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The effect of swimsuit resistance on freestyle swimming race time

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Abstract

It is known that swimming equipment (suit, cap and goggles) can affect the total resistance of a swimmer, and therefore impact the resulting swimming speed and race time. After the 2009 swimming world championships (WC) the international swimming federation (FINA) banned a specific type of full body suit, which resulted in an increase in race times for subsequent WC events. This study proposes that the 2009 suits provided a reduction in swimming resistance and aims to quantify this resistance reduction for male and female freestyle events. Due to the practical difficulties of testing a large sample of swimmers a simulation approach is adopted. To quantify the race time improvement that the 2009 suits provided, an equivalent 2009 "no-suit" dataset is created, incorporating the general trend of improving swimming performance over time, and compared to the actual 2009 times. A full race simulation is developed where the start, turn, underwater and surface swimming phases are captured. Independent resistance models are used for surface and underwater swimming; coupled with a leg propulsion model for underwater undulatory swimming and freestyle flutter kick, and a single element arm model to simulate freestyle arm propulsion. A validation is performed to ensure the simulation captures the change in swimming speed with changes to resistance and is found to be within 5% of reality. Race times for an equivalent "no-suit" 2009 situation are simulated and the total resistance reduced to achieve the actual 2009 race times. An average resistance reduction of 4.8% provided by the 2009 suits is identified. A factor of 0.47 ± 10%, to convert resistance changes to freestyle race time changes is determined.

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Keywords: Swimming; Resitance; Propulsion; Simulation; Suits

1. Introduction

Elite swimming is a highly competitive sport. Tiny race time margins (0.01s) highlight the importance of understanding the factors that relate to performance, and how they can be changed. Swimsuit developments prior to the 2009 World Championships provided a significant improvement in performance. The subsequent banning of these suits resulted in the immediate reduction in swimming performance for later events. It is proposed that this reduction in performance was due to an increase in swimming resistance. Measurement of swimming resistance has been conducted by numerous studies (e.g. tow or flume experiment) as a method of quantifying swimming performance (Toussaint and Truijens, 2005). Swimming resistance may be classified as passive resistance: when

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the swimmer is producing zero propulsion, and active resistance: when the swimmer is actively swimming and interactions from the propulsive body parts and dynamic motion cause the total resistance of the swimmer to be greater than passive resistance for the same speed. While measurement of passive resistance is straight forward, direct measurement of active resistance has never been achieved, resulting in the development of predictive methods (Kolmogorov and Duplishcheva, 1992). However comparison of these methods identified varied results and large uncertainties (Toussaint et al., 2004).

Due to the practical limitations of testing a large sample of swimmers and the associated experimental uncertainty, the resistance advantage of swimmers in 2009, in comparison to other years, has not been quantified. Another approach is the use of simulation. Simulation in swimming has previously been conducted to assess individual components of propulsion. Akis (2004) created an arm propulsion model coupled with a simple resistance model to determine if this approach could reproduce realistic swimming speeds. Lighthill (1971) developed a theory to predict the propulsion produced by carangiform fish locomotion, which was adapted by (Webb et al., 2012) to simulate underwater undulatory swimming. Nakashima et al. (2007) developed a 21 segment human swimming model (SWUM) to investigate the biomechanics of swimming; however, this approach did not replicate accurate swimming speeds. No previous studies have simulated a swimmer throughout a swimming race. This study proposes to model the swimming resistive and propulsive forces, allowing the swimming speed throughout a race and the corresponding race time to be determined. By analysing world championship race times before, during and after the use of the high performance suits, the effect on race time is quantified. The aim of this study is to use the simulation approach to predict the change in resistance necessary to achieve the change in race times. This study is performed for male and female freestyle swimming in 50 m, 100 m, and 200 m events only.

2. Theory and Methodology

2.1. Analysis of Race Times

Figure 1 quantifies the relative improvement in swimming performance for 2009, world championship race times from 2001 (2003 for females) to 2013. Excluding 2009 data, there is a trend of reduced race time for consecutive world championships, which is likely due to developments in swimming equipment and coaching/training techniques brought about by improvements in technology and understanding. It is assumed that this trend is linear and therefore a fit through the data excluding 2009 has been performed. The 2009 data in all events analysed falls beneath the fit. However, a fair comparison of the 2009 data needs to include the evolution of race time from factors other than the proposed resistance reduction from high performance swimming suits. Therefore a predicted 2009 dataset was created assuming a mean race time from the fit and a standard deviation equal to mean standard deviation of the non-2009 data. For each event 8 times were selected at random from a normal distribution possessing the correct mean and standard deviation to provide a “no-suit” 2009 dataset.

