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A brief discussion on the mechanical principles in swimming

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Abstract. Swimming involves the interaction between the human body, water, and air. Reducing the resistance encountered in the swimming direction and increasing the propulsion force are two primary methods for improving swimming performance. This paper, from a mechanical (mainly fluid mechanics) perspective, introduces the development of our understanding of the propulsion mechanism in swimming and the underlying mechanical principles. It analyzes the mechanisms of resistance generation during swimming and its basic components, and explores methods of reducing resistance and increasing propulsion from the perspectives of technical movements and swimming equipment. The paper aims to provide basic mechanical insights to better understand the technical and tactical behaviors in swimming.

Keywords: swimming, mechanical principles, fluid mechanics, propulsion mechanism

1. Introduction

Unlike aquatic animals, humans do not possess streamlined bodies or features like fish fins. Human swimming is achieved through large-scale, multi-degree-of-freedom movements of the limbs [23]. Competitive swimming is a sport in which the winner is determined by the speed at which the swimmer swims. The technical movements involved include starts, underwater swimming, mid-swim, turns, and finishing at the edge. Based on swimming postures, it is mainly divided into four strokes: freestyle, backstroke, breaststroke, and butterfly, as well as the medley, which is a combination of these four strokes [43].

Swimming involves the interaction between the human body, water, and air (mainly the movement of the free water surface at the air-water interface). Reducing the resistance encountered during swimming and increasing the propulsion force are the two key ways athletes improve their performance [17]. Understanding the interaction between the human body and water from a mechanical perspective, analyzing the mechanisms behind resistance and propulsion generation, and exploring ways to reduce resistance and increase propulsion are crucial for improving the scientific level of swimming training and competition. This is essential for athletes to develop better "swimming skills." This paper introduces the process of deepening our understanding of swimming propulsion mechanisms, the causes and basic components of resistance formation, and methods to reduce resistance and enhance propulsion.

2. The propulsion mechanism in swimming

Increasing propulsion force is the most direct way to improve swimming speed. Therefore, research on swimming propulsion mechanisms has always been a focal point. From the initial lift-drag propulsion hypothesis to the vortex energy propulsion hypothesis, and then to the axial flow (jet) propulsion hypothesis, our understanding of swimming propulsion mechanisms has deepened over time [47]. This section will briefly introduce the basic mechanical principles of these hypotheses.

2.1. Lift-drag propulsion hypothesis

According to the lift-drag propulsion mechanism hypothesis, the propulsion force in swimming is composed of two parts: drag propulsion and lift propulsion. The magnitudes of these forces are related to water density, the velocity of different body parts relative to water, the surface area of limbs, and the drag and lift coefficients of body parts under the current motion state. During swimming, athletes apply force on the water through actions such as pulling, kicking, and pushing, causing the water to exert a reactive force on the human body, which forms drag propulsion. Drag propulsion is positively correlated with the limb surface area and the square of swimming speed. Athletes can increase propulsion by increasing the surface area of their hands when pulling, or by accelerating the speed of kicking or stroking [11, 46]. Simultaneously, when the palm is at a certain attack angle during the stroke, the high-pressure region on the palm's surface and the low-pressure region on the back of the hand work together to generate lift. The component of this lift in the direction of swimming contributes to the lift propulsion force. Quantitative analysis based on the experimental results of American swimming biomechanics expert Schleihauf shows that, in four common swimming strokes, 70% of the propulsion in breaststroke comes from lift, while in the other three strokes, lift and drag each account for about half of the propulsion [42].

