A new procedure for race analysis in swimming based on individual distance measurements

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(Accepted 17 August 2012)

Abstract

The aim of this study was to develop a new application based on the "individual distances" method to analyse swimming races, and to compare it with the traditional "fixed distances" method. One hundred and seventy-nine national level 100 m (four strokes) performances obtained from the 2008 "Open Comunidad de Madrid" (Spain) were analysed using a two-dimensional Direct Linear Transformation (2D-DLT) video analysis system. Average velocities in all race segments ($P < 0.001$) were faster using the "individual distances" method than when employing the "fixed distances" method. Specifically, start and turn times were shorter ($P < 0.001$) while free swimming times were longer ($P < 0.001$) when using the "individual distances" method. Correlations between methods were moderate to high, but several gender and stroke groups showed poor to no correlation, especially during the start and turn segments. Differences between methods were higher in some groups (female swimmers and freestyle stroke) where the start and turn distances were shorter. Measurements with the 2D-DLT technique provide distances and times employed during the race segments, which do not completely agree with times at fixed distances. Therefore, when evaluating swimming races, a combination of the individual and fixed distances methods should be used.

Keywords: *sports, methods, multivariate analysis, time and motion studies*

Introduction

In swimming, performance analysis provides technical information to coaches and athletes to improve their final outcome and it has become increasingly available in major national and international competitive events (Hellard et al., 2008; Huot-Marchand, Nesi, Sidney, Alberty, & Pelayo, 2005). From a biomechanical perspective, swim race analysis reports factors following a cause-effect relationship or a deterministic model (Hay, 1985). According to this model, a swimmer's overall performance is reflected by the time he takes to complete the distance of a race, also expressed as average velocity. The total race time can be broken down for analysis into several shorter periods, characterised by the swimmers cyclic or acyclic movements: start time (time from the starting signal until the swimmer begins stroking; Miller, Hay, & Wilson, 1984), free swimming time (time spent stroking; Pai, Hay, & Wilson, 1984) and turning time (time from the swimmer initiating the turn to the resumption of stroking; Chow, Hay, Wilson, & Imel, 1984).

To our knowledge, two different methods have been utilised to report the performance criteria in swimming races. The "individual distances" method measured distances covered by each swimmer during the race segments, following the head emersion (Cossor & Mason, 2002) or the stroke movements (Miller et al., 1984) of each competitor. Distances were calculated by scaling techniques where the position of the camera was not corrected (Chow et al., 1984; Miller et al., 1984; Pai et al., 1984), which may lead to perspective errors. On the other hand, in the "fixed distances" method visual references were located at known distances from the wall (Shimadzu, Shibata, & Ohgi, 2008) to provide temporal parameters when the competitor reached the reference marks (Arellano, Brown, Cappaert, & Nelson, 1994). This procedure assumes that distances covered during each race segment are the same for every competitor, as no individual distances are measured.

In soccer, accurate photogrammetric techniques have been applied to measure distances on the field during the matches (Mallo, Navarro, Aranda, &

Helsen, 2009; Mallo, Navarro, García-Aranda, Gilis, & Helsen, 2007; Mallo, Veiga, López de Subijana, & Navarro, 2010). Based on Direct Linear Transformation (DLT) algorithms (Abdel-Aziz & Karara, 1971), the camera orientation was corrected to transform two-dimension screen coordinates (in pixels) of the video frames into real coordinates (in metres) of the field of play. This 2D-DLT technique or Fractional Linear Transformation (Robertson, Caldwell, Hamill, Kamen, & Whittlesey, 2004) has been highly recommended to reconstruct two-dimension coordinates when accuracy is paramount (Brewin & Kerwin, 2003).

To date, the estimation of race segments with fixed distances is widely accepted (Tourny-Chollet, Chollet, Hogie, & Papparodopoulos, 2002) but no previous publications have compared it with true distances covered by the swimmers. When a swimmer emerges before the start or turn reference mark, he covers the distance to the reference mark with swimming strokes. Therefore, some swimming strokes could be included into the start and turn race segments if using fixed distances. Considering that no studies have applied 2D-DLT to swimming race analysis, the first purpose of the present study was to develop and apply a new method to measure individual race segments. The second purpose was to compare the "individual distances" method with the traditional "fixed distances" method. It was hypothesised that the "fixed distances" method overestimates the contribution of the start and turn race segments to the total race time and, consequently, the estimated average velocity during race segments could not represent the true average velocity.