To compare the actual and the “no-suit” datasets a permutation significance test has been conducted (figure 2). This is the same approach used by (Webb et al., 2013) to determine differences in measured resistance where there is a small sample and high data variability. The difference between the two datasets for each condition is presented and the confidence is identified by the p value, where the largest p value of 0.04 or 96% (female 200 m event) represents the least confidence. The widening distributions from the 50 m to 200 m events represent the greater variation in race times, and therefore to achieve equivalent confidence, greater differences need to be measured in the 200 m events.

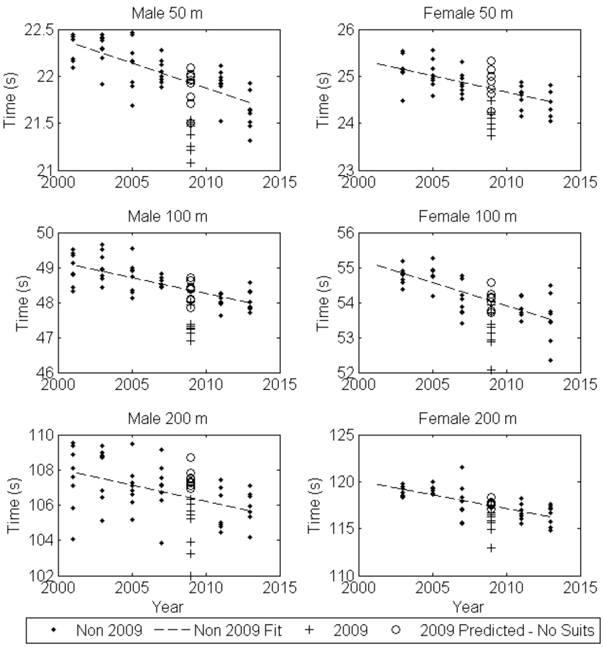

Figure 1. Final race times from world championships (Wikipedia, 2013). Race times for 2009 are also predicted assuming a linear trend through non-2009 data and average standard deviation. This provides 2009 race times assuming no high performance swimming suits.

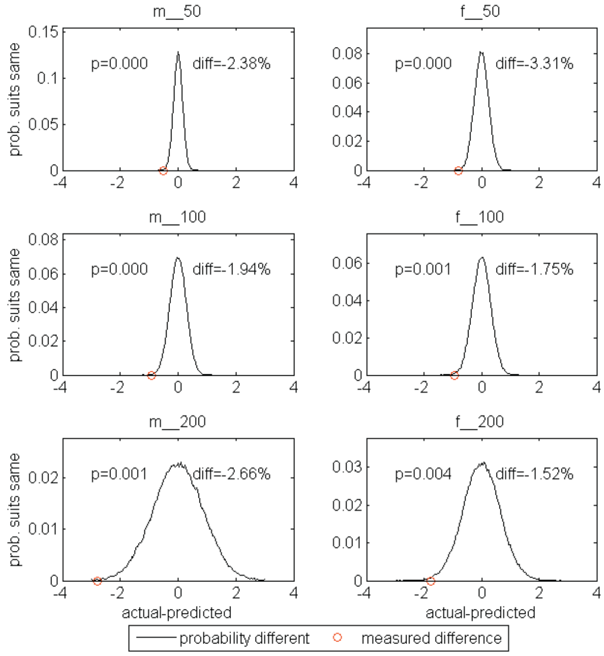

Figure 2. Permutation test to compare the actual 2009 world championship race times with times predicted for a "no-suit" condition.

2.2. Simulation Approach

The race simulation adopted in this study assumes four race phases: start, underwater swimming, surface swimming and turn. The start and the turn are not physically modelled, however the effect on distance, time and speed are included in the overall race simulation. It is assumed the swimmer enters the water at 4 ms^{-1} and 3.5 m from the wall at the start of a race, and pushes off at 3 ms^{-1} after a pause of 1.36 seconds during each turn (Cossor and Mason, 2001). Underwater swimming distances are fixed at 9 m. For surface and underwater phases, the resistance and propulsion of the swimmer are modelled independently. When swimming on the surface, propulsion is produced from the arms and legs, and the total resistance of the swimmer includes wave-making resistance. When swimming underwater, propulsion is produced from the legs only, and the total resistance of the swimmer does not include wave-making resistance. These differences influence the swimming speed; therefore, it is important the phases are modelled independently, to accurately simulate race time.