2.2. Vortex energy propulsion hypothesis

The flow of water during swimming is unsteady. Some scholars have pointed out that the vortices generated by the swimmer's strokes play a role in momentum transfer, and that the impulse released by these high-speed vortices is an important component of swimming propulsion [41]. The formation of vortices represents momentum transfer, and studies on fish movement have shown a correlation between the backward momentum generated by vortices and the forward momentum obtained by the fish. Research has found that with each stroke, a "shedding vortex" is created. When the swimmer repeatedly performs the stroke motion, these "shedding vortices" continue to be released, generating a vortex that assists in propulsion [1]. Lauder et al. found that during the underwater phase of swimming, the propulsion generated by the dolphin-like kicking is related to the area of the vortices produced by the kicking action and the size of the circulation carried by these vortices [13]. In recent years, with the help of flow field visualization technologies such as PIV (Particle Image Velocimetry) and DPIV (Digital Particle Image Velocimetry), researchers have been able to clearly observe the velocity field, vorticity field, and other flow field structures around the swimmer during swimming. This has advanced the study of the vortex energy propulsion mechanism. Biewener et al. found that during the breaststroke, humans can generate additional lift and propulsion in a manner similar to birds and insects, by utilizing the vortices created by previous movements [5]. Rouboa et al. used PIV technology to analyze the hand and lower limb movements of freestyle swimmers [27]. They found that the swimmer's stroke was closely related to the movement of the underwater vortices and changes in the swimmer's momentum. Specifically, the larger the radius of the vortex and the more circulation it carried, the greater the forward impulse obtained, and the greater the propulsion force experienced by the swimmer.

2.3. Axial flow (jet) propulsion mechanism hypothesis

The axial flow (jet) propulsion mechanism hypothesis originates from the study of single-fin fish movement and represents a deeper exploration of the vortex energy propulsion mechanism. Matsuuchi et al. conducted a visualization study on single-fin fish movement and discovered that the tailbeat of these fish induces a delayed stall effect, causing a pair of vortices (one Kármán vortex and one reverse vortex) to form in the wake [19]. The interaction between these two vortices generates a jet that flows in the opposite direction of the swimming motion, resulting in both propulsion and lift. This mechanism is similar to the aerodynamic principles by which birds generate propulsion and lift during flight. Kamata et al. using DPIV (Digital Particle Image Velocimetry) technology, analyzed the propulsion mechanism of swimming athletes' stroke movements [12]. They found that changes in the direction of the hands during a stroke also generate a pair of counter-rotating vortices. As the attack angle of the hand increases, the vortices gradually shed, creating a jet in the middle, which in turn generates propulsion force.

3. Resistance in swimming

Swimming resistance refers to the force that acts in the opposite direction of motion that the swimmer experiences during the swimming process. In swimming, more than 90% of an athlete's energy is used to overcome the resistance of water [49]. Studies have shown that a 1% reduction in resistance can result in a 0.3% increase in speed [45, 48]. During steady swimming, the total resistance experienced by the swimmer consists of three components: frictional resistance, pressure difference resistance (also known as form resistance), and wave drag [29].

3.1. Frictional resistance

Frictional resistance is the resistance caused by the friction between the body surface and water. Its magnitude depends on the total submerged area of the athlete, the surface roughness, and the flow state of the boundary layer. The flow state of the boundary layer is determined by the Reynolds number, which is related to the athlete's body size, swimming speed, and the water's density and dynamic viscosity. The Reynolds number in competitive swimming generally ranges from 10510^5105 to 10610^6106, and the boundary layer flow around the swimmer's body is primarily turbulent. This turbulence increases the frictional resistance to some extent. However, compared to pressure difference resistance and wave drag, frictional resistance accounts for a smaller proportion of the total resistance.

3.2. Pressure difference resistance

Pressure difference resistance is the resistance caused by differences in water pressure distribution on the surface of the human body. Its magnitude is determined by the water's density, the relative speed between the body and water, the projected area of the body in the direction of motion, and the shape of the body. For this reason, it is also called form resistance. Increasing swimming speed has always been the goal of competitive swimming. However, pressure difference resistance is positively correlated with the square of swimming speed, acting like an invisible wall that hinders further increases in swimming speed. In swimming competitions, athletes generally reduce pressure difference resistance by shaping a streamlined body and keeping the body as horizontal as possible to minimize the projected area in the direction of motion [14].

