A LOOK AT GLIDING AND UNDERWATER KICKING IN THE SWIM TURN

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A series of studies were conducted to examine hydrodynamic drag throughout the gliding and stroke preparation phases of the freestyle tumble turn. The first study examined the effects of velocity and depth on the passive drag forces and demonstrated that significant drag reduction benefits were found with the swimmers performing glides underwater when compared to gliding at the water surface. The second study sought to establish the appropriate velocity for initiating underwater kicking, as well as the most efficient gliding position and kicking technique. The results indicate that swimmers should initiate underwater kicking at between 1.9 and 2.2 ms^{-1}. No significant differences were found between two streamline glide positions, and similarly, between three underwater kicking styles. The results of these studies present strategies for reducing the drag forces experienced by swimmers throughout the freestyle turn.

INTRODUCTION: Swimming turns represent an important factor in determining the outcome of swimming races with turning times correlating positively with the final event time (Chow et al., 1984). Swimming turns have been reported as comprising over one-third of the total race time in all events of 200 m and longer (Thayer & Hay, 1984). Hence, an improvement in turning technique could improve event time and placing. Despite the important role and availability of anecdotal evidence, there is a paucity of detailed research carried out regarding this aspect of competitive swimming.

Because of the reported exponential increases in drag with increased swimming velocity, it is the current view that technique changes should aim to reduce drag and not just emphasise propulsive effort (Rushall et al., 1994). This rationale also applies to swimming turns where drag during the glide and stroke preparation phases are considered a major determinant of total turn performance (Hay, 1985). Previous studies have not quantified the drag created during a swimming turn. Various authors have towed swimmers in a prone, streamlined position and these results can be translated, at least in part, to the glide phase of the turn (Karpovich, 1933; Counsilman, 1955; Clarys, 1979; Maiello et al., 1998), although the results of these studies are limited by the experimental designs employed. In addition, there are no objective data on drag levels experienced by a swimmer during the commencement of the underwater kick due to difficulties in quantifying active drag. Establishing drag profiles for a swimmer throughout the turn phases would enable the merits of different turning styles to be examined in more detail and specifically quantified for each individual. The development of drag profiles would then allow inefficiencies in the turning techniques of swimmers to be determined and strategies developed for correction.

STUDY ONE – THE GLIDE PHASE:
Introduction. One method used to measure swimmer resistance in water has been to tow subjects at various velocities (Karpovich, 1933; Counsilman, 1955; Clarys, 1979; Maiello et al., 1998). This protocol has been used to quantify body drag in prone positions (passive drag) or while the subject is moving (active drag). Of these studies, only two have investigated drag forces underwater with Clarys (1979) reporting 20% higher drag while being towed underwater compared with the surface. Conversely, Maeillo et al., (1998) found higher drag force at the water surface compared to gliding underwater.

In addition, the low towing velocities used in these studies have prevented the application of these results to the higher velocities experienced by swimmers during the glide phase of a turn or following a dive start. 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.

Method. 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). Subjects were towed in a prone streamlined position 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. Further information on the experimental protocol can be found in Lyttle et al. (1999). 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.
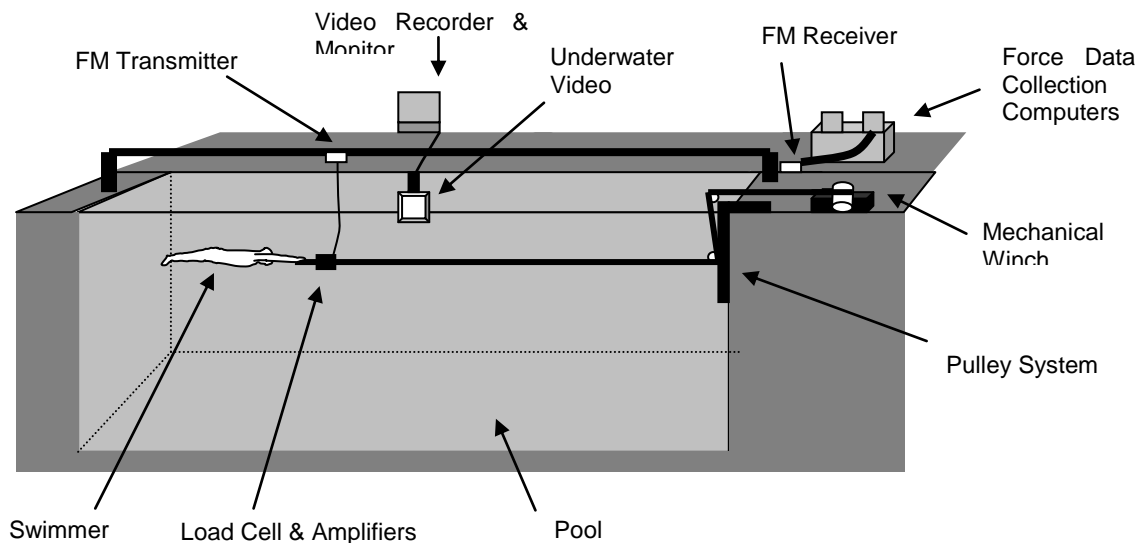

