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ISBS '99 : XVII International Symposium on Biomechanics in Sports, June 30-July 6, 1999, Edith Cowan University, Perth, Western Australia: Swimming

Ross Sanders (Ed.)

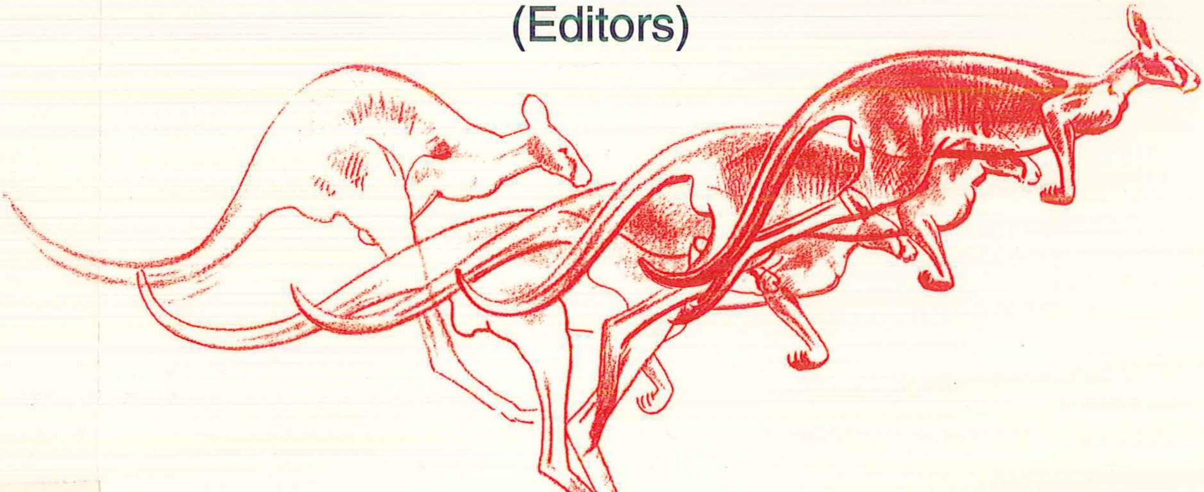
ISBS '99

INTERNATIONAL SOCIETY OF BIOMECHANICS IN SPORTS

Applied Proceedings of the XVII International Symposium on Biomechanics in Sports

SWIMMING

Ross Sanders
Joram Linsten
(Editors)



School of Biomedical and Sports Science

EDITH COWAN UNIVERSITY

FREEDOM THROUGH KNOWLEDGE

PERTH WESTERN AUSTRALIA

ISBS'99

XVII International Symposium
on
Biomechanics in Sports
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APPLIED PROCEEDINGS:

SWIMMING

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School of Biomedical and Sports Science
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PREFACE

The International Society of Biomechanics is Sports (ISBS) and the School of Biomedical and Sports Science, Edith Cowan University, are pleased to present the proceedings on swimming from the applied program of the XVII International Symposium on Biomechanics in Sports.

The papers comprising these proceedings were written by international experts in swimming research. The International Society of Biomechanics in Sports is confident that this and future publications will contribute to the major goal of the Society, that is, to 'bridge the gap between sports biomechanics researchers and practitioners in teaching, coaching, training and rehabilitation'.

Perth, June 1999

Ross H. Sanders (ISBS'99 Symposium Convenor)

Barry J. Gibson (Head of the School of Biomedical and Sports Science, Edith Cowan University)

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WHERE ARE RACES WON (AND LOST)?

Bruce Mason
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An analysis of the 1998 World Swimming Championship competition analysis data from Perth indicated that the relationship between the race performance and stroke length was not significant, apart from in the Mens 100 metre freestyle event. It was also evident that average free swimming velocity was related to the race performance for all events. This was to be expected. The race performance in the backstroke and breaststroke was related to both start and turn performance. In the butterfly events, race performance was related to turn performance. In the freestyle sprint events the start performance played a significant role whereas in the middle distance events, the turn performance was significantly related to the race performance. None of turn, finish, or start performance played a significant role in the distance freestyle events. In the individual medley events, turn performance was significantly related to race performance. The order of importance of free swimming velocity in the various strokes on race performance, with the exception of the Mens 200 metre individual medley, was in order backstroke, butterfly, breaststroke and freestyle. The above information is directly relevant to a general competition model. However, individual swimmer competition models may differ significantly from the general model.

KEY WORDS: World Championships, swimming, competition analysis, performance, elite

INTRODUCTION: Competition analysis was conducted at the 1998 World Swimming Championships in Perth by the Biomechanics Department of the Australian Institute of Sport. Assistance was provided by staff and students from the School of Biomedical and Sports Science at Edith Cowan University and by students from the Human Movement Department at the University of Western Australia. In total, the analysis involved 30 people and the analysis process continued around the clock for the duration of the championships, utilising a rotation of three analysis groups. The competition analysis was performed for every event on the swimmers who progressed from the heats to the finals in each event. The analysis was performed on both the swimmer's heat and final performances. The information from the analysis was made available to each swimmer analysed in the form of handout sheets. The handout for each swimmer contained an individual analysis sheet, an individual graph of the relationship of stroke rate and stroke frequency to the swimmer's velocity, a graph of the swimmer's velocity throughout the race in relation to that of the first and second place getter's velocity, and a summary spreadsheet for the event that contained the analysis information for all finalist competitors. The handout was provided to each swimmer prior to the next competition session commencing. A comprehensive booklet containing spreadsheets for all finalist performances in each event was provided for every nation that competed. The complete analysis booklet was available to the national swim teams from the morning following the last day of the championships.