3.3. Wave drag

Wave drag is the resistance caused by the waves generated by the swimmer's own movement in the water. The formation of these waves not only consumes a significant amount of the swimmer's energy but also creates a high-pressure zone in front of the swimmer, obstructing forward motion. Wave drag is proportional to the cube of the swimming speed, and during the middle swimming phase, it contributes significantly to the total resistance experienced by the swimmer. Studies show that the magnitude of wave drag is significantly affected by swimming depth. When the swimmer is in water deeper than 0.6 meters, wave drag becomes negligible [31]. Therefore, in swimming competitions, athletes typically make full use of the submerged phase after the start and turn, achieving an optimal swimming speed at a greater underwater depth. Similar to boats navigating on the water's surface, the wavelength of the waves generated by the swimmer during the middle swimming phase increases as the swimming speed increases. When the wavelength approaches the swimmer's height—reaching the swimmer's "hull speed"—continuing to accelerate becomes increasingly difficult. Research has shown that in middle- and long-distance freestyle events, elite athletes' swimming speeds tend to approach their own "hull speed," while in short sprints, their speed exceeds this threshold. This means that the swimmer must expend more energy to overcome the wave peaks in order to achieve higher speeds [20, 22]. Studies also show that at different swimming speeds, wave drag can contribute between 5% and 60% of the total resistance [30, 33, 35].

4. Optimization of drag reduction and propulsive force

In competitions, swimmers optimize their performance by adopting proper technical movements and swimming strategies to increase propulsive force and reduce drag, thereby improving their results [26]. Increasing propulsive force directly boosts swimming speed, while drag reduction is considered one of the most efficient methods to improve performance [2]. Therefore, optimizing drag reduction and propulsive force has always been a focus in competitive swimming tactics. This section will discuss methods to reduce drag and improve propulsive force in swimming, focusing on three areas: underwater phase and mid-course drag reduction, swimming equipment drag reduction, and propulsion force optimization techniques.

4.1. Underwater phase and mid-course drag reduction

The underwater phase and the mid-course phase account for the majority of the time during a swim race, making it crucial to reduce drag in these phases to enhance the swimmer’s performance.

The drag reduction during the underwater phase is significantly influenced by factors such as depth, posture, breathing technique, head position, and body shape. Let’s first consider the impact of depth: swimmers experience the highest drag when swimming at a depth between 0 and 0.25 meters from the water surface [16, 24]. However, when swimming at depths below 0.6 meters, wave drag becomes negligible [31, 38]. At a swimming speed of 1.6 m/s, the drag experienced by swimmers at different depths remains relatively constant, but when the speed exceeds 2.0 m/s, the drag difference across depths becomes more pronounced. For example, at swimming speeds between 1.9 and 2.5 m/s, drag at depths of 0.4 to 0.6 meters is reduced by 10.7% to 19.9% compared to drag at the water surface [15]. In terms of posture, the body’s posture during the underwater phase is closely related to shape drag. 2D simulation results show that the drag of the body in the streamlined position with both arms extended is significantly lower than when the arms are placed at the sides of the body. When the arms are extended, there is no significant difference in drag between prone and supine positions, but the drag coefficient in the side-lying streamlined position is significantly lower than in other postures [17]. From the perspective of breathing technique, abdominal breathing is recommended during the underwater phase. Compared to chest breathing, abdominal breathing moves the swimmer’s buoyancy center closer to the body’s center of mass. Additionally, abdominal breathing reduces the chest cavity area and causes the abdomen to protrude, which minimizes the unevenness of the torso and suppresses the formation of vortices in the chest and abdomen, achieving drag reduction [25]. The head position during the underwater phase also affects drag. Studies show that, when in the streamlined position with arms extended, keeping the head level or slightly lowered results in less drag than when the head is raised. Keeping the head level is even better than having the head slightly lowered, reducing total drag by 4% [37]. Moreover, different body types result in different drag during the underwater phase. Numerical simulation with a swimming speed of 2.2 m/s shows that the drag during the underwater phase decreases from large to small for body types: inverted triangle, inverted trapezoid, rectangular, and oval. This is because the inverted triangle body shape has a "teardrop" shape that is more conducive to drag reduction [14].