Figure 1   -   Testing set-up for quantifying hydrodynamic drag.

During each trial, the force resisting towing (drag force) was recorded using a uni-directional load cell. Depth was controlled using an adjustable, pulley system fixed to the pool wall which allowed the towing forces 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. 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.

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 Figure 2. Results 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.

Table 1   **Means (+SD) for the Drag Force (N) at each Depth and Velocity and %**
Decrease from Drag Recorded at the Surface Depth

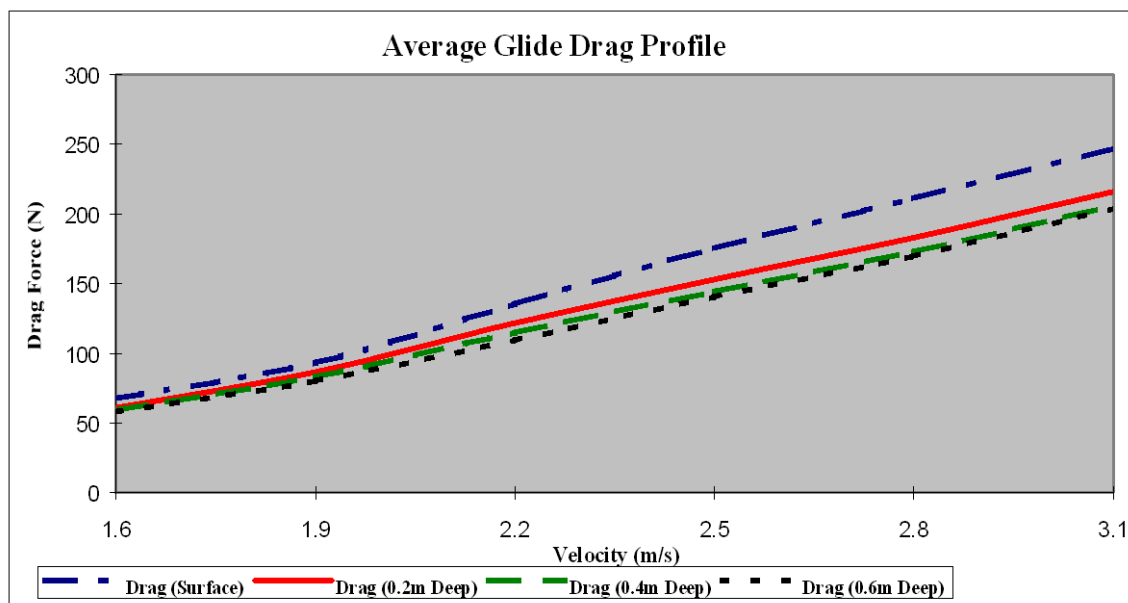| Velocity	Surface	0.2 m Deep	0.4 m Deep	0.6 m Deep
1.6 ms^{-1}	67.5 + 12.0 N	61.1 + 10.2 N (9.5 %)	59.2 + 10.3 N (12.3 %)	58.1 + 9.3 N (13.9 %)
1.9 ms^{-1}	93.2 + 12.1 N	86.6 + 10.2 N (7.1 %)	83.2 + 10.7 N (10.7 %)	80.4 + 10.0 N (13.7 %)
2.2 ms^{-1}	135.4 + 14.6 N	121.8 + 14.2 N (10.0 %)	114.8 + 13.0 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 - Combined graph of average drag force for each velocity and depth. (n=40)

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 Clarys (1979) 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 Clarys (1979) may not have been fast enough to produce a substantial wave drag. Insufficient methodological details were published to determine how the towing depth was defined in their study.