The primary purpose of the handout was to provide the coach and the swimmer with feedback as to how well the swimmer competed. The information presented in the handout could be used to identify how the swimmer performed in relation to his or her competition model and this could then be used to fine tune the swimmer's competition model for the final of the event or to perform a total revaluation of the competition model. A total change in the swimmer's competition model would only be attempted between different competition meets where there was plenty of time to train the swimmer to the new model. The information provided from the heats could be used by the coach to make small adjustments

to the swimmer's tactics prior to the finals of the event concerned. Probably the best illustration of this was in the 1500 metres Mens Freestyle event at the Atlanta Olympics in which Kieren Perkins only just qualified, by some hundredths of a second, in the eighth spot for the final of the event. The competition analysis from the heat performance indicated that Kieren lost most of his time to the other finalists in the turns. Kieren's coach, John Carew, was made aware of this problem. Even though Kieren was sick with a stomach cramp complaint at the time of the heats, the analysis information identified for Coach Carew that he and Kieren needed to concentrate on the turns in the final. The rest is history as Kieren easily won the gold medal in the 1500 metres Mens Freestyle at Atlanta. Not only is the analysis information from the heats essential for the swimmer's performance to be optimised in the particular competition. The analysis of a final may be used to make effective changes to a swimmer's competition model in the same stroke but over a different distance prior to the heats being conducted for that event.

Competition analysis can best be used to identify where a swimmer's weaknesses exist. It is far more economical to improve a swimmer's performance by eradicating weaknesses than working on the swimmer's strengths. A swimmer's weaknesses or inefficiencies can be identified by examining the competition analysis of the swimmer's performance in comparison to that of swimmers of roughly equal ability. A swimmer's weakness may involve the start, the turns, the finish or the overall free swimming performance. It could also be associated with how the free swimming is performed over the various sections of the race. The swimming velocity is the overall measure of the free swim performance, but the stroke frequency and stroke length are the two major ingredients that result in the swimming velocity that is achieved. It may have been one of either stroke length or stroke frequency that determined whether or not there was a weakness in race strategy or swimming technique. Once a weakness is identified, the swimmer's competition model may be changed by the coach to define a better race stategy. The coach then needs to train the swimmer to the new competition model. Probably the best example of this occurred in the 1500 metres Mens freestyle at the Atlanta Olympics. Although Daniel Kowalski won the silver medal in this event he only managed to beat Graeme Smith of Great Britain by some hundredths of a second. The competition analysis revealed that Daniel lost over seven and a half seconds to Graeme in the turns. This implied that Daniel needed to make up the 7.5 seconds in the free swimming to beat Graeme Smith in the final. The identification of poor turning performance resulted in a revision of Daniel's competition model by the coach to incorporate faster turns. The coach then needed to train Daniel in the turns in order to enable him to perform to the new model during competition.

The analysis booklet which contains information concerning all the swimmers who competed in the finals, could be used to identify the way other swimmers and coaches have developed their competition model. It could also be used to identify general changes that have occurred in competition strategy as a consequence of rule change or technique enhancement. An example of rule change was the revision of the turn rule in the backstroke events to now allow the swimmer to rotate onto the front of the body followed by the tumble turn. How does such a change affect turning speed? An example of technique enhancement is the undulating breaststroke used by many women in preference to the flatter breaststroke. What changes to stroke frequency and stroke length occur as a consequence of such technique enhancement changes?

Apart from the benefit that can be gained by improving the performance of a particular swimmer, the competition analysis information can also be utilised in a statistical analysis to identify the factors that are important to a general model in the various events. Information gained from such research could be used to advantage by the coach through concentrating the swimmer's attention to those aspects of an event that are closely related to the event

result. The research project attempted here was to identify those aspects of performance from the competition analysis which were related to the race performance in the various events.

METHOD:

Following the competition analysis being completed, a Pearson correlation statistical analysis was performed on the data using the swimmers' result times as the criterion or dependent variable. The result time obtained by each of the 16 finalists was the best indicator of the race performance of each swimmer and therefore was used as the criterion variable for each event. This research has direct implication to elite performance, as the 16 finalist performances used in this study may be considered to be representative of the fastest 16 swimmers in the world for each event. A number of other variables, obtained for each of the finalist performances, from the competition analysis results were used as independent variables. These included free swim velocity, start time, turn time, finish time, stroke length, stroke frequency and efficiency index. The aim of this project was to identify any relationships these variables may have had with the race performance as determined by the official race time of the finalists. It should be noted here that although correlation statistical analyses may indicate that a significant relationship exists, it does not necessarily imply a cause and effect relationship. For instance just because turn time correlates highly with performance in a particular event it does not imply that turning ability by itself will determine the race result. However, it would suggest that possibly swimmers' abilities to turn quickly may be a significant factor in determining the result of the race. This could possibly be the case as all swimmers may have had similar free swimming velocities and it was the swimmer's ability to turn quickly that determined the race outcome. It should also be noted that the statistical analysis looks at features that are common to the majority of finalists. That is, the result of such statistical analysis relied upon common trends that were displayed by the majority of the swimmers. Another way to put it is that the implications here apply to a general model and not necessarily to particular swimmer's competition model. A single swimmer's performance may be affected by a particular relationship which would not be disclosed by this statistical analysis if the swimmer was significantly different in the way he or she performed compared to the other elite swimmers in the event.

