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Which variables may affect underwater glide performance after a swimming start?

Submission type: Original Investigation

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Which variables may affect underwater glide performance after a swimming start?

Abstract:

The underwater phase is perhaps the most important phase of the swimming start. To improve performance during the underwater phase, it is necessary to improve our understanding of the key variables affecting this phase. The main aim of this study was to identify key kinematic variables that are associated with the performance of an underwater glide of a swimming start, when performed at streamlined position without underwater undulatory swimming. Sixteen experienced swimmers performed 48 track starts and 20 kinematic variables were analysed. A multiple linear regression analysis was carried out to explore the relationship between glide performance (defined as glide distance) and the variables that may affect glide performance. Four variables in the regression model were identified as good predictors of glide distance: flight distance; average velocity between 5m and 10m; and maximum depth of the hip. The results of the present study help improve our understanding of underwater glide optimisation and could potentially facilitate improvement of overall start performance.

Keywords: Kick start, performance, biomechanics, glide efficiency.

Introduction

Considering that the time spent during a start may be up to 26.1% of the overall race time for 50m events, the slightest improvements in start performance may make a substantial difference to a swimmer's success, especially in sprints events (Lyttle & Benjanuvatra, 2005). A swimming start is often defined as the period from the swimmer's first movement on the block until he/she reaches the 15m mark or re-surfaces before the 15m (Lyttle & Benjanuvatra, 2005). The start may be split into two distinct phases, the aerial and the underwater phase, which, according to Vantorre, Seifert, Fernandes, Boas, & Chollet (2010) can then be divided into sub-phases. The aerial phase can be divided into the block phase (time between the signal and the instant the swimmer's toes leave the blocks), flight phase (time between the instant the toes leave the blocks and hand entry into the water) and entry phase (time between hand entry and toe immersion). The underwater phase can be divided into the glide phase (time between toe immersion and the beginning of the underwater propulsion of the legs), leg kicking phase (time between the beginning of leg propulsion and the arm propulsion for the first stroke while still underwater) and swimming phase (time between the beginning of the first stroke while still underwater and the arrival of the head at the 15m mark).

Start performance during the aerial phase can be improved by a rapid reaction to the start signal and high impulse generated on the starting blocks. The impulse generated on the blocks can also affect other variables of the aerial phase that are linked to overall start performance, such as horizontal acceleration (García-Ramos et al., 2015), horizontal and resultant take-off velocity (García-Ramos et al., 2015; Tor, Pease, &

Ball, 2015b), and flight distance (Seifert, Vantorre, Chollet, Toussaint, & Vilas-Boas, 2010).

Following the aerial phase, the underwater phase is where the swimmers have to manage the transition from air to water (Maglischo, 2003) and where greater differences are often observed between swimmers. Cossor & Mason (2001) indicated that overall performance times are highly correlated with the time spent during the underwater glide phase, which represents between 18 and 28% of the start time (Seifert, Vantorre, & Chollet, 2007). One of the most important factors in underwater gliding is the maximum hip depth at which it is performed. Lyttle, Blanksby, Elliot, & Lloyd (1998) found that there was a reduction of between 10-20% of drag force between depths ranging from 40-60cm and depths ranging from 0-40cm below the surface of the water. In addition, Tor, Pease, & Ball (2015a) showed that depths between 50 and 100cm reduce excessive drag forces by between 8 and 24% compared with depths between 0 and 50cm.

Previous research has focused on the relationship between kinetic and kinematic variables and time to either 5m (Peterson et al., 2018) or 15m (Seifert et al., 2010; Tor et al., 2015b). However, there is a scarcity of data on the key variables that affect underwater gliding and their relationships with key variables from other phases of the swimming start, such as the block phase, flight, and rest of the underwater phase. The identification of possible links between variables of other phases and gliding ‘performance’ could potentially affect positively the overall swimming start performance.

Considering the above, the aim of this study was to analyse the relationship between glide performance and key variables of the swimming track start. As gliding efficiency may be defined as "the ability to maintain a velocity through time and minimise the deceleration over the time", the present study used gliding distance as an indicator of gliding performance. This was based on the reasonable assumption that a greater gliding distance would be the result of an improved gliding efficiency due to a decrease in deceleration during the gliding phase. Due to the lack of research in this area, there is a lack of evidence that would allow the formulation of hypotheses on how kinematic variables may affect glide performance. Nevertheless, based on previous findings on the relationship between flight distance and full start performance, it was hypothesised that flight distance would be positively associated to glide distance.