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 (1.6–3.1ms^{-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).

The results of the current study demonstrate a 10-20% decrease in the drag force when travelling at 0.4 and 0.6 m deep relative to gliding at the water surface and a 7-14% reduction when gliding at 0.2 m deep. These results, although obviously significant, cannot be used directly by coaches. It would be useful to relate the drag force (or % decrease in drag force) to a practical measure of time or distance for the coaches and swimmers. The results of the theoretical deceleration showed that an extra 0.15 s was taken to decelerate the swimmer from 3.1 to 1.6 ms^{-1} at 0.4 m underwater compared to the water surface. This equated into an increase of approximately 0.25 m of glide distance in 1 s by gliding at 0.4 m underwater compared to gliding at the water surface. These theoretical results are similar to the deceleration times experienced by swimmers during the streamlined glide following a freestyle tumble turn. Thus, the difference in the drag force between the depths is of both statistical and practical significance.

Information on the relative merits of various glide depths and velocities are important. However, in practical terms, a swimmer cannot glide at a single depth for the entire duration of the glide phase. A swimmer must negotiate his/her way to the surface from the initial glide depth in order to resume stroking. Thus, an optimal glide path exists which would allow the swimmer to transition from the initial wall push-off depth to the surface with the greatest horizontal velocity. An optimal glide path has not been determined previously despite its practical significance for swimmers. To this end, an optimal control model was developed to determine the optimal glide path using the established empirical relationships between drag, depth and velocity developed from the passive drag results.

The optimising routine revealed an optimal glide path for maximising the swimmer's horizontal glide velocity (see Figure 3). This optimal path consisted of the swimmer pushing off the wall at approximately 0.4 m underwater and maintaining this depths for a glide distance of approximately 1 m in order to obtain maximum drag reduction benefits at the higher velocities (translating into a glide time of approximately 0.4 s over the initial 1 m of gliding). Thereafter, the swimmer should begin ascending gradually for a further 1 m at a rate of approximately 0.1 m in depth per 0.2 s. This allows the swimmer to reach the water surface (midline of the body at approximately 0.1 m underwater) and begin stroking at race pace. This result is expected based on the theoretical deceleration times and glide distances for gliding at constant depths as found in the preceding passive drag section.