To model the motion of the swimmer only surge motion is considered, since this is the dominant motion of a swimmer throughout a race. A first order finite backwards-differencing Euler approach is used to solve the equations of motion. A fixed time step of size dt is used to calculate the state of the system at $t+dt$. An index value i is used to describe the progression of time for each time dependent variable in the model. Therefore, the acceleration in surge as a result of the net force acting on the swimmer may be expressed as,

$$a(i+1) = \frac{T_X(i+1) - \frac{R(i+1)}{(1-t)}}{m + m_{added}} \tag{1}$$

where T_X is the resolved thrust in the X – direction (direction of swimming), R is the resistance of the swimmer, m is the mass of the swimmer and m_{added} is the added mass of the swimmer. The resistive and propulsive forces in equation 1 are supplied by individual models and are specific to the race phase. Velocity and distance are derived from first order numerical differentiation. When the distance swum reaches the race distance, the model is stopped. The swimmer is treated as a point mass, which is assumed to cover the full distance of the race.

Swimming resistance is modelled for a generic male and female swimmer. To generate the resistance data, the process reported by (Webb et al., 2011) was adopted. Total resistance on the surface is assumed to comprise of wave making resistance, viscous pressure resistance and skin friction resistance (Molland et al., 2011). Total resistance underwater is viscous pressure resistance and skin friction resistance only. Wave making resistance is determined for a swimmer geometry using Thin Ship Theory, skin friction resistance is determined from an empirical formula and viscous pressure resistance is determined from experimental testing. The testing process is described in Webb et al. (2013, 2011). To simulate the change in resistance created by the suits, the total resistance value is scaled for both surface and underwater resistance.

Arm propulsion model is simulated for a range of stroke rates. The arm is represented as a single element, with motion on a fixed plane, following a circular pattern. Figure 3 displays how the arm model is represented.

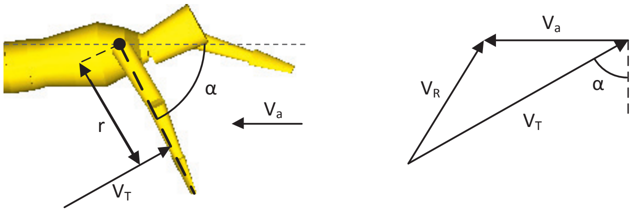

Figure 3. Arm free body diagram. The yellow graphic on the left is taken from a figure published by Nakashima (2007) and has been annotated.

The thrust generated by the arms is determined by the integral,

$$Thrust = \int_0^l \frac{1}{2}\rho(V_R \bullet [-1\ 0])^2 Wth(r) C_d(r) dr, \tag{2}$$

where l is the length of the arm, ρ is the density of the fluid, $Wth(r)$ is the width along the length of the arm and $C_d(r)$ is the drag coefficient along the length of the arm. A C_d value of 1.3 is assumed for the arm (Berger et al., 1995; Gardano and Dabnichki, 2006). Time accurate arm speed data has been determined from video analysis of a freestyle swimmer and has been normalised allowing a range of stroke rates to be simulated.

The leg propulsion model simulates the propulsion of the freestyle flutter kick, during the surface phase, and underwater undulatory swimming (UUS) during the underwater phase. The method adopted by Webb et al. (2012), which uses Lighthill's large amplitude elongated body theory to model UUS, is further adapted in this study to model freestyle flutter kick. Figure 4 displays the input motion, determined from manual digitisation of video data, used to model UUS and freestyle flutter kick.

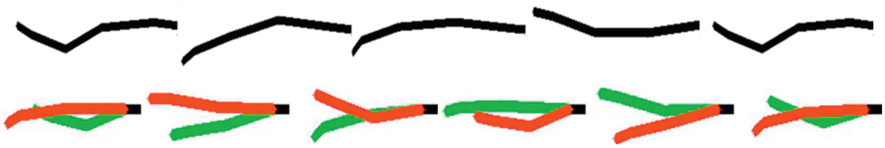

Figure 4. UUS – full body kinematic data (top) and freestyle flutter kick – legs only kinematic data (bottom)

To ensure the simulation is capable of capturing the effect of changes to resistance on swimming speed and therefore race time, the effect of a resistance augment on swimming speed was investigated. This involved measuring the total resistance of a swimmer in passive tow experiment with and without a resistance-adding device. The swimmer then conducted a number of free swims with and without the device and the swimming speed and stroke rate were measured. The same situation was simulated (fixing the stroke rate to achieve the correct swimming speed and then increasing the total resistance) to determine if the simulated speed reduced by the same amount measured experimentally. The reduction in simulated speed was within 5% of the experiment.

