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Sports Engineering

Base Ball and Golfball Aerodynamics

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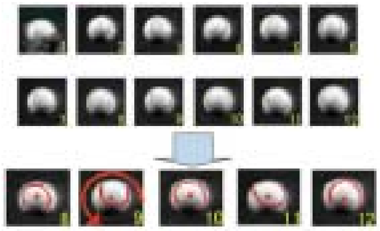
Introduction



3-dimentional-trajectory analysis of baseball and golf ball is conducted. These balls flight with various flight conditions of ball speed, revolution speed and direction of its axes. We can observe these features with TV images or flight experiments. Aerodynamic forces acting on the balls under individual flight conditions are measured by precise wind tunnel experiment. The kinematics equations are estimated by

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A mysterious flight trajectory of a rugby ball

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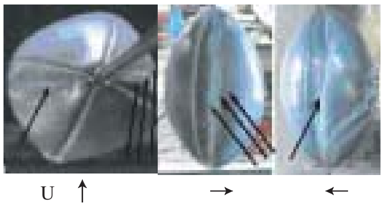
Abstract:
The aerodynamic characteristics of a rugby ball as well as its unpredictable flight trajectory are described. It is found that the side force is influenced by the four corners of the ball. The simulated flight trajectory of the ball with lower spin rate fluctuates in the lateral direction.



Introduction

There is an unpredictable flight trajectory of a rugby ball during flight. This trajectory is seen with a non-spinning (or slower

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The swimming style and fluid dynamics of swimming

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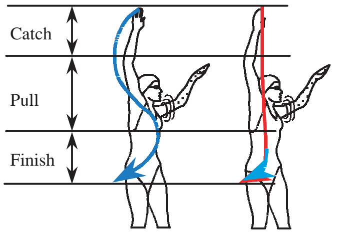

(a) S-Shaped pull (b) I-Shaped pull

Advancing movement of an animal in water can be roughly divided into two categories, locomotion of the maximal efficiency (the minimal energy consumption mode) for an usual motion and that of the maximal speed (the maximal thrust mode) for an urgent evacuation or a predatory action instinctively. Human's instinctive motion of the maximal speed might have been altered by intelligence in the swimming history.

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A current of product development for competitive swimsuits

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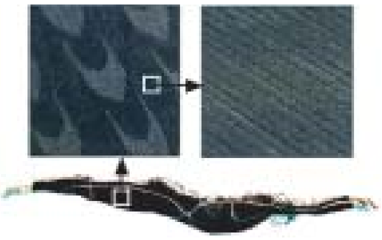
Introduction



Humans have long dream of being able to swim like fish, despite the fact that we are not physically well suited to swimming. When a human swims, the around the body undergoes a transition to turbulent flow, and drag dramatically increases. For instance, Reynolds number during human-swimming reaches a range of $2.5*10^6$ to $3.5*10^6$, then the flow around the body changes from the laminar

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Base Ball and Golfball Aerodynamics

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Continued from page 1 numerically under the initial conditions and the aerodynamic forces of ball flight. These results are confirmed by outdoor or wind tunnel experiments. These analyses are traditional or typical research method, but there is a science. When we can find the various flight equations, we feel as to find up new living thing.

Aerodynamic characteristics of sports balls1)

Sports ball is 3-D body. Reynolds number is ranging ～ 10^5～. These balls flight under lower speed of critical Re number of smooth sphere. But, the transition of surface boundary layer occurs by the influence of surface roughness of ball seams or dimples. More over, the ball rotates. The lift force acts on the backspin forward ball by Magnus effects. Index of the degree of the magnitude of aerodynamic force, which is available to make ball erratic movemant is expressed so called Mass ratio= (Ball mass) / (Air mass of ball volume). Most heavy ball with less influence of aerodynamic force is a cannonball, the sensitive ball to air force may be a beach volleyball.

Erratic behavior of baseball

Knuckle ball2),3),4)

This changing ball is special characteristics by thrown with almost zero spinning ball. Various strange changes of more than 40 cm shaking amplitudes, sudden drop and sometimes floating ball as if in the non-gravity space are observed during ball flight of 18.44m between pitcher's plate and home base.

There are two kinds of Knuckle ball with spinning axes. One is side spin knuckle ball with vertical axes with speed of about 80 Km/h. The other is rolling spin axes with horizontal axes toward home base and speed of about 110 Km/h. Tim Wakefield, measure leaguer, Boston Redsox had maneuvered the sidespin knuckleball in his earlier ages, but recently he has been throwing rolling spin knuckleball.

The aerodynamic reason of sidespin knuckle ball is explained as follows. Turbulent boundary layer on one side by a ball seam roughness → retrogression of separation line toward ball rear surface → wake shift the other side with this phenomenon → circulatory flow around ball → side force as same magnitude of drag force → change the relative position of seam with small spin by aerodynamic torque5) → reverse side force → shaking ball with alternative side force. The side forces change four times with the ball one round, so more than 0.8 round/sec, less amplitude of the flight ball results in far to the outfield of baseball park by a batter.