The results of the optimisation indicate that the optimal streamlined glide path will equate to a glide distance of approximately 2 m when pushing off the wall at 3.1 ms^{-1} and resuming stroking at the surface at 1.6 ms^{-1}. In practical terms, this optimal glide path would lead to the swimmer's head breaking the water surface at the end of the glide at just over 1 m before the 5 m backstroke flags. This is due to the average swimmer's head being at a distance of slightly less 2 m from the pool wall at toe-off. It would be expected that this distance would be increased with the introduction of the underwater kicking at the lower glide velocities due to a reduced deceleration rate.
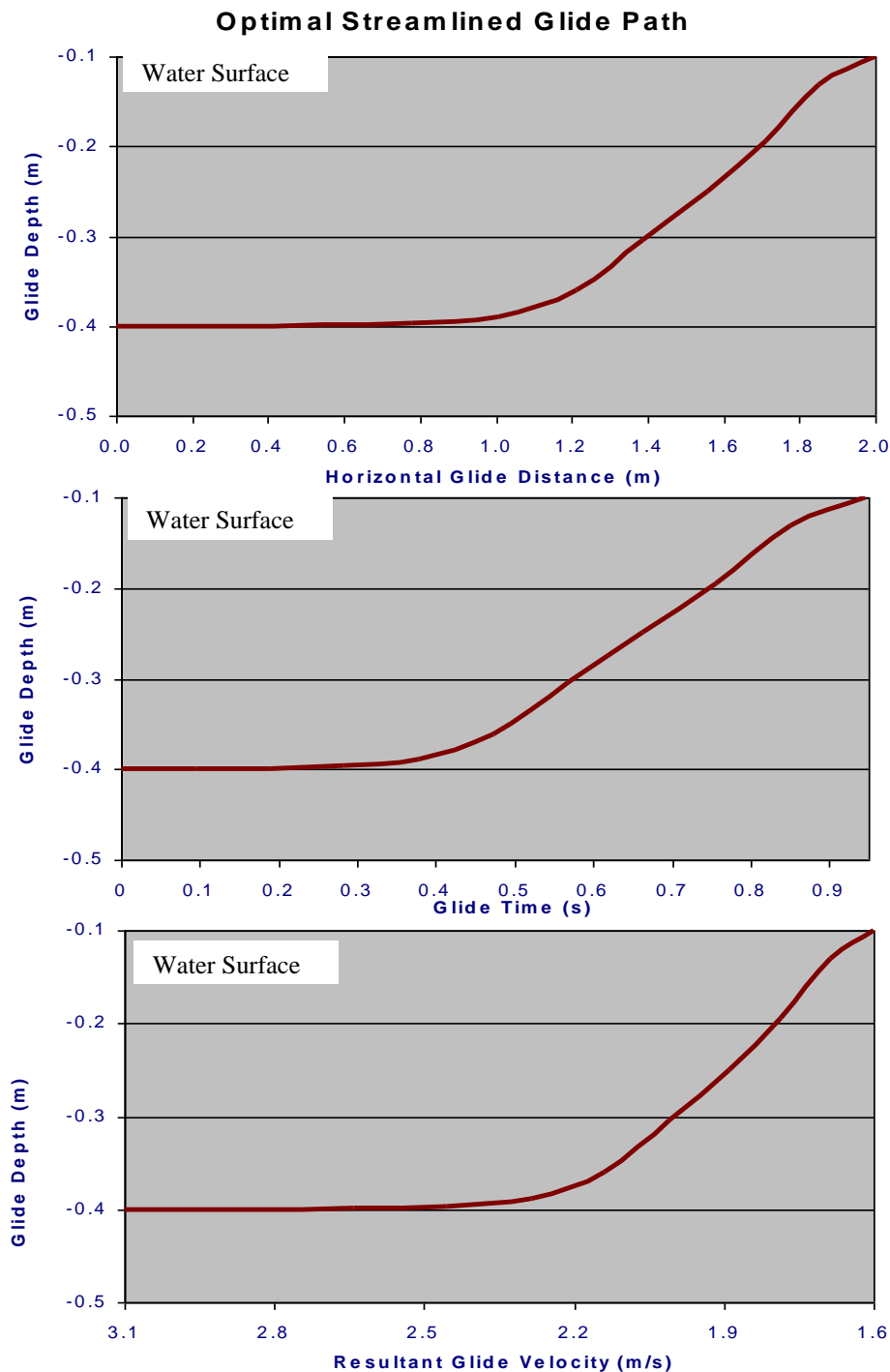
Optimal Streamlined Glide Path

Water Surface

Glide Depth (m)

Horizontal Glide Distance (m)

Water Surface

Glide Depth (m)

Glide Time (s)

Water Surface

Glide Depth (m)

Resultant Glide Velocity (m/s)

Figure 3 - Optimal glide depth vs glide distance, time and resultant velocity.

Conclusion. 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. This was extended with the development of an optimal glide path. This path indicates that swimmers should push-off the wall at approximately 0.4 m deep and maintain this glide depth for approximately 1 m for maximum drag reduction benefits at higher

velocities. Following this, swimmers should begin to ascend over the following 1 m to reach the surface and resume stroking at race pace.

STUDY TWO – UNDERWATER KICKING:
Introduction. Despite investigations of the active drag during different swimming strokes, there is little information on the hydrodynamic characteristics of underwater kicking. Coaches have also promoted a lateral streamline glide and lateral dolphin kick in competition over the traditional prone positions. Despite this, there is no evidence of any advantages of this method. Therefore, the net force created by different underwater kicking techniques and the optimal timing of the kick during the stroke resumption phase of the turn is unknown. This study sought to establish the appropriate velocity for initiating underwater kicking, as well as the most efficient gliding position and kicking technique.

Method. Sixteen adult male, experienced 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). Subjects were towed along the length of a 25 m pool at a depth of 0.5 m underwater at each of five different velocities (1.6; 1.9; 2.2; 2.5; & 3.1 ms^{-1}). The testing set-up used is similar to that used for the streamlined glide testing described above. At each velocity, the subjects performed a prone streamline glide, lateral streamline glide, prone freestyle kick, prone dolphin kick and lateral dolphin kick. All kicking trials were performed at maximal effort.
During each trial net force was recorded using a uni-directional load cell. For the kicking trials this represented the total propulsive force produced during the kicks minus the active drag force resisting towing. During the prone and lateral streamline trials the net force consisted solely of the negative passive drag forces. Therefore, it is beneficial for the swimmer to have a smaller net force during the kicking trials than that recorded during the streamline glide positions at any given velocity. The 0.5 m depth was chosen as the previous streamlined glide findings have revealed no significant differences between passive drag at 0.4 and 0.6 m deep.

