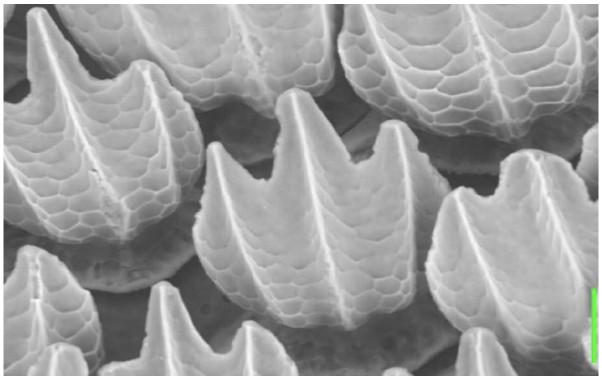

Figure 2. Close-view ESEM image of denticles from the surface of the mid-body region in a bonnethead shark (Sphyrna tiburo) to show details of typical denticle structure with the three surface ridges and three posteriorly pointing prongs. Such denticle structure is common on the body, fins and tail, although denticles of this species on the head have a different morphology. Scale bar, 50 µm (Oeffner and Lauder, 2012).

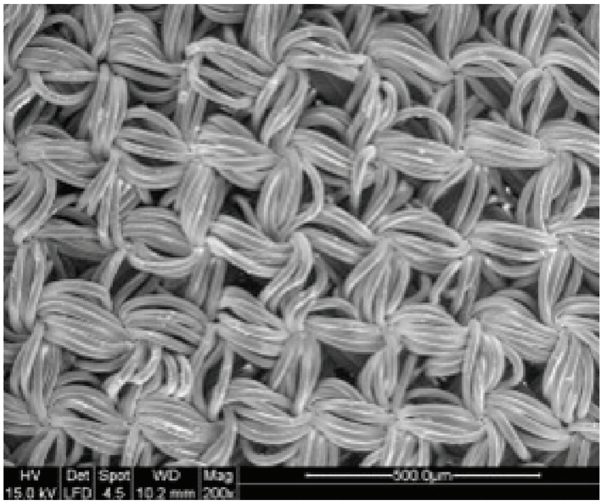

Figure 3. Left, Electron microscopic image of the Speedo® LZR Racer with 200x magnification. Scale bar, 500µm (Moria et al., 2011).

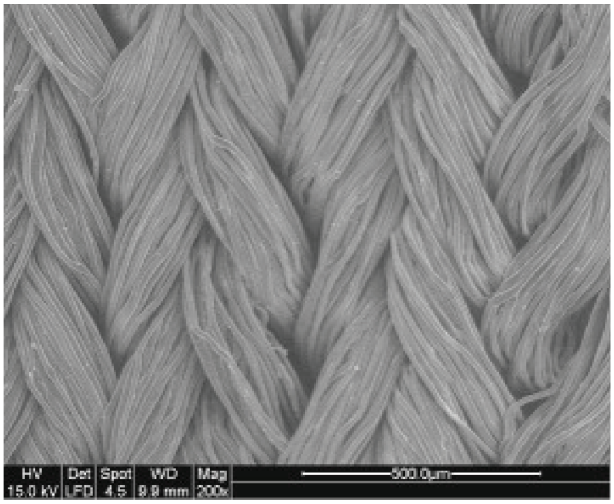

Figure 4. Right, Electron microscopic image of the Speedo® Fastskin-II with 200x magnification. Scale bar, 500µm (Moria et al., 2011).

3.2 Discussion of studies investigating the compression of the LZR Racer

Compression in swimming, especially for full-body suits, greatly affects a swimmer's performance by decreasing the cross-sectional area of the swimmer.

A study conducted by Halvorson in 2011 regarding the compression and buoyancy of tech-suits such as the Speedo LZR Racer, TYR Tracer light, Blueseventy Pointzero3, and the Jaked swimming suit, all banned by FINA after the 2009 World Aquatics Championships at Rome, Italy. As displayed in table 1, results showed that all 4 swimsuits showed apparent compression on the swimmer with the reduction of circumference of the swimmer's body ranging from 18% to 25%(Halvorson, 2011).

Table 1. Overall percent reduction in circumferences for all the locations of the swimmer's body measured. This data represents the percent reduction when the swimmer is underwater and the suit is wet (Halvorson, 2011).

TYR Tracer Light	Speedo LZR	blueseventy	Jaked
18.51 %	19.46 %	19.60 %	25.13 %

Presented in the “Performance Enhancement and Injury Prevention” handbook published by the International Olympics Committee (IOC), the passive hydrodynamic resistance, in this case, the form resistance can be described as

$$F_{DP} = \frac{1}{2} C_{DP} \rho u^2 S_M \qquad (5)$$

Where
ρ = water density,
u = speed of the fluid
S_M = the cross-sectional area
C_{DP} = drag coefficient
(Rumyantsev and Vorontsov, 2011)

As shown in table 2 the percentage increase in overall velocity of each swimsuit in the study by Halvorson can be calculated to be around 5%. This is calculated using equation (5) above.

Table 2. Percent increase in velocity for respective technical suits when the swimmer is underwater with the swimsuit wet (Halvorson, 2011)

TYR Tracer Light	Speedo LZR	blueseventy	Jaked
4.23 %	4.15 %	4.44 %	5.94 %

Scholars of Niigata University, Japan have also proposed that the compression of the swimsuits aid the swimmers’ generation of ATP. They hypothesize that the suppression of the blood circulation catalyzes the anaerobic glycolysis process while suppressing the aerobic mitochondrial system. Although both processes generate ATP, the latter requires more oxygen and is slower compared to the former, approximately by 100 times. Also, the glycolysis process powers the instantaneous force of white fibers (fast-twitch type II fibers) while the mitochondrial system powers slow-twitch fibers and cardiac muscles. For these reasons, it is plausible that the compression also helps the body generate more energy advantageous to the swimmer (Kainuma et al., 2009).

4. Conclusion

The aforementioned studies point to the clear advantage of wearing the LZR Racer in a competitive swimming race. Different aspects of the swimsuits, such as the fabric, seams, and compression are credited for this advantage. In an experiment conducted by Moria and his colleagues, the fabric of the LZR Racer showed lower drag coefficients in racing velocities compared to its predecessor and other swimsuits. Furthermore, the same experiment showed that the ultrasonic weld seams, a novel type of seam, showed no effect on the drag coefficient of the fabric (Moria et al., 2011a & b). These studies firmly establish the LZR Racer’s advantage due to its evident lower drag coefficient compared to other swimsuits. In an experiment conducted by Halvorson, the decreased volume of the swimmer’s cross-section showed to increase the swimmer’s velocity by over 5% (Halvorson, 2011). Although theoretical, a group of researchers from Japan proposed that the compression powered fast-twitch fibers in the body while also catalyzing the production of ATP (Kainuma et al., 2009).

However, this study also identified that the LZR Racer had no grooves that imitated shark skin, contradicting scholars’ claims (Tang, 2008). Not only did microscopic images of the swimsuit and sharkskin back this claim, but the patent of the LZR Racer did not show any references to sharkskin or grooves on the fabric (Moria et al., 2011b; Rance et al., 2008).

Future studies exploring other mechanisms of the Speedo® LZR Racer such as its correction of the body posture and polyurethane panel placements will greatly enhance the understanding of the LZR Racer’s advantages. Furthermore, a delve into the biological advantages the tech-suit can offer such as higher production of ATP, activation of certain muscle fibers, and more will provide a different lens towards this topic.

Furthermore, further investigation into technologies that can improve the existing tech-suits can provide insight into future technology doping in swimming.

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