Methodology

Subjects

Sixteen swimmers participated in this study (data are shown as Mean ± SD: age: 21.4±0.96 years; body mass 71.0±8.66 kg; height: 173.8±7.94 cm; training hours: >10 hours per week; personal best in 100m freestyle: 55.58±0.54 s). The inclusion criteria were: (i) Swimmers over 16 years old, (ii) Racing at national championship level (marks above 630 FINA points), (iii) Minimum of 5 years' experience at national competition level. Participants were familiar with kick starts and the starting blocks. Experimental procedures were fully explained to the participants, they were informed of the risks involved in the experiments, and they provided written consent before they participated in the study. The study was approved by the Institutional Ethics Committee of Nebrija University (application number FGM02102019) and was in accordance with the Helsinki Declaration.

Procedure

A pilot study was carried out three weeks before the study in the same pool where the tests were later performed. This was to determine the specific location for the cameras, the number of people needed to collect data, and the camera settings for the best quality of the images (brightness, zoom, focus, etc.). All tests were carried out on the same day in an indoor 25m swimming pool. Swimmers undertook an individualised warm-up, and then performed three trials of their normal swimming start from the starting blocks. They were instructed to maintain a streamlined position and perform no underwater undulatory swimming until they resurface. Any starts that did not meet these criteria were discarded and repeated. Participants were allowed to recover fully between trials, with resting time between trials set at 5 min. In total, 48 swimming starts were analysed (that is, all three starts for each participant).

For each start, the standardised starting signal was given with a whistle and five cameras were used for filming. Four cameras were located in two filming devices, positioned at the 5m and 12.5m marks, to synchronise video of the sagittal plane. Each device contained an above water camera (Casio High Speed Exilim Ex-FH20, 60Hz) to record the aerial phases and an underwater camera (Nikon 1-Aw1, 60Hz) to record the underwater phases of the swimming start. Additionally, a fifth camera (Casio High Speed Exilim Ex-FH20, 60Hz) was positioned at 2.6m from the start wall to film the block phase, as shown in Figure 1.

[Figure 1 near here]

The cameras were calibrated using a series of poles of fixed lengths, which were placed at known positions throughout the length of the distance that the swimmers travelled during each trial. Black tape was used to create body markers on the ankle, hip, shoulder and wrist joints (Figure 2). The subsequent kinematic analysis was done with the use of the Kinovea® (v0.8.15 for Windows) and Final Cut Pro X (v10.3.4 for Mac) software. Synchronisation of all five cameras was performed manually post-recording, by using the frame in which the swimmer' hands first broke the surface of the water on entry as the reference frame.

Based on the study of Seifert et al. (2010), the following angles were selected and analysed in the present study: Entry angles: (i) Horizontal axis/wrist/hip, (i) Hip/shoulder/wrist/ and (iii) Ankle/hip/shoulder; and Subaquatic entry angles: (i) Horizontal axis/hands at shoulder entry, (ii) Horizontal axis /wrist/hip at hip entry in the water, and (iii) Shoulder/hip/ankle at ankle entry. All variables that were selected for analysis in the present study are described in Table 1, with the angles also visually illustrated in Figure 2. The angles analysis was carried out in Kinovea. Time parameters were obtained in Kinovea, while the sequential speed variables were obtained using the formula: Average speed = total distance/ time.

[Figure 2 and Table 1 near here]

Statistical Analysis

Data for all variables are presented as Mean ± SD. Normality of distribution was checked and confirmed with the Shapiro-Wilk test. A multiple linear regression analysis was performed to check which variables may predict gliding distance. A standardised Beta coefficient was used to compare the weight of each individual independent variable with the dependent variable that had resulted from the regression analysis. Weights were expressed in percentages (%). Different multicollinearity tests (Determinant |X'X|, Red Indicator, Sum of Lambda Inverse, Theil's Method) have been applied on the explanatory variables of the linear regression model, rejecting in all of them the hypothesis of collinearity. Furthermore, the VIF (variance inflation factor) coefficient has been calculated for all the explanatory variables, taking in all cases values close to 1, which implies the absence of collinearity in the regression model.