Methods

Finals sessions during the Third "Open Comunidad de Madrid" (an international competition organised by the Madrid Swimming Federation in two stages between March and July 2008) were recorded in a 50 x 25 m pool. All experimental procedures were reviewed and approved by the Technical University of Madrid's ethics committee. Written informed consent was obtained from all the participants prior to the commencement of the investigation. End race times comprising from 700 to 900 points (according to the Fédération Internationale de Natation Point Scoring System) were considered as national level and were included for further analysis. In total, 179 performances during the A and B Finals of the 100 m events (four strokes) were analysed. Sample group sizes for each event as well as end race times (mean ± standard deviation) are shown in Table I.

Three fixed JVC® GY-DV500E video-cameras recording at 25 Hz, as recommended for swimming race analysis (Arellano et al., 1994), were positioned at the stands, 7 m above and 7 m away from the side of the pool. Each camera captured a different segment of the race: start (from start blocks to 15 m), free swim (from 20 to 30 m) and turn (from 35 to 50 m) segments. This study only employed recordings from the start and turn segments. The beginning of the time code was provided by a light flash connected to the official timing system and captured by the camera filming the start segment.

Two methods were used to analyse each of the 179 performances:

i) The "individual distances" method utilised 2D-DLT based algorithms (Abdel-Aziz & Karara, 1971) to reconstruct the movement plane. Computerised analysis of the frames, including a digitisation process, was carried out with the software Photo 23D (Technical University of Madrid, Spain; Cala, Veiga, García, & Navarro 2009). This method was employed to measure the race segments according to Hay's deterministic model (Hay, 1985). The beginning and/or ending of each race segment was defined by either the swimmer's hand entry or head emersion, as follows: start (from the start signal to the mark where the swimmer's head completely breaks the surface after the underwater swim), turn (from the swimmer's head at the last hand entry before the wall to the mark where the swimmer's head completely breaks the surface after the underwater swim), free swim 1 (from the end of the start segment to the beginning of the turn segment) and free swim 2 (from the end of the turn segment to the end of the total race). In breaststroke, the only action defining race segments was head emersion as no hand entry clearly occurs. Time (s), horizontal distance (m) and average velocity ($m \cdot s^{-1}$) from the beginning to the end of each segment were calculated.

ii) In the "fixed distances" method, visual reference points located at known distances from the wall were employed to overlay vertical lines on

Table I. End race times (mean ± standard deviation) and sample size of each event during III Circuito Open Comunidad de Madrid.

Event	*n*	End race times (s)	IPS
Men 100 m breaststroke	24	66.06 ± 1.21	756.73 ± 43.12
Women 100 m breaststroke	22	74.03 ± 1.66	744.22 ± 52.50
Men 100 m freestyle	30	52.35 ± 0.59	785.91 ± 26.72
Women 100 m freestyle	26	58.23 ± 0.81	798.95 ± 34.22
Men 100 m backstroke	21	59.41 ± 1.13	749.78 ± 44.58
Women 100 m backstroke	19	66.14 ± 1.75	760.45 ± 60.53
Men 100 m butterfly	18	56.61 ± 1.33	765.51 ± 54.95
Women 100 m butterfly	19	63.12 ± 1.40	764.06 ± 51.72

*IPS: Fédération Internationale de Natation Point Scoring System each camera view. In this case, the beginning and/or ending of each race segment were defined by the swimmer's head touching these digital lines. To minimise perspective bias, each camera focused on only one reference. This method represented the traditional approach for swimming race analysis and was used to estimate each race segment as follows: Start (from the start signal to the 15 m mark), free swim 1 (from the 15 m mark to the 42.5 m mark), turn (7.5 m before and after the wall) and free swim 2 (from the 42.5 m mark to the total race end). Time (s) and average velocity ($m \cdot s^{-1}$) from the beginning to the end of each segment were calculated.