The aerodynamic cause of rolling spin knuckle ball is simpler, as explained as follows. The ball rotates around an axes toward forward direction (X-direction) with large side force vector. The vector raises horizontal (Z-direction) component and perpendicular (Y-direction) one. The horizontal one becomes a force cause of ball shake. This force is one cycle change with ball one round, so up to 4 round spin per second is available to make the ball with knuckle change.

We succeed in the formulation of these flutter phenomena, and well coincidences are reported with the shaking amplitude of the ball by this theoretical result and the flutter experiments with wind tunnel.

Under these theoretical explanations, we made a shooting machine of the knuckle ball. We could observe 3-D trajectory pass of the ball thrown from this machine using video camera system. In Fig.1, one example of flight pass are shown as a top view. All balls have same initial shooting condition, but non-same-trajectory ball had observed. The knuckle ball is one of the flutters. Thanks to a conversation with Tim Wakefield6).

Forkball7)

Every time, good fork balls are utilized alternatively with good straight balls. The good straight ball has a horizontal backspin axes, which makes upward Magnus force as same magnitude of ball weight. The straight ball thrown by one of the most excellent pitcher in Japan, named Matsuzaka, falls down only 3 or 4 cm during 18.44m, so it looks like a rising ball.

The other hand, the spinning axes of good forkball has oriented to vertical direction and side spinning with 10～20rps. No lift force acts on the ball, so as to fall about 70 cm naturally with gravity force. Throwing form of the

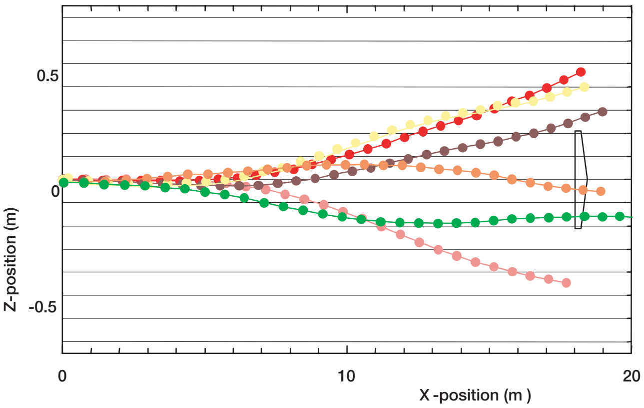

Fig.1 Knuckle ball trajectory (Top view observation: non-ball trajectory with same pass)

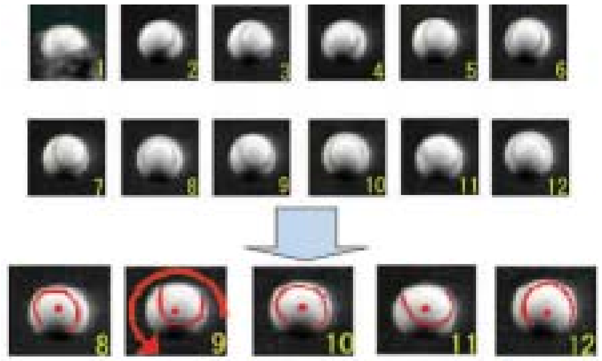

Fig.2 Vertical slider pitched by Matsuzaka, Seibu Lions, observed from catcher, U=136 Km/h, 42.5rps, 1/90sec picture.

pitcher is same as in the case of straight ball pitching. Until the half way of this ball fright, its trajectory is almost same pass of straight ball, so batter can not recognize straight or fork ball. Some time we watch on TV that batter swings one bound ball just front area at home base.

Longitudinal slider by Matsuzaka[8]

This changing ball had been much focused by many persons after that Matsuzaka became active in the Japanese professional baseball. Lundy Johnson, Diamond Backs, also has same nice slider ball. The changing feature is same as the fork ball, fall. Matsuzaka pitches this near around 140Km/h, so we call this as high speed slider. Fig.2 is high speed slider pitched by Matsuzaka photographed from catcher side. The ball seam appears in every frame as rotating U-type symbol. This means that the spinning axes direction of the high speed slider by Matsuzaka oriented to ball forward one. This ball kinematical conditions result in non-lift and non-side force on ball and the ball falls more than 70cm only by the action of gravity force. The spinning axes of U-type slider is oriented toward ball proceed, they say this as a gyro-ball, which falls down abruptly near home base by non-lift force. Less drag force of this ball spinning direction, as well known characteristics of rotating sphere, makes less speed down.

3-D trajectory analysis of golf ball fright[9]

Recent golf ball fright is achieved more than 270m distance. Maximum initial fright and spinning speed are 80m/s and 10000rpm. This fright distance is beyond 7000 times of the ball diameter. The 2-dimentional formulation of golf ball fright had already studied by Bearman and Harvey[10]. However, when we play golf, we can easily observe that golf ball fright is toward right and left detaching from its initial pass. The cause of this phenomenon had been explained as ball side spin concepts during these 100 years.