The quality of the start was determined by the time it took in seconds from the starting gun until the swimmer's head passed the 15 metre mark from the starting block. The quality of the turn was determined by the time in seconds that it took from the swimmer's head to pass the 7.5 metre mark from the turning wall on the way in until the head again passed the 7.5 metre mark on the way out. The finish was determined by the time in seconds that it took the swimmer's head to pass the 5.0 metre mark from the finishing wall until the swimmer actually touched the wall. The 50 metre pool is divided into halves in order to examine the swimming velocity in metres per second throughout the race. The swimming velocity is measured in each of the pool's halves throughout the race. However, that part of the swimmer's performance that is considered as part of the start, turn or finish sections is not used in computing the free swim velocity. As well as measure the swimming velocity in the free swimming sections of the race, the stroke length and stroke frequency are also computed in these sections. Stroke length was measured in metres and stroke frequency in strokes per minute. The stroke length was defined as the distance the swimmer's head travelled from right hand entry until the next right hand entry. Stroke frequency was defined as the number of these stroke cycles that would occur in a minute if the present rating was continued. The efficiency index was defined as the product of stroke length and the average swimming velocity during that same section of the race. Efficiency indices can not be compared between strokes. It is debatable whether efficiency indices can be compared between swimmers using the same competitive stroke, however it appears quite meaningful to look at the change in efficiency for a particular swimmer throughout the race or for the

same swimmer in different races. The higher the number for the efficiency index, the better was the swimmer's efficiency.

RESULTS:

The independent variables that related highly to performance in the various events are provided below (see also, Tables 1 to 7):

Freestyle 50m and 100m:

Males: In the 50m, only free swimming speed (0.862) had a significant correlation with performance. This was at the 0.01 level of significance and this is not an unexpected observation. In the 100m, free swim velocity (0.792), start time (0.626), turn time (0.635), stroke length (0.640) and index (0.756) all correlated at the 0.01 level of significance with performance. That is, with improved performance, the free swimming speed increased, the start and turn times were reduced, and stroke length and the efficiency index increased.
Females: In the 50m, free swimming speed (0.904) was significant at the 0.01 level and start (0.599) and finish (0.585) times were significant at the 0.05 level. That is, as performance improved the free swimming velocity increased and the start and finish times decreased. In the 100m, none of the independent variables correlated with performance.

Freestyle 200m and 400m:

Males: In the 200m, free swim velocity (0.946) and turn time (0.782) were significant at the 0.01 level of significance. In the 400m, free swim velocity (0.893) and turn time (0.783) were significant at the 0.01 level of significance. That is, as performance improved the free swimming speed increased and the turn times decreased for both distances. Free swimming speed in the second 200m (0.823) correlated more highly than the first 200m (0.756) with performance in the longer event.
Females: In the 200m, free swim velocity (0.945) was significant at the 0.01 level and turn time (0.587) was significant at the 0.05 level of significance. In the 400m, free swim velocity (0.914) and turn time (0.827) were significant at the 0.01 level of significance. That is as performance improved the free swimming velocity increased and the turn time decreased for both distances. Free swimming speed in the second 200m (0.913) correlated more highly than the first 200m (0.639) with performance in the longer event. Both were significant at the 0.01 level of significance

Freestyle 800m and 1500m:

Males: In the 1500m, free swimming speed (0.865) was significant at the 0.01 level and efficiency index (0.721) was significant at the 0.05 level of significance. Performance improved as swim velocity increased and efficiency index increased. Free swimming speed in the second 750m (0.862) correlated more highly than in first 750m (0.758) with performance. Both were significant at the 0.01 level of significance. A sample size of only eight swimmers was used in the analysis.
Females: In the 800 m, only free swimming speed (0.800) was significant at the 0.05 level of significance. Free swimming speed in the second 400m (0.906) correlated more highly at the 0.01 level of significance than the first 400m (0.317) at no significant level with performance. A sample size of only eight swimmers was used in the analysis.

Butterfly:

Males: In the 100m, free swimming speed (0.902) was significant at the 0.01 level and turn time (0.499) was significant at the 0.05 level of significance. Performance improved as swim velocity increased and turn time decreased. In the 200m, free swim velocity (0.945) and turn time (0.809) were significant at the 0.01 level of significance. That is, as performance improved the free swimming speed increased and the turn times decreased.

Females: In the 100m, free swimming speed (0.975), start time (0.822) and turn time (0.778) were significant at the 0.01 level of significance. Performance improved as swimming speed increased and start time and turn time decreased. In the 200m, free swimming speed (0.926) and turn time (0.806) was significant at the 0.01 level and efficiency index (0.605) and finish time (0.559) were significant at the 0.05 level of significance. Performance improved as free swimming speed increased, turn time and finish time decreased and the efficiency index increased.

Backstroke:
Males: In the 100m, free swim speed (0.606) and start time (0.550) were significant at the 0.05 level of significance. In the 200m, free swimming speed (0.894) and turn time (0.671) were significant at the 0.01 level of significance. That is as performance improved the free swimming speed increased and the turn times decreased for both distances.
Females: In the 100m, free swim speed (0.978), turn time (0.960) and start time (0.908) were significant at the 0.01 level of significance. In the 200m, free swim velocity (0.778) and finish time (0.633) were significant at the 0.01 level and start time (0.526) and turn time (0.521) were significant at the 0.05 level of significance. That is as performance improved the free swimming speed increased and the finish, turn and start time decreased.

Breaststroke:
Males: In the 100m, only start time (0.542) was significant at the 0.05 level of significance. That is as performance improved the start time decreased. In the 200m, free swimming speed (0.886) and turn time (0.717) were significant at the 0.01 level and start time (0.499) and finish time were significant at the 0.05 level of significance. That is as performance improved the free swimming speed increased and the start time decreased
Females: In the 100m, free swimming speed (0.962), turn time (0.729) and start time (0.650) were significant at the 0.01 level and finish time (0.575) was significant at the 0.05 level of significance. In the 200m, free swim velocity (0.920) was significant at the 0.01 level and turn time (0.503) and and finish time (0.503) were significant at the 0.05 level of significance. That is as performance improved the free swimming speed increased for both distances and for the 100m, the turn, start and finish time decreased and for the 200m the finish and start time decreased.