Eight pool-side building marks uniformly distributed on the horizontal plane were recorded in each camera and were used as control points for calibration purposes in both methods. The accuracy of the 2D-DLT technique was assessed reconstructing the positions and distances between 32 control points, represented by coloured buoys from the floating lanes. Reference lines connecting the near and far sides of the pool were used to place the coloured buoys at exactly the appropriate distance. The root mean square error of the 2D-DLT technique was 0.050 m when reconstructing the position of the 32 control points, and 0.046 m when reconstructing the distance between them. Even though there is no way to evaluate the accuracy of every measurement during the race (Challis, 1995), the consistency of the measurements was also checked. Two freestyle technical actions defining race parameters (head emersion and hand entry) were repeatedly digitised 32 times, with a coefficient of variation between 0.53% in lane 1 and 0.93% in lane 8.

Measurements with 2D-DLT technique from the beginning to the ending of each race segment are expressed as means and standard deviations (s). Repeated-measures MANOVA (multivariate analysis of variance) using the multivariate mixed model (Schutz & Gessaroli, 1987) were utilised to compare the "individual distances" method with the "fixed distances" method. Time and average velocity were compared in each race segment (start, free swim 1, turn and free swim 2) regarding the stroke (backstroke, breaststroke, butterfly and freestyle) and gender (male and female).

Significant multivariate differences between methods were followed up with univariate analyses using Wilks' methods. Bonferroni adjustments were performed to prevent an inflated experiment-wise error rate (EER) and effect sizes (ES, as partial eta-squared values) were used to interpret meaningful effects (Knudson, 2009). The assumption of homogeneity of covariance was tested using the Mauchly Test of Sphericity and, where necessary, the critical value of F was increased according to the Huynh-Feldt Epsilon value (Schutz & Gessaroli, 1987).

Finally, the relationships between methods for each inter-subject group were analysed using Pearson's correlation coefficients, in order to facilitate the interpretation of previous MANOVA analysis. All analyses were conducted with SPSS 15.0 (SPSS Inc., Chicago, IL, USA). The alpha level was set at 0.05 for all the statistical tests.

Results

The kind of method used for race analysis was found to exert a significant multivariate effect (method x race segment) on the race segment data (Wilks lambda = 0.02; $F_{6.988} = 977.49$; $P < 0.001$; ES = 0.85), both on time ($F_{1.585} = 2928.90$; $P < 0.001$; ES = 0.94) and velocity measurements ($F_{2.451} = 263.09$; $P < 0.001$; ES = 0.62). The start, turn and free swim average velocities were faster ($P < 0.001$) using the "individual distances" than the "fixed distances" method. Start and turn times were shorter ($P < 0.001$) while free swim times were longer ($P < 0.001$) when using the "individual distances" method. All gender and stroke comparisons between methods are presented in Tables II and III. Significant differences were detected for all the comparisons during the start, free swim 1 and turn segments, except for the velocity during the backstroke turn, the breaststroke free swim 1 and the butterfly free swim 1. Significant differences between methods during free swim 2 were only detected for some comparisons. Time and average velocity differences (%) between methods were greater for the female swimmers and freestyle stroke inter-subject groups.

Measurements with the 2D-DLT technique from the beginning to the ending of each race segment are presented in Table IV. Distance covered during the start segment reached between 8.05 m (female's 100 m freestyle) and 12.87 m (male's 100 m backstroke). Distance covered during the turn segment was in the range from 5.66 m (female's 100 m freestyle) to 11.06 m (male's 100 m backstroke). The maximum contribution of the non-swimming segments (start and turn) reached 23.9% of the total race distance.

Average velocity showed a high correlation between methods whereas time was moderately correlated, as presented in Table V. In some groups, the average velocity showed a moderate correlation between methods during the start (freestyle and butterfly), free swim 2 (breaststroke and butterfly) and turn (backstroke) segments. In addition, no correlation ($P > 0.05$) between methods was observed in time during all stroke starts and turns. Finally, an inter-methods negative correlation ($P < 0.05$) was found during the backstroke and butterfly turn times.