In the mid-course phase, the relative positioning of swimmers can also significantly impact drag, particularly in open water swimming. In open water, "drafting" refers to swimmers swimming behind or beside another swimmer to conserve energy and increase speed. When two swimmers swim in a straight line, the closer the trailing swimmer's head is to the leader's feet, the greater the drag reduction [4]. When the trailing swimmer's front is in the trough (low pressure) and the back in the crest (high pressure) of the wave, they will experience a forward propulsive force. Conversely, if they are positioned differently, they will encounter additional drag. Furthermore, when the trailing swimmer is close enough to the lead swimmer, the pressure difference between the lead swimmer's head and feet can create forward thrust [36]. However, when the lead swimmer is more than half a body length ahead, the lead swimmer must expend extra energy to overcome drag [34]. Numerical simulations have found that when two swimmers swim side by side with a lateral distance of at least 1 meter, the interference from wave drag can be neglected. At this lateral distance, if the trailing swimmer is 0.5 to 1 meter behind the lead swimmer, the drag on the trailing swimmer can be reduced by 6% to 7% [6, 34].

4.2. Swimming equipment drag reduction

Swimming equipment drag reduction is primarily achieved through innovative designs of swimsuits and swim caps. Regarding swimsuits, appropriate fabric selection and surface microstructure design can significantly reduce water resistance during swimming. In 2000, the Australian company Speedo introduced the groundbreaking FASTSKIN sharkskin swimsuit. This swimsuit mimics the structure of shark skin using fibers, which guide the surrounding water to create small vortices, thereby improving swimming speed by 3% to 7.5%. In 2004, Speedo launched the second generation of the sharkskin swimsuit, FASTSKIN FS2, which reduced drag by 4% by adding granular dots to the fabric surface. In 2007, the third generation of the sharkskin swimsuit, FASTSKIN FS PRO, was released. This swimsuit used a fabric composed of ultrafine nylon and anti-oxidation elastic fibers, which increased elasticity by about 15%. This improvement helped reduce muscle and skin vibrations, saving energy and improving performance. In 2008, Speedo, in collaboration with NASA and the Australian Fluid Mechanics Laboratory, developed the fourth generation of the sharkskin swimsuit, the FASTSKIN LZR RACER. Made from ultra-light, low-resistance, waterproof, and quick-drying nylon elastic fabric, this material displaces water close to the skin, minimizing contact with the body and reducing drag. The LZR RACER was also the first swimsuit in the world to use 100% ultrasonic bonding, eliminating the additional drag caused by seams. Compared to the previous generation, the LZR RACER reduced dynamic water resistance by 24% [40]. The application of biomimetic drag reduction technology and new materials during the "sharkskin era" (2000-2009) led to frequent world records in swimming, making swimsuit technology a major factor dominating the swimming world during that time. Later, with the introduction of restrictive regulations by FINA (International Swimming Federation), sharkskin swimsuits were phased out. However, the development of new swimsuits that comply with the competition rules has never ceased. Lightweight, more ergonomic and biomimetic designs continue to play a role in helping athletes reduce swimming drag, decrease energy consumption, and improve performance.

As for swim caps, when the swimming speed is between 1.5 and 2.5 m/s, athletes can reduce about 15% of passive underwater drag by wearing a swim cap [18]. Compared to the two-piece 2D swim caps made from silicone, the one-piece 3D swim cap fits the head better and eliminates wrinkles when worn. Studies have shown that at a swimming speed of 1.9 m/s, athletes wearing 3D swim caps experience a 6% reduction in water resistance [10]. Additionally, reasonable designs for the surface of the swim cap, such as smooth, golf ball dimples, or embossed patterns, can further reduce the flow resistance for certain swimming postures [9].