Individual Medley:
Males: In the 200m, free swimming speed (0.884), turn time (0.848) and finish time (0.759) were significant at the 0.01 level of significance. That is as performance improved the free swimming speed increased and the turn and finish times decreased. Of the strokes only the freestyle free swimming speed (0.666) was significant and this was at the 0.01 level of significance. In the 400m, free swimming speed (0.919), turn time (0.920) were significant at the 0.01 level and start time (0.568) and finish time (0.536) were significant at the 0.5 level of significance. That is as performance improved the free swimming speed increased and turn, start and finish times decreased. Of the strokes involved, the backstroke (0.790), the breaststroke (0.724), the butterfly (0.671) at the 0.01 level and the freestyle (0.597) free swimming speeds at the 0.05 level of significance correlated with performance.
Females: In the 200m, free swim speed (0.938), turn time (0.738) and finish time (0.654) were significant at the 0.0l level of significance. That is as performance improved the free swimming speed increased and the turn and finish times decreased. Of the strokes involved, the backstroke (0.812) and the butterfly (0.672) at the 0.01 level and the breaststroke (0.584) and the freestyle (0.576) free swimming speeds at the 0.05 level were significant. In the 400m, only free swimming speed (0.932) was significant at the 0.01 level of significance. That is as performance improved the free swimming speed increased. Of the strokes involved the backstroke (0.899), the butterfly (0.876) and the breaststroke (0.698) correlated with performance at the 0.01 level of significance.

Table 1 **Significant Correlations with Independent Variables: Freestyle**

Distance	Gender	Free Swim	Start Time	Turn Time	Finish Time	Stroke Length	Stroke Freq	Eff Index
50m	Male	**(0.86)						
50m	Female	**(0.90)	* (0.60)		* (0.59)			
100m	Male	**(0.79)	**(0.63)	**(0.64)		**(0.64)		**(0.76)
100m	Female							
200m	Male	**(0.95)		**(0.78)				
200m	Female	**(0.95)		* (0.59)			* (0.59)	
400m	Male	**(0.89)		**(0.78)				
400m	Female	**(0.91)		**(0.83)				
800m	Female	* (0.80)						
1500m	Male	**(0.87)						* (0.72)

Note ** indicates 0.01 level of significance
* indicates 0.05 level of significance

Table 2 **Significant Correlations with Halves of the Race: Freestyle**

Distance	Gender	First Half Swim Speed	Second Half Swim Speed
400m	Male	**(0.76)	**(0.82)
400m	Female	**(0.64)	**(0.91)
800m	Female		**(0.91)
1500m	Male	**(0.76)	**(0.86)

Note ** indicates 0.01 level of significance
* indicates 0.05 level of significance

Table 3 **Significant Correlations with Independent Variables: Butterfly**

Distance	Gender	Free Swim	Start Time	Turn Time	Finish Time	Stroke Length	Stroke Freq	Eff Index
100m	Male	**(0.90)		* (0.50)				
100m	Female	**(0.98)	**(0.82)	**(0.78)				
200m	Male	**(0.95)		**(0.81)				
200m	Female	**(0.93)		**(0.81)	* (0.56)			* (0.61)

Note ** indicates 0.01 level of significance
* indicates 0.05 level of significance

Table 4 **Significant Correlations with Independent Variables: Backstroke**

Distance	Gender	Free Swim	Start Time	Turn Time	Finish Time	Stroke Length	Stroke Freq	Eff Index
100m	Male	* (0.61)	* (0.55)					
100m	Female	**(0.98)	**(0.91)	**(0.96)				
200m	Male	**(0.89)		**(0.67)				
200m	Female	**(0.78)	* (0.53)	* (0.52)	**(0.63)			

Note ** indicates 0.01 level of significance
* indicates 0.05 level of significance

Table 5 Significant Correlations with Independent Variables: Breaststroke

Distance	Gender	Free Swim	Start Time	Turn Time	Finish Time	Stroke Length	Stroke Freq	Eff Index
100m	Male		* (0.54)					
100m	Female	**(0.96)	**(0.65)	**(0.73)	* (0.58)			
200m	Male	**(0.89)	* (0.50)	**(0.72)	* (0.62)			
200m	Female	**(0.92)		* (0.50)				

Note ** indicates 0.01 level of significance
* indicates 0.05 level of significance

Table 6 Significant Correlations with Independent Variables: Individual Medley

Distance	Gender	Free Swim	Start Time	Turn Time	Finish Time	Stroke Length	Stroke Freq	Eff Index
200m	Male	**(0.88)		**(0.85)	**(0.76)			
200m	Female	**(0.94)		**(0.74)	**(0.65)			
400m	Male	**(0.92)	* (0.57)	**(0.92)	* (0.54)			
400m	Female	**(0.93)						

Note ** indicates 0.01 level of significance
* indicates 0.05 level of significance

Table 7 Significant Correlations with Strokes: Individual Medley

Distance	Gender	Butterfly	Backstroke	Breaststroke	Freestyle
200m	Male				**(0.67)
200m	Female	**(0.67)	**(0.81)	* (0.58)	* (0.58)
400m	Male	**(0.67)	**(0.79)	**(0.72)	* (0.60)
400m	Female	**(0.88)	**(0.90)	**(0.70)	

Note ** indicates 0.01 level of significance
* indicates 0.05 level of significance

DISCUSSION:

All Events: As was expected, in most events for both genders, the average free swimming velocity correlated highly with the race performance. That is, the faster you swam, the most likely you were to win in all events. This occurred because of the physical fact, that most time in each event was spent in the free swimming phases of the race. The analysis of the data suggested that stroke lengths, stroke frequencies and efficiency indices were very much an individual factor rather than generally applicable to all swimmers and an examination for the group did not indicate that any significant relationship existed between them and with the race performance.

Freestyle:

In the sprint events for both genders, there was a slight relationship between starting performance and race performance. For distances longer than a sprint, the starting performance did not significantly affect the race performance. The turn performance in the sprint events indicated only a slight relationship with the race performance. The turn performances in the middle distance events played a most significant role in the race performance. This was not the case for the long distance events where the turn performance was not significantly related to the race result. The quality of the finishes were only significant in the 50 metre sprint. The stroke length was only significantly related to race performance in the Mens 100 sprint as was the efficiency index. In the case of the long

distance events, the race performance was more highly related to the free swimming velocity in the second half of the race as opposed to the first half of the race.