Discussion

In this study we developed a new method for race analysis in swimming based on the 2D-DLT technique. The technical characteristics of the 2D-DLT or Fractional Linear Transformation (Robertson et al., 2004) allowed direct measurements,

Table II. Comparisons of methods (mean ± standard deviation) for the inter-subject groups swimming race velocity measurements ($m \cdot s^{-1}$).

	Race segment	Group	Fixed distances	Individual distances	% difference
Gender	Start	Male	2.15 ± 0.18	2.33 ± 0.26***	8.31%
		Female	1.87 ± 0.18	2.10 ± 0.27***	11.80%
	Free swim 1	Male	1.69 ± 0.17	1.69 ± 0.17***	0.39%
		Female	1.53 ± 0.14	1.54 ± 0.15***	0.57%
	Free swim 2	Male	1.59 ± 0.19	1.61 ± 0.16**	1.25%
		Female	1.42 ± 0.15	1.45 ± 0.16***	1.94%
	Turn	Male	1.79 ± 0.16	1.84 ± 0.23***	3.10%
		Female	1.58 ± 0.15	1.63 ± 0.16***	3.00%
Stroke	Start	Breaststroke	1.84 ± 0.17	2.03 ± 0.16***	10.74%
		Freestyle	2.19 ± 0.16	2.51 ± 0.18***	15.04%
		Backstroke	1.88 ± 0.17	1.95 ± 0.15***	3.90%
		Butterfly	2.14 ± 0.16	2.34 ± 0.17***	9.33%
	Free swim 1	Breaststroke	1.40 ± 0.08	1.40 ± 0.08	0.12%
		Freestyle	1.79 ± 0.10	1.81 ± 0.10***	0.95%
		Backstroke	1.57 ± 0.08	1.58 ± 0.08***	0.79%
		Butterfly	1.66 ± 0.09	1.66 ± 0.09	0.17%
	Free swim 2	Breaststroke	1.29 ± 0.09	1.33 ± 0.09**	2.65%
		Freestyle	1.70 ± 0.10	1.71 ± 0.09	0.39%
		Backstroke	1.50 ± 0.10	1.51 ± 0.09	0.46%
		Butterfly	1.52 ± 0.17	1.57 ± 0.09***	3.10%
	Turn	Breaststroke	1.49 ± 0.12	1.54 ± 0.10***	3.34%
		Freestyle	1.87 ± 0.12	1.99 ± 0.18***	6.50%
		Backstroke	1.71 ± 0.12	1.71 ± 0.13	0.07%
		Butterfly	1.68 ± 0.11	1.71 ± 0.10*	1.98%

Significant differences between methods: *$P < 0.05$;**$P < 0.01$; ***$P < 0.001$

Table III. Comparisons of methods (mean ± standard deviation) for the inter-subject groups swimming race time measurements (s).

	Race segment	Group	Fixed distances	Individual distances	% difference
Gender	Start	Male	7.02 ± 0.60	5.07 ± 1.29***	−27.78%
		Female	8.09 ± 0.80	5.08 ± 1.44***	−37.21%
	Free swim 1	Male	16.46 ± 1.64	21.74 ± 1.90***	32.08%
		Female	18.17 ± 1.76	25.05 ± 2.33***	37.86%
	Free swim 2	Male	26.66 ± 2.68	26.57 ± 2.25	−0.34%
		Female	29.68 ± 3.13	30.55 ± 2.82***	2.93%
	Turn	Male	8.45 ± 0.77	5.23 ± 1.55***	−38.11%
		Female	9.55 ± 0.97	4.82 ± 1.43***	−49.53%
Stroke	Start	Breaststroke	8.25 ± 0.80	5.58 ± 0.49***	−32.36%
		Freestyle	6.89 ± 0.51	3.44 ± 0.64***	−50.07%
		Backstroke	8.04 ± 0.70	6.34 ± 0.93***	−21.14%
		Butterfly	7.06 ± 0.53	4.93 ± 0.98***	−30.17%
	Free swim 1	Breaststroke	19.65 ± 1.16	26.53 ± 2.31***	35.01%
		Freestyle	15.42 ± 0.86	22.17 ± 1.74***	43.77%
		Backstroke	17.56 ± 0.90	22.34 ± 1.85***	27.22%
		Butterfly	16.63 ± 0.93	22.53 ± 2.14***	35.48%
	Free swim 2	Breaststroke	32.21 ± 2.11	32.17 ± 2.69	−0.12%
		Freestyle	24.94 ± 1.27	26.5 ± 1.65***	6.26%
		Backstroke	28.32 ± 1.76	28.19 ± 2.54	−0.46%
		Butterfly	27.21 ± 1.68	27.37 ± 2.54	0.59%
	Turn	Breaststroke	10.15 ± 0.80	5.98 ± 0.66***	−41.08%
		Freestyle	8.04 ± 0.50	3.18 ± 0.37***	−60.45%
		Backstroke	8.83 ± 0.61	5.90 ± 1.21***	−33.18%
		Butterfly	8.97 ± 0.57	5.04 ± 1.11***	−43.81%