Results. The means and standard deviations (SD) for the net forces at each of the velocities and towing conditions are listed in Table 2, and presented graphically in Figure 4.
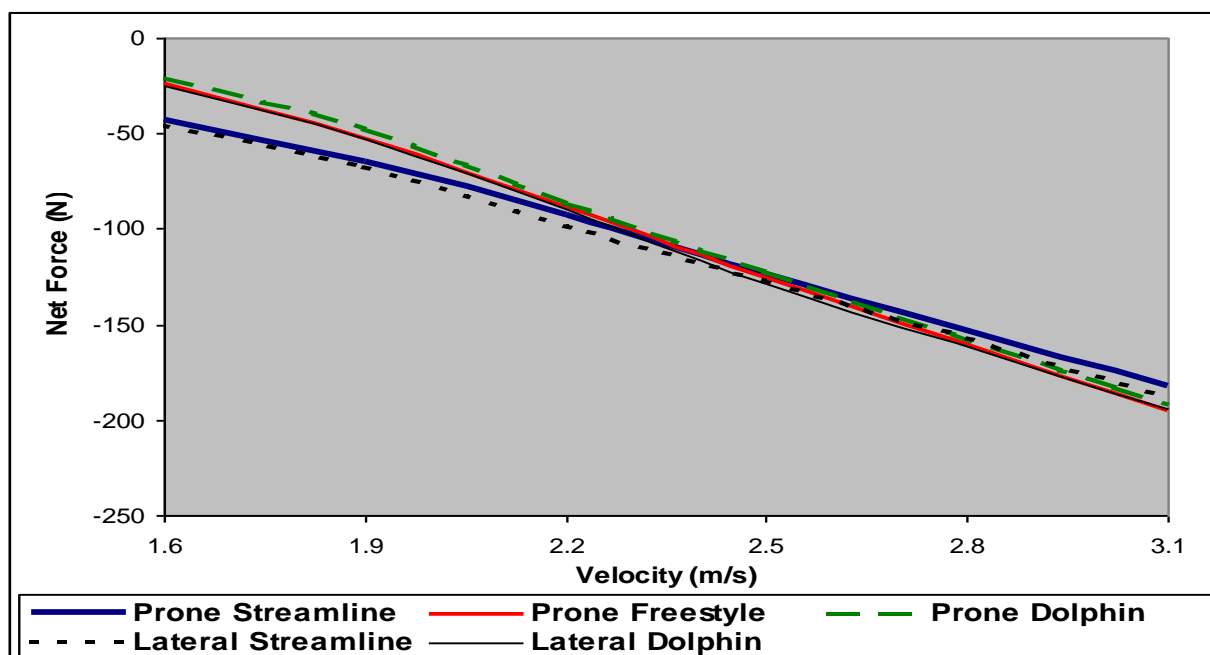

Figure 4 - Average net force for each velocity and towing condition.

Table 2   Means and SD for the Net Force (N) Recorded at each Velocity and Towing Condition

Velocity	Prone Streamline Glide	Lateral Streamline Glide	Prone Freestyle Kick	Prone Dolphin Kick	Side Dolphin Kick
1.6 ms^{-1}	- 43.3 ± 6.1	- 45.5 ± 7.3	- 24.2 ± 12.1	- 21.3 ± 12.6	- 24.9 ± 11.9
1.9 ms^{-1}	- 64.3 ± 6.7	- 67.5 ± 7.1	- 52.4 ± 15.3	- 48.3 ± 14.8	- 53.1 ± 15.9
2.2 ms^{-1}	- 92.9 ± 8.5	- 98.3 ± 9.5	- 88.7 ± 18.6	- 87.0 ± 18.3	- 89.9 ± 17.7
2.5 ms^{-1}	- 123.1 ± 12.7	- 127.5 ± 10.9	- 125.6 ± 22.7	- 122.1 ± 20.0	- 128.9 ± 19.8
3.1 ms^{-1}	- 182.5 ± 16.0	- 188.7 ± 16.6	- 195.3 ± 22.5	- 192.7 ± 22.0	- 194.3 ± 22.8