3. Results and Discussion

Figure 5 displays an example simulation output for a female 100 m event. The start and turn phases are characterized by the high velocities from dive and push-off. The underwater phase where the swimmer performs UUS occurs while the swimmer is decelerating after the dive and push-off. The surface swimming phases are the constant speed regions for the majority of the race. The surface swimming speed undulates due to the oscillatory delivery of the propulsion from the arms and the legs. Changes in swimming resistance affect the velocity achieved in each phase, and therefore affect race time.

Table 1 displays the simulated race times for the various events and resistance conditions. For each event (male and female), the race time predicted for the 2009 "no-suit" condition was achieved by adjusting stroke rate. To achieve the reduction in race time due to the suits, determined in figure 2, the total surface and underwater resistance were reduced, keeping the same stroke rate as for the "no-suit" condition. This assumes the reduction in race time is only due to a change in swimming resistance. This identifies a resistance reduction due to the suits of 3.9 – 6.9% or an average of 4.8%. It is important to note that these resistance reductions are directly influenced by the predicted race times simulated. Assuming final race times are normally distributed enables the difference in mean race times to be used as the comparison between the two suit conditions for 2009. Analysis of the winning race times identifies a less linear fit and therefore comparison of the actual and a range of predicted winning times might produce different results. However, if all swimmers perform a maximum effort and are of similar physiological construct, it may be assumed that a similar amount of energy is delivered over the duration of a race and therefore changes in race time represent changes in efficiency governed by technique or equipment. Since all swimmers used super suits in 2009, mean race time should provide a valid metric. Interestingly the ratio of race time saving to drag saving is on average 0.47 ± 10%. This provides a useful, but crude, conversion for resistance measurements performed in a lab to the effect on freestyle race time. For example, a measured 10% reduction in resistance would produce a 4.7% reduction in freestyle race time.

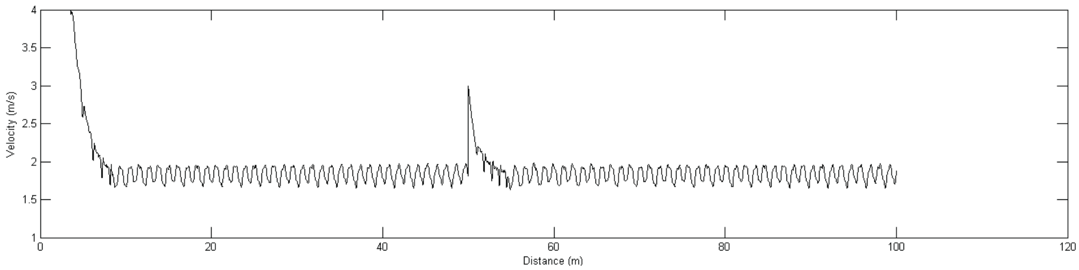

Figure 5. Simulation output displaying velocity variation throughout a 100 freestyle race.

Table 1. Simulated race times without super suits, and the % resistance reduction required to achieve the % race time reduction due to super suits, determined from the race analysis in figure 2.

Event	Simulated time without super suits (s)	% Change from race analysis	Simulated time with super suits (s)	% Resistance change to achieve reduction in race time	Time saving/ drag saving
Male 50 m FS	22.04	-2.38	21.53	4.4	-0.54
Male 100 m FS	48.49	-1.94	47.57	3.975	-0.49
Male 200 m FS	107.04	-2.66	104.27	5.7	-0.47
Female 50 m FS	24.78	-3.31	23.99	6.9	-0.48
Female 100 m FS	54.21	-1.75	53.28	4.1	-0.42
Female 200 m FS	118.92	-1.52	117.14	3.9	-0.39

4. Conclusion

It was proposed that an increase in race times after the banning of the suits used in the 2009 swimming world championships was a result of an increase in resistance. Through analysis of the race times for male and female freestyle events, a % race time difference to an equivalent 2009 prediction, if suits were not present, was determined. A full race simulation was adopted to determine the required change in resistance to result in this change in race time. To ensure accurate simulation of swimming speed and race time, independent surface and underwater resistance models were used coupled dedicated arm and leg propulsion models for surface and underwater swimming. Race times for an equivalent "no-suit" 2009 situation were simulated and the total resistance reduced to achieve the actual 2009 race times. This identifies an average resistance reduction of 4.8% provided by the 2009 suits. A factor of -0.465 ± 10%, to convert resistance changes to freestyle race time changes is determined.

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