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OPTIMAL DEPTH FOR STREAMLINED GLIDING

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ABSTRACT

This study examined drag forces created when towing swimmers through water at predetermined depths and velocities. Forty experienced male swimmers, of similar body shape, mass and height, were towed in a prone streamlined position through the water using a motorised winch and pulley system. A load cell was used to measure drag at the surface, 0.2, 0.4 & 0.6 m deep, and velocities of 1.6, 1.9, 2.2, 2.5, 2.8 & 3.1 ms^{-1}. A 2-way repeated measures ANOVA revealed significantly higher drag at the surface than at 0.2, 0.4 and 0.6 m underwater for all velocities tested. For the two slowest velocities, no significant difference was found between 0.2, 0.4 and 0.6 m deep. For the remainder of the velocities (2.2 – 3.1 ms^{-1}), the drag at 0.2 m deep was significantly higher than the drag recorded at 0.4 and 0.6 m deep, where no significant difference was found. Results suggest that it may be beneficial for swimmers to perform their glides at 0.4 m underwater to gain maximum drag reduction benefits, especially at velocities above 1.9 ms^{-1}. The inclusion of chest girth and a slenderness index as significant co-variates, highlights the need to include these variables in analysis of passive drag.

Keywords: hydrodynamic drag, streamlining, gliding, swimming.

INTRODUCTION

The resistance (hydrodynamic drag) experienced by swimmers moving through water has become an area of focus for coaches and sport scientists. Minimising the resistance could produce better results than the usual practice of increasing effort during propulsion. Knowledge of the magnitude and make up of hydrodynamic drag forces at various depths and velocities enables technique changes which reduce deleterious drag.

One method used to measure swimmer resistance in water has been to tow subjects at various velocities (Karpovich, 1933; di Prampero et al., 1974; Jiskoot & Clarys, 1975). This protocol has been used to quantify body drag in prone positions (passive drag) or while the subject is moving (active drag). However, with one exception, these studies have not analysed the drag experienced underwater. Jiskoot and Clarys (1975) found that the passive drag experienced by swimmers at 0.6 m underwater averaged 20% higher than that recorded at the surface. This result was, in part, unexpected due to the increased contribution of wave drag to the total drag at the water surface.

These results appear to contradict previous fluid dynamics studies which showed greater drag immediately under the water surface than at a depth equivalent to a depth-to-length ratio of 0.2 to 0.4 (Hertel, 1966; Larsen et al., 1981). Insufficient methodological procedures were published by Jiskoot & Clarys (1975) to determine how the depth was measured. Therefore, the evidence regarding drag remains equivocal and further clarification is required. This study sought to establish the optimal depth for streamlined gliding and whether this depth is dependent on the glide velocity.

METHODS

Forty experienced adult male swimmers acted as subjects. All were of similar body shape, mass and height to minimise the variation in drag resulting from differences in body form (Clarys, 1979). Body mass, stature, arm span, sum of 6 skinfolds; chest, waist, hip and calf girths; and bi-acromial and anterior-posterior chest breadth were measured. In addition, three variables were selected to represent the three components of drag and used as co-variates in the statistical analysis. Surface area, as calculated by Clarys (1979), was used as an indication of the frictional drag, chest girth as a measure of form drag and a slenderness index (height/weight$^{1/3}$) as an indication of wave drag. A comparison between the experienced swimmers used in the current study and elite swimmers from the 1991 World swimming championships showed no significant differences between the two groups for any of the anthropometric variables (Mazza et al., 1994).

Subjects were towed along the length of a 25 m pool at four different depths (0.6 m, 0.4 m & 0.2 m underwater and at the water surface). Figure 1 outlines the experimental set-up used during testing. At each depth, swimmers were towed at six different velocities ranging from 1.6 to 3.1 ms^{-1} in 0.3 ms^{-1} increments. This velocity range covers the practical velocities experienced by club to elite level swimmers during the push-off and glide following a turn. Swimmers maintained a prone streamlined position with hands overlapping, head between the extended arms, and feet together and plantar flexed. Each swimmer was given practice tows at different velocities and depths to become familiar with the towing protocol. The depths and velocities were randomised to prevent an order effect and swimming caps were worn during trials. Water temperature was maintained at 28 °C ($\pm$ 0.6 °C) to prevent variations in the coefficient of drag associated with different water temperatures (Clary, 1979).