The results revealed significant differences between the towing conditions for each velocity with the exception of 2.5 ms^{-1}. At the 1.6 ms^{-1} and 1.9 ms^{-1} velocities, results revealed no significant differences between the three kicking conditions or between the two streamline positions. The streamline positions however recorded significantly higher net force than the kicking conditions. For the 2.2 ms^{-1} velocity, there was also no significant difference between the three kicking conditions or between the two streamline positions. However, for this velocity the prone streamline position was not significantly different from the kicking conditions, indicating that there is no advantage for the swimmers in kicking at this velocity. The lateral streamline position again recorded significantly higher net forces than the kicking conditions. The final velocity of 3.1 ms^{-1} demonstrated a reversal in trends. Again, no significant differences were found between the three kicking conditions or between the two streamline positions. However, at this velocity, the prone streamline position demonstrated significantly lower net forces than the kicking positions which indicate that kicking at this velocity would be detrimental to the swimmer. The lateral streamline position recorded no significant differences in net force than those recorded for the kicking conditions.

DISCUSSION: Choosing the correct time for resuming kicking after a turn as well as the relative merits of the different gliding and kicking styles, have not been determined previously despite the practical significance for swimmers. Optimising the glide and underwater kicking phases can reduce turn times and energy loss by decreasing drag. As the wall push-off and glide of experienced swimmers generally produces velocities similar to those used in this study, the net force results can indicate when swimmers should initiate underwater kicking. Information on the relative strength of swimmers' kicking styles and their streamlining ability require investigation as these will influence their gliding and underwater kicking strategy.
The preferred kicking resumption velocity can be determined from the towing testing by identifying the highest velocity at which the kicking positions produce less net force than streamline positions. This infers that the swimmer creates more propulsive force while kicking than the active drag force created by deviating from the streamline glide position. An equal or greater negative net force recorded during kicking than in the streamline glide position at the same velocity indicates that the swimmer is creating more active drag than propulsion, leading to wasted energy and/or decelerating the swimmer. It should also be noted that at no velocity did a positive net force occur, which would have indicated that the swimmer was accelerating as a result of underwater kicking.
This study found that most swimmers followed a similar trend in both the proficiency of the kicking styles and also in the streamline positions. Results indicated that swimmers should start underwater kicking at between 1.9 ms^{-1} and 2.2 ms^{-1} as this was the maximum velocity which produced a significant reduction in net force in the kicking conditions compared with the streamline positions. It was also found that no significant difference was evident between the prone freestyle kick, prone dolphin kick or the lateral dolphin kick at any of the velocities. Hence, neither kick resulted in a significant advantage over the other. In addition, no significant difference was found between the prone and lateral streamline glides at any velocity, although

the lateral streamline position tended to consistently record higher negative net forces at each velocity.

CONCLUSION: An optimal outbound turning technique incorporates maximising the distance achieved from the wall push-off by minimising the deceleration rate caused by the drag force. By initiating the underwater kick too early in the glide, there will be an increase in active drag which will act to slow the swimmer down. Conversely, gliding too long underwater before kicking will decelerate the swimmer to less than race pace and mean an increased energy demand having to accelerate the swimmer back to free swimming speed. Hence, correct timing and efficient transition from streamlined gliding to commencing and maintaining the underwater kick before swimming resumption can result in a reduced total turn time. The results demonstrated that swimmers should initiate underwater kicking using either kicking technique at between 2.2 and 1.9 ms^{-1}. This testing procedure should be performed on an individual basis in order to gain a more specific analysis of that individual's kicking strengths and streamlining ability.

SUMMARY: At the elite swimming level, the opportunity for performance improvements becomes relatively restricted. However, one possible area is to enhance turning efficiency throughout the glide and stroke resumption phases. Currently, little is known about the mechanics of an effective turn technique. When an optimal streamlined gliding and kicking path is used, the drag reduction benefits will be maximised and performance increased. Coaches should not neglect the potential benefits to be accrued by efficient turns given the increased importance of turns in longer distance events (eg. 1500 m) and in short-course (25 m pool) swimming events.

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