Significant differences between methods: ***$P < 0.001$

Table IV. Descriptive data (mean ± standard deviation) of individual distances measurements during the race segments of each event (m).

Gender	Stroke	Start	Free swim 1	Free swim 2	Turn
Male	Breaststroke	12.06 ± 0.69	36.11 ± 0.92	41.85 ± 0.76	9.97 ± 0.90
	Freestyle	9.17 ± 1.50	39.07 ± 1.63	44.71 ± 0.58	7.04 ± 0.65
	Backstroke	12.87 ± 1.80	34.54 ± 1.89	41.52 ± 2.17	11.06 ± 2.27
	Butterfly	12.16 ± 1.77	36.43 ± 1.84	41.75 ± 2.09	9.66 ± 2.20
Female	Breaststroke	10.52 ± 0.71	37.89 ± 0.96	43.11 ± 0.60	8.48 ± 0.98
	Freestyle	8.05 ± 1.04	40.68 ± 1.08	45.61 ± 0.51	5.66 ± 0.54
	Backstroke	11.87 ± 1.99	35.99 ± 2.07	43.02 ± 1.86	9.11 ± 1.88
	Butterfly	10.69 ± 1.85	38.11 ± 1.96	43.52 ± 1.55	7.68 ± 1.66

Table V. Relationships between methods (individual distances and fixed distances) for the gender and stroke groups during swimming race segments.

	Start	Free swim 1	Free swim 2	Turn
Average Velocity				
Total	0.899**	0.995**	0.932**	0.930**
Male	0.890**	0.993**	0.941**	0.890**
Female	0.905**	0.997**	0.880**	0.954**
Breaststroke	0.960**	0.997**	0.618**	0.923**
Freestyle	0.793**	0.991**	0.927**	0.877**
Backstroke	0.933**	0.938**	0.876**	0.765**
Butterfly	0.658**	0.995**	0.833**	0.939**
Time				
Total	0.493**	0.845**	0.928**	0.463**
Male	0.598**	0.798**	0.895**	0.612**
Female	0.632**	0.820**	0.945**	0.655**
Breaststroke	0.256	0.952**	0.970**	−0.348
Freestyle	−0.114	0.898**	0.979**	−0.179
Backstroke	−0.115	0.733**	0.867**	−0.328*
Butterfly	−0.175	0.853**	0.913**	−0.448*

**$P < 0.01$

without estimations, of the causal mechanical variables based on Hay's deterministic model (Hay, 1985). To our knowledge, this has been the first time that 2D-DLT methodology, previously validated and applied in team sports (Mallo et al., 2007), has been applied to swimming race analysis.

The main finding of this study was that the individual start, free swim and turn variables do not completely agree with their estimation when using the fixed distances method. As expected, high inter-methods differences (effect size close to 1) were detected with temporal measurements, due to the different operational definitions. Additionally, average velocity during the race segments, the main performance criteria in competitive swimming, was meaningfully different when comparing both experimental techniques. According to our results (Table IV), distance covered during the non-swimming race segments varied between 14% and 24% of the total race depending on the event. These data are considerably different than the estimated 30% when the start and turn segments are defined as 15 m fixed distances. Thus, even though the estimation of race segments with visual references is widely accepted (Tourny-Chollet et al., 2002), precautions should be taken when solely evaluating performances with fixed distances.