Butterfly:
In both genders and for both distances, turn performance was related to race performance. There was however a more significant relationship between turn performance and the race performance in the longer distance. The start performance was only significant in the Womens 100 metre distance event.

Backstroke:
In both genders and for both distances, start performance played a significant role for this stroke. It was however more significant at the shorter distance. Turn performance was also significantly related to the race performance and this was more significant in the longer distance.

Breaststroke:
In both genders and for both distances, start performance was significantly related to the race performance for this stroke. It was however more significant at the shorter distance. Turn performance was also significantly related to the race performance and this was more significant in the longer distance event. The finish performance appeared to be more significantly related in this stroke than in any of the other strokes.

Individual Medley:
Start performances were not significantly related to the race performance. Both turn performance and finish performance were significantly related to the race performance for both genders, with the exception of the Womens 400 metre Individual Medley. Of the four strokes, the backstroke free swim velocity was most significantly related to the race performance in the individual medley events. The order of significance for free swim velocity of the various strokes with overall race performance was backstroke, butterfly, breaststroke and freestyle. This did not hold true for the Mens 200 metre individual medley event where the freestyle swim velocity was the only stroke that was significantly related to the overall race performance.

CONCLUSIONS:

Many people believe that the total race performance is related to the stroke length of the swimmer, with the better swimmers having longer stroke lengths. The analysis of the World Championship competition analysis data indicated that stroke length, stroke frequency and the efficiency index was not significantly related to the race performance apart from in the Mens 100 metre freestyle event. It was also evident that average swimming speed was related to the race performance for all events, but this was to be expected. The race performance in the backstroke and breaststroke were related to both start and turn performance. In the butterfly events, race performance was related to turn performance. In the freestyle sprint events the start performance was significantly related to overall race performance. In the middle distance events, the turn performance was significantly related to overall race performance. None of turn, finish or start performance were significantly related to overall race performance in the distance freestyle events. In the individual medley events, turn performance was significantly related to race performance. The order of importance of various stroke free swimming velocities on race performance, with the exception of the Mens 200 metre individual medley was, in order of significance, backstroke, butterfly, breaststroke and freestyle.

From experience in dealing with competition analyses, I have found that all independent variables collected in competition analyses can relate to the overall race performance when

dealing with a particular swimmer. While it is important to understand the implications of the general competition model on overall performance, an individual swimmer's performance is related to:

1. The ability of the coach to determine the most effective competition model for the swimmer.
2. The coach and swimmer ensuring that appropriate training occurs to achieve the competition model.
3. Ensuring that the swimmer swims to the model in competition.

Using the competition analysis for the swimmer concerned is an important ingredient in determining the most effective competition model for the swimmer. The results of the competition analysis can also be used for assessing whether the swimmer performed to the model derived for the swimmer.

WORLD CHAMPIONSHIPS PERTH AUSTRALIA Timing by OMEGA January-1998 Pg 1 of 1
A Final Biomechanical Analysis Australian Format
100m Free Style Open Mens 14-JAN-1998 A.I.S. Biomechanics analysis for Australian Swimming and FINA

	Alexander POPOV	*Michael KLIM*	*Lars FROLANDER*	*P VAN DEN HOOGENB*	*Gustavo BORGES*	*Attila ZUBOR*	*Chris FYDLER*	*Scott TUCKER*
	RUSSIA	AUSTRALIA	SWEDEN	NETHERLANDS	BRAZIL	HUNGARY	AUSTRALIA	U.S.A.
Lane #	5	4	7	3	6	8	1	2
25m Lap#	1	1	1	1	1	1	1	1
StartTime15m	5.86	6.08	6.26	6.12	6.06	6.34	6.16	6.32
StrkeLeng(m)	2.49	2.31	2.34	2.27	2.46	2.13	2.39	2.23
StkFreq(S/m)	50	55.6	54.5	56.3	48.4	58.4	52.9	53.6
Velocty(m/s)	2.07	2.14	2.13	2.13	1.98	2.07	2.11	1.99
Index(m*m/s)	5.17	4.93	4.98	4.83	4.88	4.42	5.03	4.44
25m Split(s)	10.68	10.76	10.96	10.82	11.1	11.16	11.2	11.34
50m Lap#	1	1	1	1	1	1	1	1
StrkeLeng(m)	2.57	2.37	2.14	2.29	2.69	2.17	2.22	2.18
StkFreq(S/m)	48.4	50	54.2	52.3	43.7	53.6	52.3	53.6
Velocty(m/s)	2.07	1.97	1.93	2	1.96	1.93	1.93	1.95
Index(m*m/s)	5.31	4.67	4.14	4.59	5.25	4.19	4.29	4.24
25m Split(s)	12.88	12.87	13.09	12.76	13.01	13.18	13.08	13.04
Lap Time(s)	23.56	23.63	24.05	23.58	24.11	24.34	24.28	24.38
25m Lap#	2	2	2	2	2	2	2	2
TurnTm 7.5*2	7.12	7.08	7.12	7.32	7.16	7.28	7.12	7.24
StrkeLeng(m)	2.6	2.29	2.14	2.25	2.52	2.2	2.22	2.05
StkFreq(S/m)	48.4	49.5	53.6	48.4	45.9	52.3	51.1	54.2
Velocty(m/s)	2.1	1.89	1.91	1.81	1.93	1.92	1.9	1.85
Index(m*m/s)	5.46	4.32	4.08	4.08	4.84	4.21	4.22	3.8
25m Split(s)	12.06	12.35	12.25	12.64	12.19	12.28	12.32	12.64
50m Lap#	2	2	2	2	2	2	2	2
StrkeLeng(m)	2.29	2.26	2	2.26	2.38	2.22	2.07	2.08
StkFreq(S/m)	48.4	49.5	54.9	48.4	45.9	50	50	53.6
Velocty(m/s)	1.85	1.86	1.83	1.82	1.82	1.85	1.72	1.86
Index(m*m/s)	4.24	4.21	3.65	4.11	4.34	4.1	3.57	3.86
FinTime(5m)	2.49	2.48	2.29	2.39	2.34	2.38	2.55	2.56
25m Split(s)	13.31	13.22	13.23	13.37	13.32	13.2	13.35	13.34
Lap Time(s)	25.37	25.57	25.48	26.01	25.51	25.48	25.67	25.98
Reslt(m:s.s)	:48.93	:49.20	:49.53	:49.59	:49.62	:49.82	:49.95	:50.36
Place	1st	2nd	3rd	4th	5th	6th	7th	8th
AvSwimVelcy	2.02	1.97	1.95	1.94	1.92	1.94	1.92	1.91
AvStrokeFreq	48.8	51.2	54.3	51.4	45.975	53.6	51.6	53.8
AvStrokeLeng	2.49	2.31	2.16	2.27	2.51	2.18	2.23	2.14
Av Index	5.05	4.53	4.21	4.40	4.83	4.23	4.28	4.09
StartTm(sec)	5.86	6.08	6.26	6.12	6.06	6.34	6.16	6.32
Turn Tm(sec)	7.12	7.08	7.12	7.32	7.16	7.28	7.12	7.24
Fin.Tm(sec)	2.49	2.48	2.29	2.39	2.34	2.38	2.55	2.56
Free Swim Tm	32.43	33.57	33.85	34.10	34.04	33.82	34.65	34.21
Accounted Tm	47.90	49.21	49.52	49.93	49.60	49.82	50.48	50.33