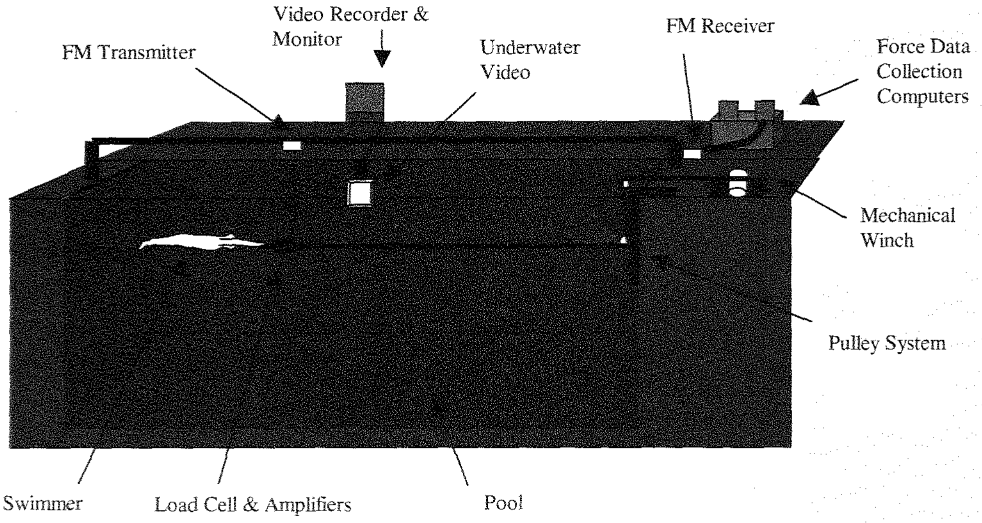

Figure 1. Testing set-up for quantifying hydrodynamic drag.

Towing was performed using a 2 HP, variable control, motorised winch. Stainless steel wire was attached from the winch to the swimmer via a pulley system, and was wound around a metal drum as the swimmer was towed through the water. A nylon webbing loop was connected to the end of the wire and positioned around the subject's wrist during towing. This allowed a more specific streamlined position of overlapping hands to be maintained with minimal flow disturbance from the towing apparatus.

The towing velocity was determined by using a variable control unit attached to the motor, which was adjustable to 0.1 ms^{-1}. Pilot testing showed that this unit enabled velocity to be consistently controlled over a range of values between 1.6 and 3.1 ms^{-1} while towing different body types. The motor was controlled remotely via a monitoring unit which initiated towing, triggered data collection on the acquisition program after 3 m of towing and acted as a safety cut-off by ceasing the towing 5 m prior to the pool wall (total towing distance of 15 m). The monitoring unit also served to calculate the displacement and velocity of the swimmer during towing. A pre-loaded mechanical clutch was added to the towing system as a back up safety measure to disengage the motor in case of a failure in the electronic cut-off.

The drag forces resisting towing were recorded using a uni-axial load cell which incorporated four strain gauges mounted on a stainless steel cylinder. Calibration of the strain gauges was performed by suspending static weights from the cylinder with results demonstrating a linear relationship (R = 1.00) between the load applied and the voltage recorded. The strain gauges were attached directly to a waterproof PVC capsule, which contained the strain gauge amplifiers and voltage-to-frequency converter. The frequency information was transferred from the load cell capsule via electrical cable to a FM modulator transmitter. This travelled along a roller system, above water, as the swimmer was towed. The FM data signals were received on the pool deck using a FM receiver/demodulator. The signals were then passed through a frequency-to-voltage converter with the resultant voltage signals collected on a PC computer for processing using the AP30 Force Analysis Program.