Recently, Mizota and Naruo[9] had succeeded in the formulation of 3-D trajectory of golf ball under the inclination of ball back spin axes, and conducted out door flight experiments to clarify the effects of natural wind by atmospheric boundary layer

Conclusion remarks

In this short article, we suggest that there are many scientific un-explored subjects in sports ball aerodynamics. Numerical analysis by computer is powerful weapons to approach in the problem but wind tunnel experiments are more reliable tool.

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A mysterious flight trajectory of a rugby ball

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spinning) punted ball. A slower spinning punted ball sometimes fluctuates during flight like a knuckle ball does in baseball. This has been recognized by players as a mysterious phenomenon. Why does it fluctuate?

We have carried out wind tunnel tests to measure the aerodynamic forces on a non-spinning ball, and we have simulated the flight trajectory on the basis of aerodynamic forces. The objective of this JSME international News is to reveal why the punted kick fluctuates and to simulate the mysterious flight trajectory of a rugby ball.

Wind tunnel test

A commercially available rugby ball (Triple Crown, Gilbert) was tested in a low-speed wind tunnel with a 1.5 m×1.0 m rectangular nozzle, as shown in Fig.1-a. A stainless steel rod inserted along the longitudinal axis, with urethane foam surrounding the rod (Fig.1-b).

A definition of the characteristic parameters is shown in Fig.2. Fig.2-a is the side view, and Fig.2-b is the front view. The wind speed is denoted by U. The drag, the lift and the side force are denoted by D, L and S, and the rolling, the pitching and the yawing moments are denoted by l, m and n, respectively. The angle of attack, which is the angle between the longitudinal axis of the ball and the direction of the flight path, is denoted by α. In the case of the non-spinning ball, the lace angle is denoted by σ. When the lace is situated on the top against the wind, $\sigma=0^\circ$. When the lace is situated on the right, $\sigma=90^\circ$. When the lace is backward, $\sigma=180^\circ$. When the lace is the left, $\sigma=270^\circ$. The σ variation of 360° corresponds to one rotation of the lace position.

The experimental conditions were as follows. The wind speed U was set at 20 m/s. The angle of attack α and the lace angle σ were varied from 0 to 90° and from 0 to 360°, respectively. The data were acquired with strain-gage load cells over about 10 seconds using a PC with the aid of a 12-bit A/D converter board.

The drag, lift and the pitching moment coefficients are shown as a function of the angle of attack α in Fig.3. The drag & lift coefficients are defined as the drag & lift divided by the dynamic pressure and the volume to the 2/3 ($V^{2/3}$), respectively. The pitching moment coefficient is defined as the pitching moment divided by the dynamic pressure and the volume of the ball. Since there is little lace angle dependence on these 3 coefficients, the mean values are shown. C_D increases with increasing α. C_L also increases up to 60°, and then decreases over the stall. C_m is positive except for $\alpha=0$ & 90°, that is the nose-up rotation.

The lace angle dependence of C_S is shown in Fig.4. It can be seen that C_S is almost 0 at $\alpha=0^\circ$. There is a cycle at $\alpha=30^\circ$ during one rotation of the lace. However, it appears needle-like at $\alpha=90^\circ$. There are 4 cycles during one rotation. This phenomenon might be caused by the 4 corners of the ball.

The oil flow experiment was carried out to investigate the effect of the corner. Figs. 5 & 6 show the results at $\sigma=0^\circ$ & $\alpha=90^\circ$ and at $\sigma=330^\circ$ & $\alpha=90^\circ$, respectively. The arrows below each photo denote the wind direction. When σ equals 0°, the separation lines of the boundary

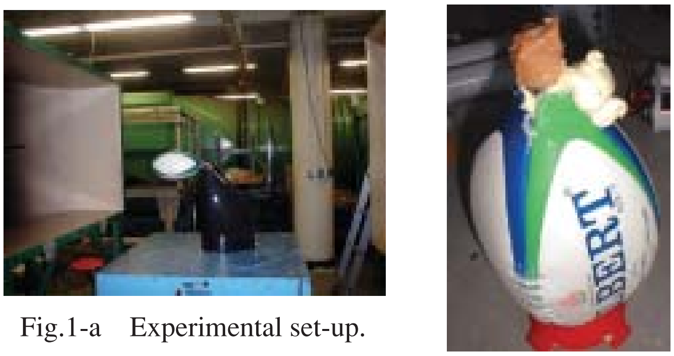
Fig.1-a Experimental set-up.

Fig.1-b Rugby ball.

Fig.1 Experimental set-up.

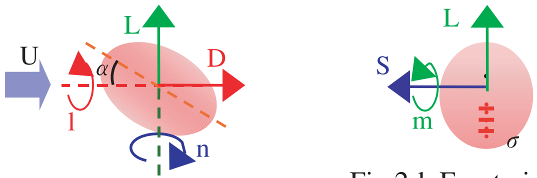

Fig.2-a Side view

Fig.2-b Front view

Fig.2 Definition of the characteristic parameters.