4.3. Propulsion optimization techniques

In swimming, the primary ways athletes generate propulsion are through arm strokes and kicking. Experience shows that rapid arm strokes or kicking can generate significant propulsion [44]. In fact, the hand position during the stroke, the amplitude and frequency of underwater kicking, and other factors can all influence the magnitude of the propulsion. Studying these factors and understanding how they impact propulsion, thus guiding improvements in technical movements, is crucial for enhancing athlete performance. Research indicates that during a 30-second all-out sprint, male athletes' arm strokes and kicking contribute 70.3% and 29.7% to propulsion, respectively, while for female athletes, the contributions are 66.6% and 33.4% [21].

Hand position is the primary factor affecting the magnitude of propulsion during arm strokes and is the key area for optimization. Vilas-Boas et al. classified arm positions (including the hand and arm) into 9 categories based on the extent of finger spread and adduction [32]. Their research showed that the drag coefficient of each hand position increases as the angle of attack increases, reaching its maximum when the attack angle is 90°. The lift coefficient, on the other hand, is maximized within the range of 40° to 60° attack angles, which is considered the optimal angle range for maximizing both drag and lift propulsion effects. Further detailed analysis showed that the drag coefficient has a weak correlation with the spread and adduction of the thumb but is significantly influenced by the spacing between the other four fingers. In contrast, the lift coefficient correlates positively with the thumb's positioning [28]. Moreover, the hand shape also influences both drag and lift coefficients. Data indicate that flat and natural palm shapes result in higher drag values compared to cupped and basketball hand shapes, with the difference ranging from 0.4% to 0.9%, which can contribute to greater drag-induced propulsion. The reverse curve hand shape has the lowest drag coefficient [3].

During the underwater phase following the start or turn, athletes extend their arms forward into a streamlined position, while their legs rhythmically move up and down along the sagittal plane to propel the body forward. This action is commonly referred to as the underwater dolphin kick. Athletes need to adjust the body posture, amplitude, frequency, force, and form of the kick to balance drag reduction, drag propulsion, and energy conservation. Research has found that the propulsion efficiency of human underwater dolphin kicks is only 19.6% to 51.8% of that achieved by whales. The position and body posture of the athlete in the water directly influence the efficiency of the dolphin kick. In the underwater position, the lateral body position is more efficient than the prone position. However, when near the water's surface, the lateral body position causes part of the body to protrude above the water, reducing the efficiency of the dolphin kick [7]. Through comparisons of underwater kicking frequency, amplitude, and corresponding swimming speed across different levels of athletes, it was found that there was little difference in kicking frequency between athletes of varying skill levels. The primary difference lay in the amplitude of the kick—larger amplitude correlates with faster swimming speeds. Data also revealed that at a 2.18 m/s swimming speed, reducing the ankle's plantar flexion by 10° results in a loss of 16.4 N of drag-induced propulsion, while increasing the ankle's dorsiflexion by 10° can increase drag-induced propulsion by 31.4 N [39].

5. Conclusion

Swimming involves interactions among the human body, water, and air. Reducing resistance in the direction of swimming and increasing propulsive force are the two primary ways for athletes to improve their swimming performance. This paper, from a mechanical perspective (primarily fluid mechanics), introduces three hypotheses of swimming propulsion mechanisms — the lift-and-drag propulsion mechanism, the vortex energy propulsion mechanism, and the axial flow (jet) propulsion mechanism — along with their underlying mechanical principles. It also analyzes the mechanisms behind the three types of resistance encountered by athletes during swimming: frictional resistance, pressure (form) resistance, and wave-making resistance. On this basis, the paper explores common methods for reducing resistance and enhancing propulsion from the perspectives of technique and swimming equipment. This provides fundamental mechanical insights for understanding technical and tactical behaviors in swimming.

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