Comparisons were carried out between groups using ANOVA and post-hoc analyses. In order to establish a range of data that would present more influence on the dependent variable, pairwise post hoc Bonferroni adjustments were also performed using estimated marginal means for each variable. From the full range of data in each variable, either four or five groups were formed depending on data dispersion. For flight distance, five groups in 20cm ranges were established (210-230, 230-250, 250-270, 270-290, 290-310), and for subaquatic entry angle also five groups in 5º ranges (10-15, 15-20, 20-25, 25-30, 30-35). Maximum depth of the hip was set in five groups in 40cm ranges (85-125, 125-165, 165-205, 205-245), with the velocity between 5 and 10m divided into four groups of 0.30 m/s (0.65-0.95, 0.95-1.25, 1.25-1.55, 1.55-1.85). All analyses were performed using the R software. The level of significance was set at $p \leq 0.05$.

Results

Descriptive data for all variables are presented in Table 1 and are expressed as mean ± SD for all the starts performed by the swimmers. As shown in Table 2, the multiple regression analysis showed that the model had great predictive ability ($r^2 = 0.7613$), and revealed four main factors of this predictive ability: flight distance; 5 to 10m velocity; angle between horizontal axis, wrist and hip at hip entry in the water, and; maximum depth of the hip. The Beta coefficients were calculated for the aforementioned significant variables in the multiple regression model. If flight distance increases by 1cm, glide distance decreases by 3cm (β=-0.03). If the angle between the horizontal axis, wrist and hip at hip entry (β=-0.07) increases by 1º, glide distance decreases by 7cm. On the contrary, the multiple regression model showed that when the maximum hip depth increases by 1cm, glide distance increases 1cm (β= 0.01). Finally, if the 5-10m velocity increases by 1 m/s (β= 2.45), glide distance increases by 245cm.

Each variable of the regression model has an eigenvalue that reflects the importance of the variable within the regression model and in relation to gliding distance. The variables that have a greater weight within the regression are: 5 to 10m velocity (14.3%); maximum depth of the hips (12.5%) and flight distance (8.1%). The phases of the start that are shown as most relevant in the regression model are: underwater phase (38.6%), entry phase (31.5%), and flight phase (28.4%) (Table 2).

[Insert Table 2 here]

The Bonferroni Post-Hoc tests ($p<0.05$) and the mean gliding distance of each sub-group are presented in Table 3. For flight distance, group 1 (210-230cm flight distance) had significantly longer gliding distance than group 3 (250-270cm flight distance), but there were no other between-group differences. For the maximum depth of the hips, groups 2 to 4 (125-245 cm) had significantly longer glide distances than Group 1 (85-

125 cm). Finally, for the 5 to 10m velocity, groups 3 and 4 (1.25-1.85 m/s) had significantly longer gliding distances than group 1 (0.65-0.95 m/s).

[Insert Table 3 here]

Discussion

The present study focused on the underwater gliding after a swimming start, with the main aim being to explore several variables from other phases of the start and identify which ones of those variables may be associated with glide performance (defined as maximum gliding distance). The results revealed four significant predictors of gliding distance: flight distance; average velocity between 5 and 10m; angle between horizontal axis, wrist and hip at hip entry, and; maximum depth of the hip.

Although flight distance was a predictor of gliding distance, the sub-group analysis did not provide a straight-forward relationship. The group that achieved the longest flight distances (group 5) seemed to also achieve the longest glide distances, but these results did not reach significance. Interestingly, the group with the shortest flight distances (210-230cm) had very similar glide distances to group 5 that had the longest flight distances (290-310cm), and it also had significantly longer glide distances than group 3 (which had flight distances of 250-270cm). It may be speculated that, although a shorter flight distance may be a disadvantage, it may also allow a more acute entry angle, with less resistance during the entry and a deeper gliding depth, which could lead to longer gliding distances. Although the long flight distance of group 5 does not allow for such an entry angle and potentially decreased resistance at entry, it seems to have similar effect on glide distance to that of group 1. This could be due to the speed difference between the flight phase and the underwater phase. The speeds reached in the flight phase are circa 6 m/s, while in the underwater phase speeds are circa 2.5-3 m/s (Tor, Pease, & Ball, 2014). Therefore, if a swimmer covers a greater distance during the flight, the time spent underwater will be relatively shorter (Breed & Mcelroy, 2000; Vantorre et al., 2010). In the past, swimmers have been advised to cover the longest possible distance during the flight without affecting their water entry (Mason, Alcock, & Fowlie, 2007; Ruschel, Araujo, Pereira, & Roesler, 2007). This may be difficult to achieve in practice though. Thus, considering the results of the present study, an optimum combination of flight distance and entry angle may be preferable. This combination may be dependent on the individual characteristics of the swimmer (e.g. body height, gliding and kicking ability), as well as on the specific demands of the race and the stroke. Cossor & Mason (2001) reported a significant correlation between flight distance and start time in the 2000 Olympic Games events. Similarly, Peterson et al. (2018) observed a high inverse correlation (r=-0.80) between flight distance and time to 5m. Nevertheless, the above studies did not directly explore the effect of flight distance on the distance of a full glide.