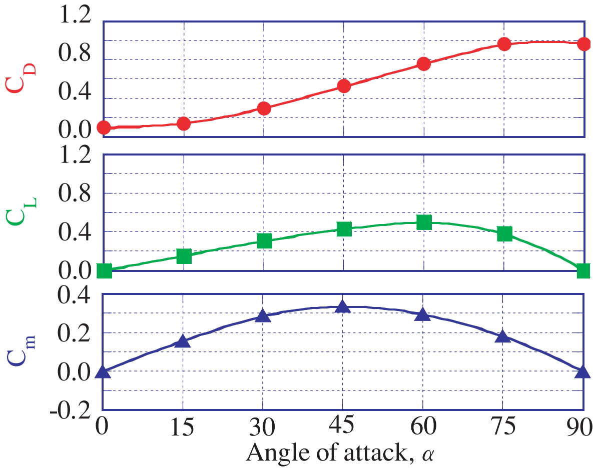

Fig.3 C_D, C_L & C_m as a function of the angle of attack α.

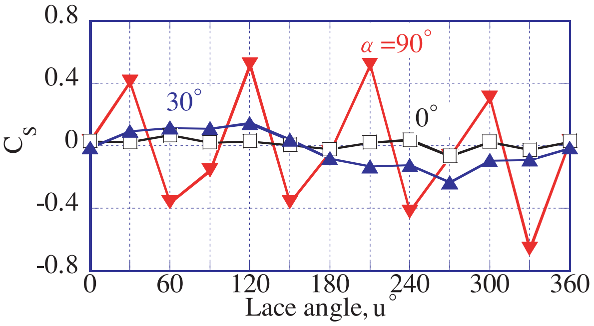

Fig.4 The side force coefficient as a function of the lace angle σ at α =0, 30 & 90°.

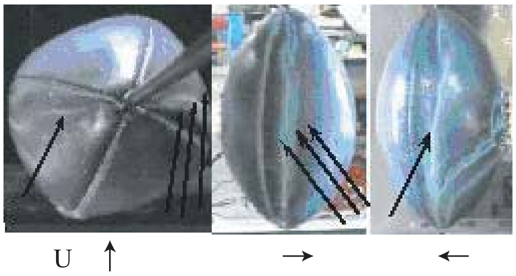

Fig.6 Oil flow pattern @ σ =330° & α =90°

layer should be symmetrical as shown in Fig.5. Therefore, no side force acts on the ball. However, the separation line is asymmetrical at σ =330° as shown in Fig.6. There are three lines on the right side, and there is a separation line on the left side. There is a chance that the right-side front corner could become a trigger of making the boundary layer turbulence, so that the boundary layer could separate further downstream side. The left-side front corner could not become a trigger because it is too close to the stagnation line. Therefore, the side force acts to the right in this case. At σ =300°, the situation is the opposite of the case at σ =330° and the side force now acts to the right. Since the streamline should be symmetrical again at σ =270°, there is no side force. This represents a cycle within 90° of rotation, so there will be four similar cycles in 360°. It can be concluded that the side force depends on the lace position because of asymmetrical flow produced by the lace and 4 corners of the ball.

Flight trajectory

Fig.7 shows an example of the flight trajectory of a punted kick from the catcher's view. This trajectory is obtained by integrating the full nonlinear six degrees of freedom equations of motion numerically1). The lateral and vertical axes in the inertial coordinate-system are denoted by Y_E and Z_E, respectively. The positive direction

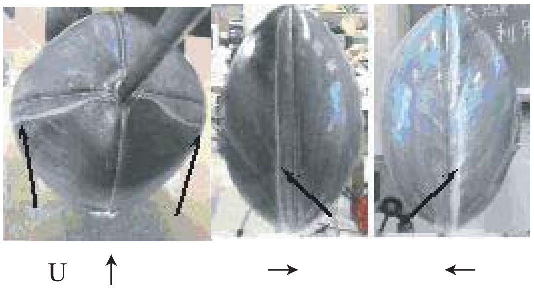

Fig.5 Oil flow pattern @ σ =0° & α =90°

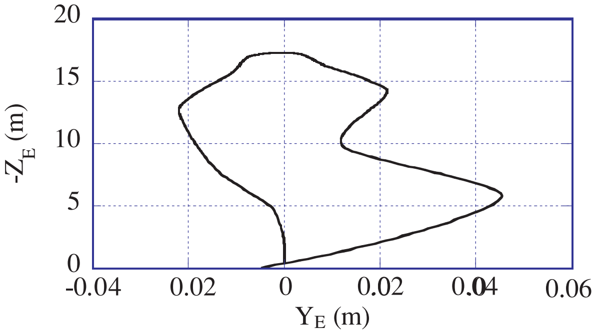

Fig.7 Flight trajectory of a punted kick from the catcher's view.

of Z_E is vertically downwards. The initial conditions are as follows; U=25m/s, α =70°, σ =0° and the spin rate on the longitudinal axis=2°/s.