Depth was controlled using an adjustable, two pulley system fixed to the pool wall. The top, fixed pulley was attached to the main stainless steel tube. The lower pulley position was adjustable vertically along a track, which reached from the surface to 1.2 m deep, in 0.05 m increments. The lower pulley permitted the towing force vector to be horizontal at the required depth. An underwater video camera was positioned perpendicular to the swimmer's line of motion to ensure the swimmer was at the correct depth, and the body position was streamlined and horizontal throughout the towing trial. The underwater camera was connected to a video timer and to a video recorder where the image was displayed on a monitor. Prior to the trials, calibration of the set depths was performed with each depth marked with a horizontal line on the viewing monitor.

A swimmer's depth was defined by using the mid-line of the frontal plane when the subject was in a prone streamlined position. This applied for each of the depths underwater, with the exception of the surface depth. The surface depth was defined as the depth at which the dorsum of the swimmer's back broke the water surface, which resulted in the midline being approximately 0.1 m deep for the surface towing. Towing the midline of the body at the surface could not be achieved due to the inability of the swimmers to hydroplane across the surface at the velocities tested. During the towing trials, swimmers were provided with feedback from the video image regarding the depth level, degree of streamlining and whether a horizontal position was assumed. Any trial where the swimmer was not within +/- 0.05 m of the set depth, or was not in a horizontal streamlined position, was repeated. Most swimmers were consistently able to maintain the correct depth and streamlined position.

An LED was placed underwater within the view of the underwater camera to synchronise the drag force recordings with the underwater video footage. This enabled exclusion of sections of the trial where drag forces were inconsistent due to poor streamlining, or the subject being neither horizontal nor at the prescribed depth.

A 2-way repeated measures ANOVA was used with the drag force as the criterion measure, and the glide depth and glide velocities as the independent variables. Body surface area, chest girth and a slenderness index were included as co-variates in the analysis to represent the three components of drag: frictional, form and wave drag. Intra-day reliability of a swimmer's drag profiles was examined by one subject performing eight trials at two different depths (02. & 0.6 m) and two different velocities (1.9 & 2.8 ms^{-1}) at each depth. Inter-day reliability was quantified by re-testing a subject on separate days.

RESULTS

The means and standard deviations (SD) for the drag forces at each of the depths and velocities are listed in Table 1, and presented graphically in Figures 2 and 3. High intra-day reliability was indicated by coefficient of variation measures for these tests ranging from 1.1 % to 2.7 %, and a coefficient of multiple determination (R^2) of 0.998. Good inter-day reliability was reflected in a strong correlation ($R^2 = 0.89$) and no significant difference ($p = 0.15$) being found between the testing sessions.

Table 1. Means and SD for the drag force (N) at each depth and velocity and the percentage decrease from drag recorded at the surface depth.

Velocity	**Surface**	**0.2 m Deep**	**0.4 m Deep**	**0.6 m Deep**
1.6 ms^{-1}	67.5 ± 12.0 N	61.1 ± 10.2 N (9.5 %)	59.2 ± 10.3 N (12.3 %)	58.1 ± 9.3 N (13.9 %)
1.9 ms^{-1}	93.2 ± 12.1 N	86.6 ± 10.2 N (7.1 %)	83.2 ± 10.7 N (10.7 %)	80.4 ± 10.0 N (13.7 %)
2.2 ms^{-1}	135.4 ± 14.6 N	121.8 ± 14.2 N (10.0 %)	114.8 ± 13.0 N (15.2 %)	109.4 ± 11.1 N (19.2 %)
2.5 ms^{-1}	175.3 ± 17.3 N	153.1 ± 16.8 N (12.7 %)	144.2 ± 15.6 N (17.7 %)	140.5 ± 14.4 N (19.9 %)
2.8 ms^{-1}	211.0 ± 23.1 N	182.9 ± 19.1 N (13.3 %)	173.0 ± 17.0 N (18.0 %)	169.7 ± 16.1 N (19.6 %)
3.1 ms^{-1}	247.0 ± 25.6 N	216.0 ± 20.7 N (12.6 %)	205.6 ± 21.0 N (16.8 %)	204.1 ± 19.2 N (17.4 %)