A swimmer's initial gliding velocity is affected by their actions in the preceding, phases of take-off and entry (Li, Cai, & Zhan, 2017). In the present study, the subaquatic entry angle 2 (horizontal axis / wrist / hip at hip entry) was a key predictor of gliding distance; an angle between 10-35° for the horizontal axis / wrist / hip at hip entry, seemed to positively affect glide distance. Although the sub-group analysis showed no significant differences, it is worth mentioning that there seemed to be a pattern of increased glide distances with larger angles. It may be possible that the range of angles in the present study, or the distinction of the angle sub-groups, were not sufficient for a significant difference to emerge. It is therefore recommended that larger or different angle ranges for sub-groups are explored in future studies.

The maximum gliding depth was also an important predictor of gliding distance. Interestingly, group 1 (max depth under 125cm) produced the shortest glide distances. The glide distances of groups 2 to 4 were very similar, suggesting that an increase in maximum depth beyond 165cm may not benefit further the gliding distance. It may be possible that the drag coefficient reduces with increasing depth. For example, Marinho et al. (2010); Marinho et al. (2009), used computational fluid dynamics simulations and determined that the drag coefficient and drag force is 44% greater in depths to 20 cm than to 250 cm. This was because a glide close to the surface contributes to the formation of surface waves, causing wave drag. Although the maximum depth of group 1 in the present study much more than 20cm, it is perhaps more likely that this group has spent a longer time gliding closer to the surface at depths that are expected to increase drag (e.g. less than 40cm). Therefore, it is recommended that average glide depth, as well as the time spent gliding closer to the surface, are both explored further in future studies. Lastly, it should also be mentioned that a deeper glide may increase the time back to surface, increase overall start time and reduce speed. Thus, the glides of groups 3 and 4 in the present study (165-245cm) may not be beneficial to performance. Future research should therefore consider both the gliding distance and the swimmers' underwater kicking and surface speed, for the purpose of optimising the combination of those factors in improving start performance.

A better glide efficiency (lower speed loss during the glide) is directly related to the speed achieved during the underwater displacement. The average speed during this phase is highly dependent on horizontal speed at entry, resistance caused during the entry and drag forces acting on the swimmer during the glide phase (Lyttle & Benjanuvatra, 2005; Naemi, Easson, & Sanders, 2010; Naemi & Sanders, 2008). The results of the present study showed that longer glide distances were achieved when the 5-10m average velocity was between 1.25-1.85m/s, compared to groups that had slower velocities, as expected. There was a noticeable trend of glide distance increasing with higher 5-10m velocities, although not all pair-wise group comparisons reached significance, highlighting the importance of high underwater velocities on glide distance.

Overall, the present study showed that some key variables from different phases of the swim start are good predictors of subsequent underwater gliding distance. A high average velocity between 5 and 10m is clearly advantageous. An angle between 10-35° for the horizontal axis, hip and wrist angle (at the instant of hip entry in the water) is also beneficial, with the angles at the higher end of this range likely to benefit more the glide distance. Maximum gliding depths of over 125cm also seem to be associated with longer glide distances, although depths of more than 165cm may be unnecessary. Finally, although flight distance is also a predictor of glide distance, their relationship is not linear and other factors, such as entry angle and body position at entry, should be considered together with flight distance, when the aim is to maximise glide performance. These findings are useful for coaches, as a training focus on the variables identified in this study could help swimmers improve underwater gliding. This would then potentially reduce energy cost of swimming, improve start performance and, subsequently, overall swimming performance.