It can be seen that the punted kick fluctuates in the lateral direction during the flight because of the proper combination of large angles of attack and the lace angles. The amplitude of the fluctuation is several centimeters. Since it must be difficult for the opposition to catch this kind of punted kick, it will become a powerful weapon in the game.

Summary

1. The side force depends on the lace position because of asymmetrical flow produced by the lace and 4 corners of the ball. This causes the mysterious flight trajectory.
2. The amplitude of the fluctuation is several centimeters.

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The swimming style and fluid dynamics of swimming

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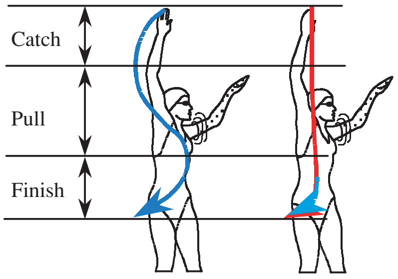
For competitive swimming, an operation of the maximal propelling force is desirable. On free style swimming, forms of the operation were calculated [1] by using equations of turtles' instinctive locomotion.

The result is reproduced in Fig.1. An S-shaped pull stroke, a popular form for the conventional front crawl, is resulted as a form of the maximum efficiency mode utilizing lift and drag force by palm paddles. On the other hand, An I-shaped pull stroke produces the maximum thrust force. It happened to coincide with the form of Ian Thorpe who has four individual world records.

1. Introduction

James Counsilman [2] is one of the first to apply physical principles to try to understand the mechanism of propulsion. His study, where underwater cameras were used for the first time, showed a skillful swimmer moved his arms in an S-shaped pattern over the body axis in rolling motion. This arm motion produced lift like a propeller on an airplane. He suggested that propeller-like diagonal sculling motion, S-shaped pull stroke, was used by skilled swimmers, acknowledging the importance of lift forces.

A speed is determined at the steady state of the body where the resistance of the whole body and propelling force are balanced. In order to reduce resistance of the body, a shark skin swimsuit has been developed. On the other hand, what affects the propulsion for its increase? In free style swimming, thrust force is mainly generated by movements of the arms (Hollander et al. [3]). They reported that the propelling force ratio of arms to legs was from 10:1 to 6:1. Moreover, the lift-drag characteristics of an arm are similar to those of a palm, says Berger et al. [4] Therefore, the lift-drag force characteristics of a palm can be considered as a main factor that rules over the impelling force



(a) S-Shaped pull (b) I-Shaped pull

Fig.1 Difference of the form on freestyle swimming

Azuma and the author [5] studied optimal ways of paddling locomotion theoretically and verified by observing swimming locomotion of reeve's and soft-shelled turtles in a water channel.

While the equations obtained by the above are applied to swimming forms of humans based on their instinct, the author introduces freestyle swimming strokes for the maximal efficiency and for the maximal speed.

2. Method

In general, when an object moves through a fluid, a force R acting upon it can be decomposed into two components: a drag force D acting opposite to a direction of an advancing direction and a lift force L acting perpendicular to it.

An inclined hand by a tilt angle θ is moved diagonally with a driving velocity U and a driving angle δ while the body moves with an advancing velocity V. As a result, a relative velocity W with an angle of attack α to the hand was shown in Fig. 2. The drag force D acts opposite to the direction of W and the lift force L acts perpendicular to W. A thrust force T is the component of the resultant force R to the advancing direction.

As an aspect ratio changes, significant differences in characteristics of lift-drag forces appear with varying

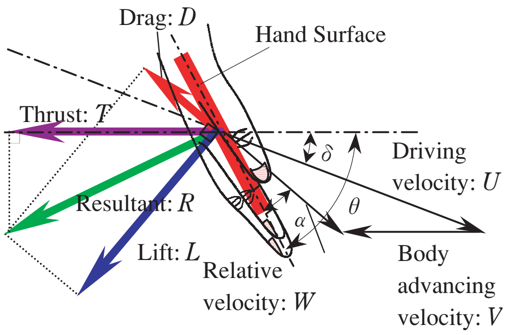


Fig.2 Forces acting on hand

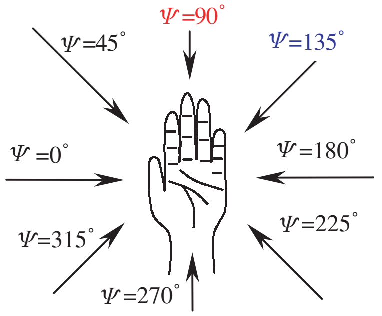


Fig.3 Sweepback angle convection

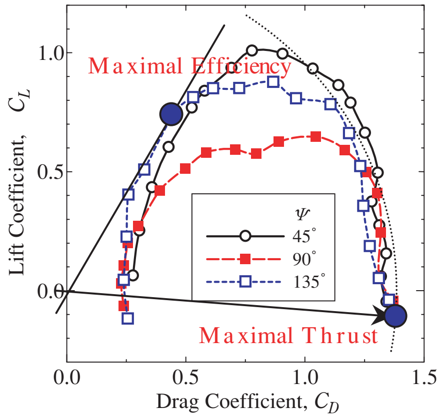


Fig.4 Hydrodynamic specification acting on a hand replica for given Ψ[6]