GAINING ON TURNS

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Biomechanics in all sport revolves around technique. There is a relatively small amount of research in the biomechanics of swimming turns in the four individual competitive strokes and individual medley. This is probably because of the difficulty in measuring underwater, implementing intervention strategies without regular feedback via underwater windows, and underwater force platforms being unavailable until recently.

The human anatomy, physiology and skill level of the swimmer is as important during the turn as in the free swimming stage of a race. The degree of segmental flexion during the pivoting and placement of the feet on the wall determines how effectively a swimmer can generate force for streamlined propulsion off the wall, and the degree of resistance created which offsets the propulsive motions. The lower limbs comprise many two joint muscles which can exert more force during their mid range of motion than when fully extended. The quadriceps and hamstrings are both two joint muscles that extend the thigh at the hip and the leg at the knee. Because of the mechanical advantage of the quadriceps at the knee and the hamstrings having an advantage at the hip (Lombard's Paradox), an appropriate degree of flexion at both joints renders them both capable of exerting force over a longer time period throughout the push-off. A paper by Ae (in Takahashi, 1982) suggested that ~120° flexion at the knee was desirable. No hip angle figures could be found for swimmers. Prior to driving backwards during a breaststroke kick, Counsilman (1968) wrote that around 50-60° of thigh flexion significantly increased the force of the hip extensor muscles to 96 kg, especially the gluteals; while it was 28 kg when the hip was flexed at 30°. As this movement emanates from a similar body position to that assumed in the turn push-off, perhaps this approximates the preferred range of motion.

The fastest animal swimmers are dolphins who do not have limbs and are driven through the water by oscillations of the rear end of the body (Brazier Howell, 1970). It is interesting that streamlined underwater dolphin kicking by humans is possibly the second fastest stroke to front crawl by humans and is commonly used after turning in freestyle, backstroke and butterfly competition.

A strongly built mesomorph could have an advantage in swimming turns because of a large muscle mass and proportionally more fast twitch, power generating muscle fibres. However, this creates extra form drag in the water because of the greater cross sectional body surface area of frontal drag and a 'lumpier' shape; and could detract from a turn because the larger the push-off force into the mass of water creates greater deceleration.

When turning, a tall swimmer has to rotate a long body. This increases the arc of rotation and requires greater effort than for a short torso. But, the tall person, with similar degrees of hip and knee flexion, can commence turning ~10-15 cm further out from the wall than a shorter swimmer and the push-off begins from that position. Hence, in a 1500 m F/s in a 25 m pool, with 63 turns, less distance needs to be swum (63 x 30 cm = 18.9 m). The act of shaving down has been shown to significantly increase the distance travelled following a streamlined push off the wall. Physiologically, it has been demonstrated that blood lactates are considerably less after having swum 200 m freestyle in a 25 m pool than in a 50 m pool (Telford et al., 1988; Sharp and Costill, 1989). Hence, the anatomical and physiological structures with which we have been endowed, enable astute coaches and sport scientists to modify turning techniques to those which are most suited to a swimmer's physical attributes. Human anatomy dictates that there are 'different strokes for different folks'.

The University of Western Australia Aquatics Research Laboratory operates from a large learn-to-swim and coaching program within the Department of Human Movement and Exercise Science. This creates research opportunities for the sport psychology, biomechanics, exercise physiology and motor control personnel. The development of an underwater 2D force platform (Blanksby, Marshall & Gathercole, 1996) has enabled the study of turn kinematics and kinetics.

Breaststroke turns can account for up to one third of race time in 25 m pools (Thayer & Hay, 1984). A study of turns by age group breaststrokers revealed that increased height, surfacing distance, surfacing horizontal velocity and peak velocity; and decreased pivot time were included in a stepwise regression equation to predict faster breaststroke turning times (Blanksby, Simpson & Elliott, 1998). Choosing the depth with least resistance at which to push off the wall, and the appropriate velocity at which to perform the underwater arm pull and leg kick are important skills to be learned by young breaststrokers (Lyttle et al., 1998; Blanksby et al., 1998). Mean peak force exerted on the wall was equivalent to 1.22 body weight (bw) for age group breaststrokers and 1.36 bw for senior breaststrokers (Davies, 1998).