There are some limitations in the present study that should be taken into consideration when interpreting the results. First, because the focus was on underwater gliding and gliding distance, kicking had to be excluded and, therefore, there was no direct ‘start performance’ measure. Although such a performance measure was not necessary for the present study design, it is recommended that in future studies sub-group analysis of the key indicators of glide performance is also conducted for full starts, so that the association of these variables with overall start performance can be assessed. Second, the group of swimmers tested in the present study, as well as the sub-group distinction for subsequent analysis, may have been too homogenous in skill or too limited in the range of values, for large differences to be evident. It is therefore recommended that different sub-group analyses are conducted and swimmers of other skill levels are also tested in the future.

Conclusion

The present study sought to identify the main variables that are associated with longer underwater gliding distances after a swimming start. A high average velocity between 5-10m and a maximum gliding depth of more than 125cm were associated with longer glides. An angle between 10-35° for the horizontal axis, wrist and hip (at the instant of hip entry in the water) was also beneficial. Flight distance was also a good predictor of gliding distance, although the nature of the relationship suggested that this variable should be considered in combination with some other inter-related factors that may affect start performance. Swimmers and coaches may use these findings in their training programmes, for the purpose of increasing glide distance and, potentially, improving start performance.

Declaration of interest statement

The authors have no conflicts of interest.

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Table 1. Description of the variables measured in the present study. The group data are presented as mean ± standard deviation (SD) for all starts of the swimmers. All velocities were calculated by dividing displacement with time.

	Description	Mean ± SD
Entry angle 1 (º)	Angle between the horizontal axis, wrist and the hip at hands entry in the water	41±5.4
Entry angle 2 (º)	Angle between the hip, wrist and shoulder at hands entry in the water	171±6.7
Entry angle 3 (º)	Angle between the ankle, hip and shoulder at hands entry in the water	170±11.7
Subaquatic entry angle 1 (º)	Angle between the horizontal axis and hands at shoulders entry in the water	31±5.3
Subaquatic entry angle 2 (º)	Angle between the horizontal axis, hip and wrist at hip entry in the water	22±4.6
Subaquatic entry angle 3 (º)	Angle between shoulder, hip and ankle at ankle entry in the water	190±7.7
Entry velocity (m/s)	Instantaneous velocity of the hip when the hands enter the water	5.85±0.6
Takeoff velocity (m/s)	Instantaneous velocity of the hip when the feet leave the blocks	4.5±0.5
Entry to 5 meters velocity (m/s)	Average velocity between entry and 5m (using the head as a reference point).	4.95±0.6
5 meters to 10 meters velocity (m/s)	Average velocity between 5m and 10m (using the head as the reference point)	1.25±0.2
10 meters to surface velocity (m/s)	Average velocity between 10m and surface (using the head as the reference point)	0.47±0.8
Underwater velocity (m/s)	The segmental average velocity of the underwater (using the head as the reference point)	1.25±0.2
Block time (s)	The time between the starting signal and the moment when the swimmer's feet left the blocks	0.51±0.06
Flight phase duration (s)	The time between leaving the blocks and the hands first contact with the water.	0.28±0.1
Flight distance (cm)	Horizontal distance between the the starting wall and the point of hands entry in the water	253.75±23.1
Maximum depth of the hip (cm)	The maximum vertical distance below the surface of the water that is reached by the swimmer's hip.	147.99±41.1
Gliding distance (m)	The distance between the starting wall and the point at which the swimmer's head breaks the surface of the water for the first time.	11.91±1

Table 2. Multiple linear regression.

Multiple R-squared: 0.7613	Std. Error	t value	Pr(>|t|)	β	Weights (%)	VIF(variance inflation factor)
			(I) Fly Phase			
Flight distance	0.01	-4.10	<0.001***	-0.03	8.14	1.72
			(II) Entry Phase			
Subaquatic entry angle						
(II) Horizontal axis/hip/wrist at hip entry	0.03	-2.12	0.044 *	-0.07	4.54	1.45
			(III) Underwater Phase			
5 to 10 m velocity	0.76	3.22	<0.001***	2.45	14.28	1.63
Maximum depth of the hip	0.00	2.30	<0.001***	0.01	12.47	1.97

Note: Only significant results are shown.
***: p<0.001
**: p< 0.01
*: p<0.05

Table 3. Bonferroni Post-Hoc analysis for the predictor variables of the multiple regression model. Subaquatic entry angle 2 is the angle between horizontal axis, wrist and hip, at the instant of hip entry. The $\bar{x}$ values represent the mean gliding distance of each sub-group.