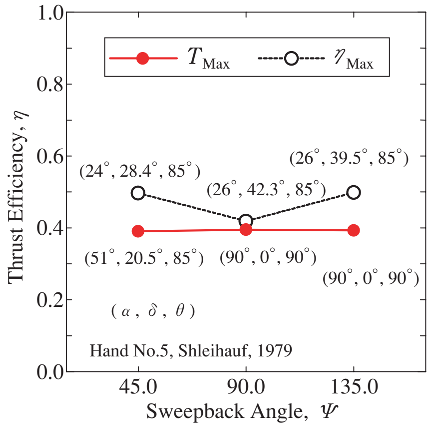


Fig.6 Differences of thrust efficiency, η in maximum thrust T and maximum efficiency η among sweep back angle Ψ

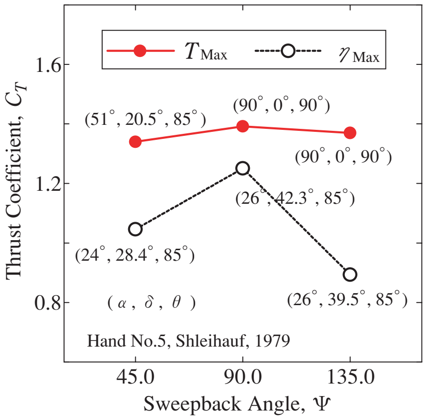


Fig.5 Differences of thrust coefficcient, C_T in maximum thrust T and maximum efficiency η among sweep back angle Ψ

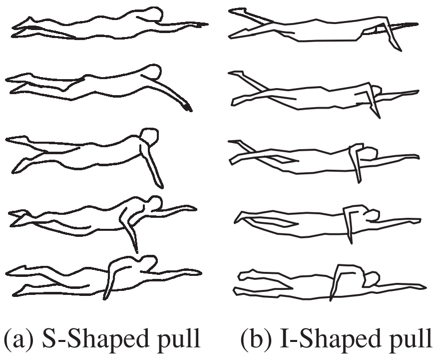

(a) S-Shaped pull (b) I-Shaped pull

Fig.7 Decomposed images of S-Shaped pull and I-Shaped pull (drag pull) form on freestyle swimming

sweepback angles Ψ whose convention is shown in Fig. 3.

Sweepback angles of a palm, Ψ=135°, 90° and 45° correspond to the catch, the pull and the finish phase on freestyle stroke shown in Fig.1 respectively.

In a constant swimming speed or in a quasi-steady state, propelling force T is equivalent to the dynamic whole body derivative resistance D_{DP}. Relation of each variable above are formulated and solved simultaneously by using lift-drag characteristics of the palm.

3. Results

The calculations show very interesting and unexpected results which differ from what were said conventionally. Moreover, they are clearly understandable as indicated in Fig. 4, whose data are rearranged by the author. The original data of lift and drag coefficient of a hand palm replica were measured by Schleihauf[6].

(i) Fig. 5 shows the differences in thrust coefficient C_T between the swimming of the maximal efficiency and that of the maximal thrust. The highest thrust coefficient C_T =1.39 is 1.11 times larger than C_T=1.25 at the time of highest efficiency. The maximum thrust can be obtained when θ=90° or θ=85°. Namely, the hand plane is almost perpendicular to the axis of the advancing direction. Each of the maximal points has the angle of attack α =90°. where coefficient C_R ($=\sqrt{C_L^2+C_D^2}$) is the maximum for the cases of Ψ=135° 90°. That is to say, the hand should be driven along the body axis parallel to the advancing direction for the entire drag forces to be used. It corresponds to the I-shaped pull motion shown in Fig.1(b).

(ii) The difference in thrust efficiency between the both methods is demonstrated in Fig. 6. It is a remarkable result that the difference of thrust efficiency in the maximum thrust, η_{TMax}=41.9%, and the maximum efficiency, η_{Max} =39.5%, is only 2.4%. The maximum efficiency η_{max} can be obtained when θ=90° or θ=85°. The angle of attack α at each of the maximum points is the stage where lift-to-drag ratio is the maximum, γ_{max}= $[\tan^{-1}(L/D)]_{max}$. It corresponds to an S-shaped pull motion shown in Fig.1(a). It reveals the under water motion of skilled swimmers.