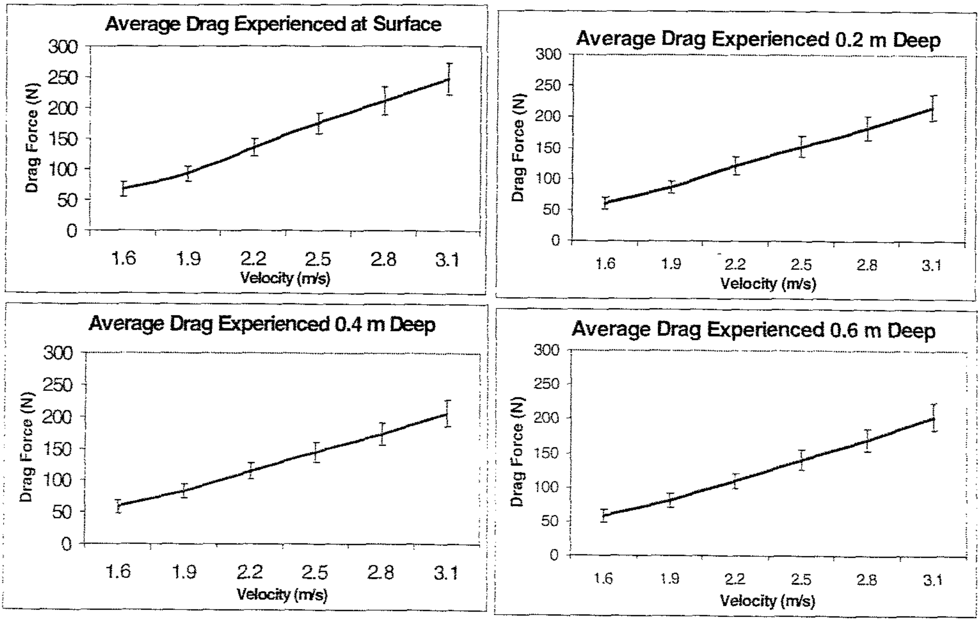

Figure 2. Graph of average drag force ± 1 standard deviation for each individual depth.

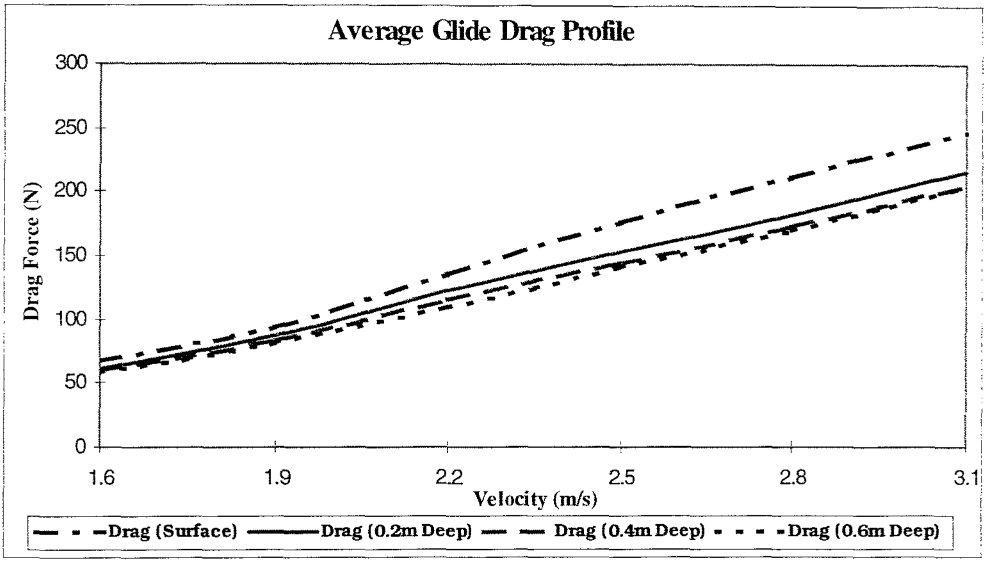

Figure 3. Combined graph of average drag force for each velocity and depth (n=40).