Flight distance (cm)	G.1	G.2	G.3	G.4	G.5
	$\bar{x}$=12.50	$\bar{x}$=11.79	$\bar{x}$=11.27	$\bar{x}$=11.94	$\bar{x}$=12.71
G.1 (210-230)	▨	1.000	0.020*	1.000	1.000
G.2 (230-250)		▨	1.000	1.000	1.000
G.3 (250-270)			▨	1.000	0.092
G.4 (270-290)				▨	1.000
G.5 (290-310)					▨

Subaquatic entry angle 2 (º)	G.1	G.2	G.3	G.4	G.5
	$\bar{x}$= 10.80	$\bar{x}$=11.72	$\bar{x}$=11.82	$\bar{x}$=12.47	$\bar{x}$=13.06
G.1 (10-15)	▨	1.000	0.967	0.128	0.135
G.2 (15-20)		▨	1.000	0.806	0.731
G.3 (20-25)			▨	1.000	0.891
G.4 (25-30)				▨	1.000
G.5 (30-35)					▨

Maximum depth of hips (cm)	G.1	G.2	G.3	G.4
	$\bar{x}$=10.95	$\bar{x}$=12.17	$\bar{x}$=12.26	$\bar{x}$ =12.80
G.1 (85-125)	▨	0.001*	0.049*	0.000*
G.2 (125-165)		▨	1.000	0.634
G.3 (165-205)			▨	1.000
G.4 (205-245)				▨

5 to 10 m Velocity (m/s)	G.1	G.2	G.3	G.4
	$\bar{x}$=10.64	$\bar{x}$=11.69	$\bar{x}$=12.37	$\bar{x}$=13.61
G.1 (0.65-0.95)	▨	0.425	0.031*	0.039*
G.2 (0.95-1.25)		▨	0.177	0.302
G.3 (1.25-1.55)			▨	1.000
G.4 (1.55-1.85)				▨

Figure 1. Set-up of the cameras in the swimming pool.

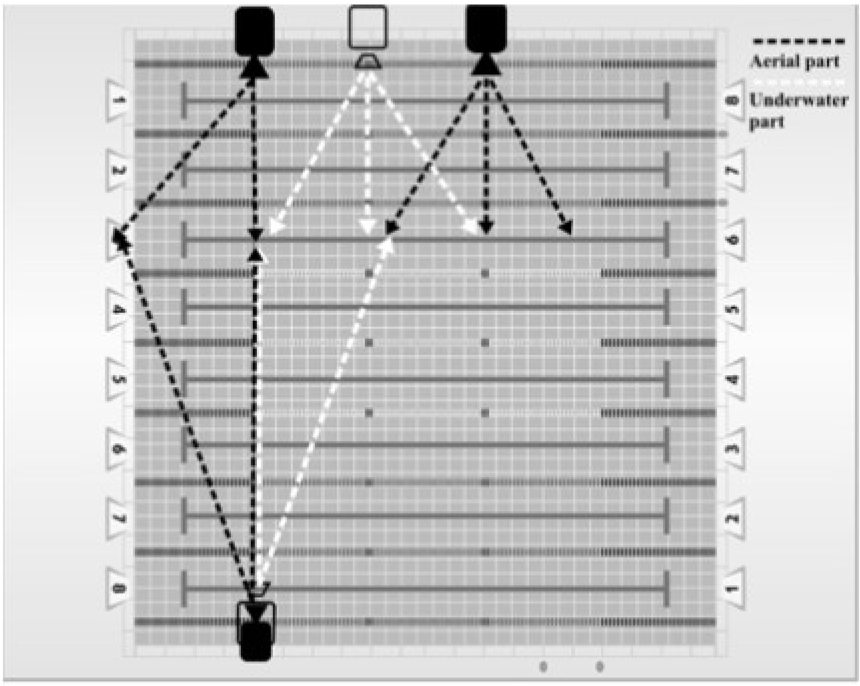

Figure 1. Cameras setup in the swimming pool

Figure 2. Illustration of the angles analysed in the present study.