4. Track record

It was shown by the above that drag type swimming is the fastest swimming form which generates the max thrust. Then, is this drag type swimming an impracticable theory? The answer is no. There is an actual swimmer who swims with this I-shaped pull and has 4 individual world records. His name is Ian Thorpe, an Australian swimmer, 22 years-old. Figs.7 show underwater images compared with I-shaped and S-shaped stroke by side-view. As for S-shaped pull swimming shown in Fig.7(a), the swimmer's elbow is extended in a catch phase. On the other hand, on I-shaped pull in Fig.7(b), the elbow is bent immediately after putting into water.

According to Okuno et al. [7], it is reported that his number of stroke per 50 meters is actually low compared with other swimmers and his swimming distance per stroke is longer than the others.

The author is convinced that I-shaped pull method should be the fastest form in freestyle swimming. It is not a dream that Japan's swim team could win gold medals in freestyle events in Beijing Olympic 2008.

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A current of product development for competitive swimsuits

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flow to the turbulent flow. In addition, as the Froude number corresponds a range of 0.4 to 0.5, the wave drag becomes the largest theoretically.

Swimming is a battle against drag, and only those who can beat the drag factor will become champions. To reduce drag, swimmers originally concentrated on improving their stroke or form, but now there is considerable work being done to improve swimsuits.

Aim for ultimate swimsuits

Manufacturers of sportswear have been in fierce competition to develop a new low-resistance and comfortable swimsuit. In the 1980s, swimsuits were developed that repelled water. They were light, thin and fitted the body as closely as possible. A great deal of emphasis was placed on minimizing the area of contact with the water and on materials that would expel and water that entered the suits [1][2].

After Barcelona Olympics in 1992, however, there was a radical change in swimsuit development. Application of the theory of boundary layer control of hydrodynamics gave birth to a new approach. The theory says that when a surface in uneven, such as the surface of a golf ball, the flow moves parallel to the shape of the object and resistive drag is reduced. Experiments on the efficiency of products manufactured in line with this concept had been conducted at Tsukuba University in Japan more than ten years ago [3]. However, the dimpled suits developed at that time did not yield the expected results and were uncomfortable for practical use.

The manufacturers tied to develop a new swimsuit which satisfies both of low-resistance and comfort by improving the fabric and surface treatment. Mizuno Corporation and Mie University in Japan co-developed the new swimsuit for Atlanta Olympic games in 1996. The fabric of swimsuit is "stripe printed" with slick water repellent resin to create contrasting smooth and rough stripes. The contrasting stripes generate two currents: one slow, one fast. When the fast and slow currents interact, vertical vortexes or spirals are formed. As a result the speed of water flow increases and stays closer to the body longer. The experimental result [4], which evaluated drag-reduction effects by investing the swimsuit with a mannequin, revealed up to nine percent improvement comparing to a conventional swimsuit (Fig.1). Moreover, they allocated a total of 126 small projections on the chest region of the latest swimsuit and tried to control the boundary layer. As a result, the fluid drag additionally decreased a range of 1.5 to 2.0 percent by reducing separation area [5]

Further, for Sydney Olympics 2000, a swimsuit that imitated the skin of a shark was created. These swimsuits use a material that has minute V-shaped riblets set lengthways on its surface, just like the skin of a shark (Fig.2). In addition, the cutting and sewing of the suit to cover the whole body without impeding the movement of the swimmer. Mizuno Corp. and Toray Industry Inc. in Japan were the first sportswear manufacture to develop the material. The scientific grounds for the effectiveness of sharkskin had already been established by the NASA's Langley

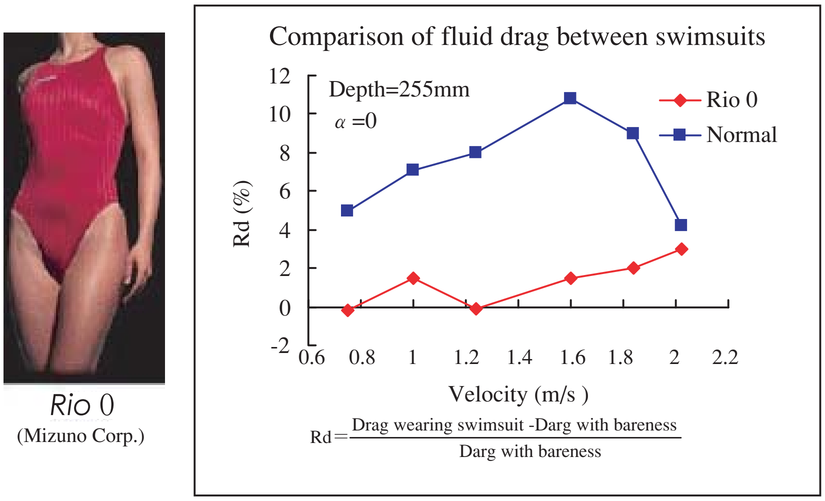

Fig.1 Comparison of fluid drag between a new concept swimsuit (red squares) and a conventionale (blue squares) (Shimizu *et al.* 1997)