The approach for the butterfly turn resembles that of breaststroke, and the pivot and push-off are also similar. Twenty-eight age group butterfliers with a mean 50 m time of 36.7 s turned on a 2-D force platform and were filmed underwater (Ling, 1998). They exerted a mean 1.38 bw force against the wall and recorded 19.34% of 50 m time for the 5 m RTT (ie from the backstroke flags to the wall and back; 20% of distance). Lyttle and Mason (1997) recorded a peak Z force of 1.72 bw for four national level male butterfliers. Stepwise regression revealed that increased height, arm resumption distance and speed, and decreased pivot time predicted 80% of the variance for 5 m RTT. Hence, tall swimmers who pivoted fast, exerted a strong push-off force against the wall to leave with a high speed for a long distance were the most successful.

The roll-over backstroke turn no longer requires swimmers to touch the wall with the hands. It has been claimed that it decreases the time for each turn by 0.2-0.6 s (Peyrebrune, et al., 1992). A study of competent, but not highly skilled, age group swimmers doing backstroke turns revealed that those with longer legs who achieved faster wall exit velocities, peak Z (horizontal) forces, higher tuck indexes, lower wall contact times and greater Y forces recorded faster 5 m RTTs (Blanksby, Skender, Elliott & McElroy, currently submitted). Walker (1995) observed a strong Z force was evident in both the breaststroke and butterfly turns but that a slight upward Y force was found which he considered could assist in pushing down to a better depth for streamlining after the push-off. With backstrokers streamlining and dolphining off the wall, this could explain why Blanksby et al. (currently submitted) noted a mean Y force of 12.6% of Z; and X force of 5% of Z. The age groupers had a net gain from the turn in that they completed the 5 m RTT in 19.56% of the 50m time. They tended to surface too early after the push-off and only exerted a mean peak force of 0.55 bw. This latter finding demonstrated that a loss of momentum into the wall occurred and coaches should work to enhance this part of the turning motion (Blanksby et al., currently submitted).

World records are faster in 25 m pools than 50 m pools. The reason given has been that there are more turns and push-offs from which to gain an advantage. As well as this, there are reduced blood lactates found over a 200 m swim in the short course pool (Sharp and Costill, 1989; Telford, 1988). Again, the few seconds of turning redistributes the muscular load and some physiological recuperation can occur.

Freestyle turns by age-group swimmers revealed no gender differences (Blanksby et al., 1996). The criterion measure of 5 m round trip time correlated significantly with increased peak force of 1.5 bw, decreased wall contact time, increased tuck index (straighter legs),

swim resumption distance and peak speed (Blanksby, Gathecole & Marshall, 1996). The best predictors of the 5 m RTT were peak force, swim resumption distance, turn start distance and height. Swimmers were recommended to approach the wall fast, rotate the body quickly and hit the wall firmly with a relatively high tuck index (ie. straighter legs). The glide off the wall needs to be held until one returns to swimming speed. In this study, even though height was restricted to people within one standard deviation of the population mean for their ages, it still featured in the stepwise regression equation (Blanksby, Gathercole & Marshall, 1996). Male senior competition swimmers (Hodgkinson & Blanksby, 1996) recorded lower wall contact times, increased velocity-in at 2.5 m higher peak forces (1.64 bw) and tuck indexes. In addition, trochanteric height was also included as a predictor for females.

Drag issues are important in starting and turning where the velocities are highest. Hay (1988) outlined the importance of streamlining after diving into the water by revealing underwater gliding distance to account for 95% of the variance in the start time, and that streamlining to minimise the resistive forces during the glide was crucial in this process. Clarys et al. (1973) supported this finding with evidence that merely raising the head above the fully extended arms, increased considerably the drag encountered by the body. Following a tumble turn, Blanksby et al. (1996) found faster round trip times when swimmers were streamlined following the push-off. At the elite swimming level, the opportunity for performance improvements becomes relatively restricted. However, enhanced turning efficiency throughout the push-off, glide and stroke resumption phases could be a fruitful area for improvement. Lyttle, Blanksby, Elliott & Lloyd (1998) investigated the propulsive and drag forces during the wall push-off phase of a turn and the optimal depth for streamlined gliding.

Previous kinetics studies were mainly descriptive in nature (Nicol and Kruger, 1979; Takahashi et al., 1982; Blanksby et al., 1996; Lyttle and Mason, 1997). The hydrodynamic parameters during wall push-off have not been studied. Because hydrodynamic drag is important during all facets of a swimming event, analysis of the drag during the wall push-off is essential to complete a thorough examination of turns.

Takahashi et al. (1982) also found the wall contact time to be less for competitive swimmers (0.36 s) than it was for the recreational swimmers (0.48). Blanksby et al found a wall contact time of 0.73 s and 0.47 s for bottom third and top third of their age group freestylers, respectively. A mean wall contact time of 0.38 s as recorded for males and 0.46 s for females who were national finalists in freestyle swimming (Hodgkinson and Blanksby, 1995). Blanksby, Cossor & Elliott (1998) revealed significant decreases in total wall contact time over a 22 week season but the controls improved as much as the experimental group who undertook 3 x 15 minute plyometric sessions per week plus swimming. Hence, a greater in-depth study of how the wall contact time was made up was carried out. An exploratory analysis was made of how the various kinetic and hydrodynamic variables during the wall push-off part (active portion of wall contact) of wall contact time are related to the wall exit velocity. The hydrodynamic drag is primarily a consideration only during this phase, and push-off time represented the period from the first forward displacement of the hips after wall contact until the feet left the wall.