The actual distance covered by national level swimmers during the start segment (until the swimmer's head completely breaks the surface after the underwater swim) is in the range from 8 to 13 m, whereas distances in the turn segment (from the last stroke before the wall) average 8 m. Both measurements are longer than previously reported in competition, where freestyle start and turn distances were close to 10 m (Miller et al., 1984) and 7 m (Chow et al., 1984), respectively, at the completion of the first freestyle stroke after the emersion. Significant changes in the development of underwater techniques since 1984 could explain this increase in the start and turn distances.

The criterion to define each race segment when measuring individual distances should depend on the positive or negative acceleration affecting the swimming strokes (Havriluk, 1983), due to the technical elements of the start and turn segments. This has been hypothesised to occur at the emersion (Cossor & Mason, 2002), the first meter (Havriluk, 1983) or the first stroke cycle (Miller et al., 1984) following the underwater swimming phase. In this study, the end of the underwater phases in start and turns was considered at head emersion for all events to allow event comparison.

According to our results, the "fixed distances" method underestimated the average velocity of the swimmers during the start and turn, whereas it overestimated the duration of the start and turn segments. The inclusion of swimming strokes into the start and turn race segments could help explain this. When a swimmer emerges before the 15 m start reference mark, he covers the distance to the reference mark with swimming strokes usually at a slower velocity than the previous underwater swimming phase (Burkett, Mellifont, & Mason 2010). As an example, the swimmers in our study emerged between 3 and 6 m before the 15 m reference mark.

In the turn segment, recordings with a single camera measured the same fixed distance in and out the turn, in order to avoid perspective errors (Shimadzu et al., 2008). Using this procedure, several stroke cycles are included from the reference mark (usually at 7.5 m) to the wall (Tourny-Chollet et al., 2002).

Discrepancy between the two compared methods is even greater in some of the groups (female swimmers and freestyle stroke: Tables II and III), where the start and turn distances are relatively shorter (Table IV). In these groups the differences between the true distance covered by the swimmer and the estimated distance with a reference mark are greater, possibly due to a shorter underwater phase. This has been previously reported for turn (Chow et al., 1984) and start distances (Miller et al., 1984) in these groups. Therefore, the performance assessment with fixed distances in the freestyle stroke should be cautious, as this has been the most studied stroke in swimming race analysis (Thompson, Haljand, & MacLaren, 2000).

Even though the two methods for race analysis are different, high correlations between them could recommend the use in some cases of the "fixed distances" method, which is experimentally simpler (Brewin & Kerwin, 2003). In the present study, high correlations were obtained during the free swim 1 but not during the start, free swim 2 and turn segments, especially for the strokes (backstroke and butterfly) with underwater undulatory swimming (Connaboy, Coleman, & Sanders, 2009). As the "fixed distances" method includes several swimming strokes in the start and turn segments, the lack of concordance between methods would suggest poor correlation between the swimming and non-swimming actions (Prins & Patz, 2006), especially the underwater undulatory techniques. Thus, when evaluating the race segments, non-swimming actions and swimming strokes should be identified to lead to an effective analysis of the performance criteria. The estimation with fixed distances could fail to predict the small differences between competitors during the start and turn segments (Guimaraes & Hay, 1985).

At this point, however, the "individual distances" method should not completely replace the "fixed distances" method. By measuring the time to cover a set distance, the "fixed distances" method allows for a comparison between swimmers (Thompson, Haljand, & Lindley, 2004) which can be easily replicated in training. At a national competitive level, the start and turn times could be measured to the 10 m and 7.5 m reference mark, respectively, from the starting or turning wall. Coaches could employ the mean individual distance values in this study to establish more accurate fixed distances by gender and stroke.

Conclusion

A new method for race analysis in swimming based on the 2D-DLT technique was developed and applied. Individualised race performance variables with a great concordance with the theoretical (deterministic) model of reference were provided. The "individual distances" method showed statistical differences and moderate correlations with the "fixed distances" method, especially when some swimming strokes were included into the non-swimming race segments. Therefore, a combination of both methods should be used to analyse swimming races.

Acknowledgements

This study was partially granted by the Madrid Swimming Federation with grant number P0711001056. Also, the authors would like to thank Cristina Lopez de Subijana for his valuable help editing the manuscript.

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