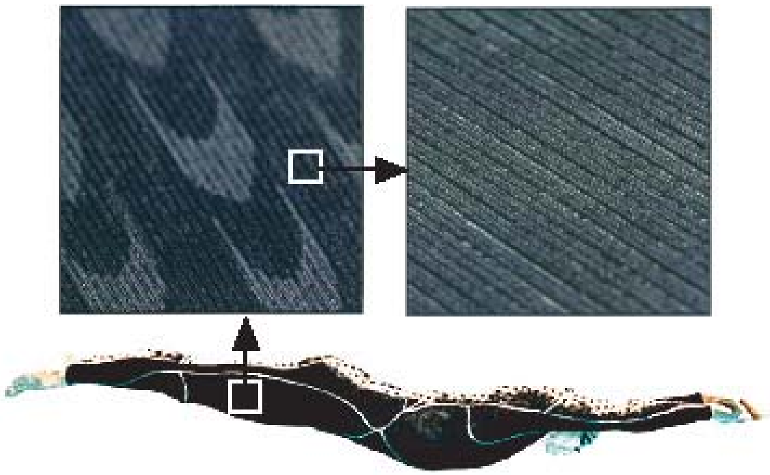

Fig.2 Surfaces of the swimsuit (*Fast-skin*™) that imitated the skin of a shark (Mizuno Corp. Japan)

Research Center [6]. However, even though the principle of the effect was understood, a great deal of technological innovation was necessary before a product could be developed. It took more than four years before the new material was perfected.

Speedo International Ltd. was largely responsible for the design of the new swimsuit. To keep the suits from impeding the muscle contractions of swimmers, it was necessary to take detailed measurements that allow for the build of each swimmer. A three-dimensional body scanner is used to measure body shape. The data from this combined with the movement analysis data of the swimming action to make a swimsuit. The swimsuits improved streamlining while allowing a full range of motion. The vibrations on the surface of the body caused by strong water currents are controlled, resulting in more reduction in drag.

To evaluate effects of the new swimsuit (*First-skin* ™), Benjanuvatra *et al.* [7] and Toussaint *et al.* [8][9] conducted experiments in different methods. Benjanuvatra at the university of Western Australia analyzed net towing force differences between swimsuit types. As a result, the new swimsuit produced significantly less resistance (range 4.8 to 10.2%) than a normal suit when swimmers were towed passively at the surface, 0.4 meter deep and when kicking at the surface [7]. These results, however, cannot apply to actual swimming because the condition is quite different between towing and self-propelling. Consequently, Toussaint at the Free University in Amsterdam measured dynamic drag force of a swimmer wearing various swimsuits during self-propelling [8][9]. Fig.3 shows that mean drag for each trial wearing the *Fast-skin* (red squares) and conventional suit (blue dots) depending on swimming speed for all subjects. The graph makes clear that no statistical significant reduction in drag was found as a result of wearing the Fast-skin. There was, however, a subject who got a significant advantage by wearing the *Fast-skin* (Fig. 4). At this time, it is undetermined whether the new swimsuit is advantageous for all swimmers. The effects must vary depending on a swimmer's body type and/or

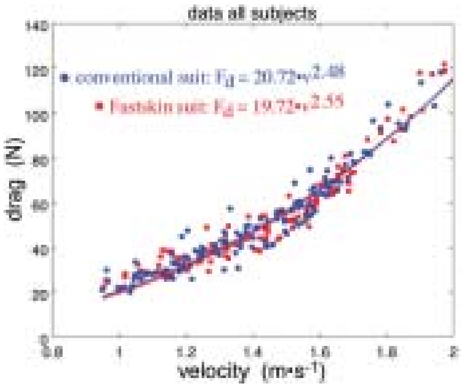

Fig.3 Drag wearing the “*Fast-skin*” (red squares) and convention al suit (blue dots) depending on swimming speed for all subjects

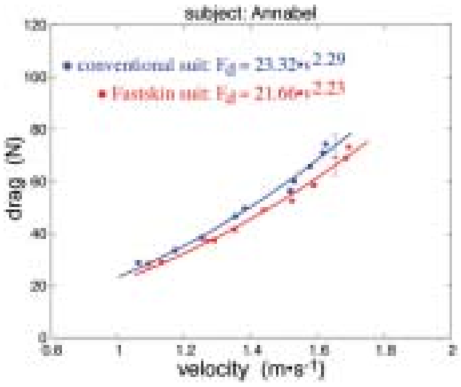

Fig.4 Comparison of drag between “*First-skin*” (red squares) and a conventional suit(blue dots) for a particular subject

specific event. Sanders at the University of Edinburgh concluded that "If you are a swimmer contemplating purchasing the new devices, suit yourself, but think about it first and be sure that the bodysuit suits you". [10]

Future outlook

In the last summer, more advanced swimsuits appeared in Athens. There is no limit to develop. The effect is modest, but can be extremely relevant for the athlete in the serious competitive situation where 1/100th second may determine the difference between rankings or breaking a record. Swimmers must be in fierce competition to get the gold medal in the future. We can't keep our eyes off only a swimmer but also a high-tech device which will be produced.

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