The 2-way ANOVA revealed significant depth and velocity main effects and depth-by-velocity interactions. All depth and velocity main effects were significant with the exception of the 0.4 and 0.6 m depths. Scheffe Post Hoc tests on the interactions demonstrated significantly higher drag at the surface than at 0.2, 0.4 and 0.6 m underwater for all velocities tested. For the two slowest velocities (1.6 & 1.9 ms^{-1}), no significant difference was found between the 0.2, 0.4 and 0.6 m depths. For the remainder of the velocities (2.2 – 3.1 ms^{-1}), the drag at the 0.2 m depth was significantly higher than the drag recorded at the 0.4 and 0.6 m depths. No significant drag force change occurred between the 0.4 m and 0.6 m depths. The inclusion of the three anthropometric variables as co-variates in the ANOVA revealed no changes in the significant interactions, despite the chest girth (F=24.3; p=0.000) and the slenderness index (F=9.8; p=0.002) reaching significance. The surface area co-variate demonstrated no significant influence (F=0.59; p=0.441) on the outcome of the analysis.

DISCUSSION

Optimal glide depth has not been determined previously despite its practical significance for swimmers. Reducing the drag experienced by swimmers during the glide off the wall can reduce turn times and unnecessary energy loss. As the push-off generally produces velocities similar to those used in this study, the results indicate that swimmers should perform their glides at approximately 0.4 m underwater to gain maximum drag reduction benefits. This is true for all velocities above 1.9 ms^{-1} where a 15-18 % reduction in drag was found when compared with that found at the surface.

These results differ from those of Jiskoot and Clarys (1975) who found significantly higher drag forces 0.6 m underwater than at the surface. They suggested that the combined frictional and eddy resistance when immersing the body in the water was greater than the extra wave making resistance resulting from a partially submerged body. Given that wave drag increases with the cube of swimming velocity, its contribution to the total resistance increases at high velocities. Hence, the low glide velocities (1.5 – 1.9 ms^{-1}) used by Jiskoot and Clarys (1975) may not have been fast enough to produce a substantial wave drag.

The present study recorded a higher drag which could represent the greater contribution of wave drag closer to the water surface resulting from the higher velocities used (1.6 – 3.1 ms^{-1}). These findings concur with results obtained by Hertel (1966) where a streamlined cylindrical body recorded the highest drag force just under the water surface, however significantly less drag at a depth equivalent to a depth-to-length ratio of 0.2 to 0.4. This is supported by fluid dynamic studies which demonstrate that the coefficient of drag decreases rapidly as the body increases in depth due to a decrease in wave drag (Larson et al., 1981).

Although the body size range of the swimmers was limited, both chest girth, which represented the subjects' form drag; and the slenderness index, which represented the subject's wave drag; significantly influenced performance. However, the body surface area, which is an indication of a subject's frictional drag, did not influence performance, which supports the data from Clarys (1979). Therefore, frictional drag could represent only a small proportion of the total drag. It is likely that, at the higher velocities, the squared relationship between form drag and velocity, and the cubed relationship between wave drag and velocity, resulted in these variables being significant. This is supported by Clarys (1979) who found that the relationship between body shape and passive drag typically increases with an increase in the glide velocity.

An optimal gliding technique incorporates maximising the distance achieved from the wall push-off by minimising the deceleration rate caused by the drag force. A more efficient glide depth and streamlining will result in an increased glide distance for the same time period, thereby reducing total turn time. Results of this study suggest that, for experienced swimmers, a depth of 0.4 m will minimise the drag for velocities above 1.9 ms^{-1}, and a depth of 0.2 m for slower velocities.

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