Figure 1 outlines a sample profile of the variables measured during the data analysis of the push-off. A 2D force platform was used to calculate drag profiles in the horizontal direction (direction of push-off). The drag measures used in the analysis represented the total resistive force to the swimmer's motion (friction drag, form drag and wave drag) as well as the force used to accelerate the water surrounding the swimmer (added mass).

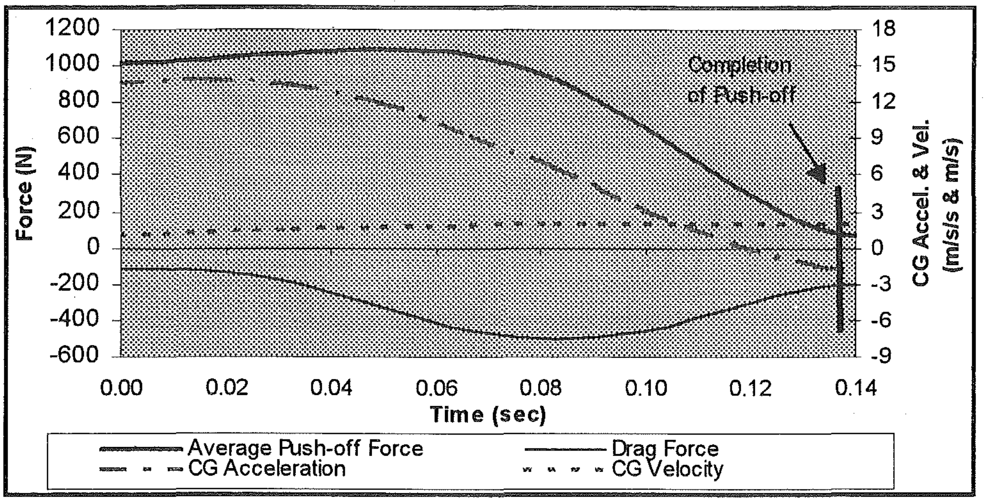

Figure 1 - Sample profile of a freestyle turn push-off outlining the CG velocity and acceleration, and drag and average push-off forces.

Table 1 Means (M) and Standard Deviations (SD) for the Measured Variables (n=30).

Variable	M $\pm$ SD
Peak Propulsive Force (N)	1189.6 $\pm$ 246.0
Total Propulsive Impulse (Ns)	204.0 $\pm$ 54.9
Push-off Time (s)	0.218 $\pm$ 0.054
Total Wall Contact Time (s)	0.324 $\pm$ 0.040
Peak Drag Force (N)	-570.0 $\pm$ 238.0
Total Drag Impulse (Ns)	-62.6 $\pm$ 41.8
Wall Exit Velocity (m/s)	2.45 $\pm$ 0.45

The wall push-off time was the best single predictor of a swimmer's velocity immediately after leaving the wall. Longer wall push-off times resulted in faster final push-off velocities for the swimmers. Intuitively however, an optimal wall push-off time exists. A rapid push-off might not allow sufficient time to develop an optimal impulse, thus reducing the potential to effectively increase the acceleration of the CG. An extended push-off time may not directly affect final push-off velocities, but may be detrimental to the overall turn time. It is also possible that, rather than the total wall contact time or the push-off time, the proportion of WCT spent pushing off contributes more to the final push-off velocity because of force production strategies and stretch shorten cycle augmentation. Further research is required to clarify events occurring during the total wall contact time.

Lower peak drag values resulted in faster wall exit velocities and highlighted the importance of drag when pushing off the wall. The velocity of the swimmer, the degree of streamlining and the swimmer's body shape affect the magnitude of the drag force. The velocity of the swimmer is related to the size of the effective propulsive force, with higher velocities causing greater drag. A streamlined transition from a flexed position at the start of push-off, to a fully extended position at the end of push-off, is necessary also to prevent the production of excessive drag (Clarys, 1979). This could explain previous findings that, the larger the tuck index during a flip turn (ie. straighter legs), the faster were the turn times (Takahashi et al., 1982; Blanksby et al., 1996).

The third and final factor in the stepwise regression was the peak propulsive force. A higher peak push-off force resulted in a higher wall exit velocity for the swimmer. A higher peak force results in higher instantaneous acceleration and, therefore, higher push-off velocity.

However, this only applies if drag is not appreciably increased simultaneously. Therefore, a trade-off exists where an excessive peak push-off force with the swimmer in a non-streamlined position is likely to create an excessive peak resistance to rapidly decelerate the swimmer. This is evidenced by the significant negative correlation between peak push-off force and peak resistance in this study ($R = -0.77$, $p = 0.00$).

The peak drag recorded the highest regression weighting, followed by peak propulsive force and then wall push-off time. In essence, the peak drag force had the greatest ability to predict the swimmer's final push-off velocity. Hence, attempts to improve the swimmer's final push-off velocity should not be at the expense of increasing the peak resistances experienced by the swimmer. Factors such as high push-off forces when the swimmer is in a non-streamlined position, or exaggerated body movements such as tucking up tightly to try and exert more force, may lead to higher peak resistance and detract from the overall turning performance. To achieve a high push-off velocity, an optimal combination of a low resistance, high peak propulsive force and a wall push-off time of sufficient period to develop this force is required.

For example, in Figure 2, subject A performs his turns 'hard and fast', developing a peak push-off force of 1396 N in a push-off time of just 0.18 s (47% of WCT). This resulted in a high peak drag force of 929 N and a relatively low push-off velocity of 2.46 m/s (see Figure 2).

Subject B 'sinks into the wall' and then develops 1727 N of peak push-off force in 0.23 s (66% of WCT) to produce a very high impulse (296 Ns). This push-off resulted in 1085 N of peak drag force which, all other factors being equal, acted to slow the swimmer down to a final push-off velocity of 2.64 m/s.

Subject C could possibly be more representative of the optimal wall push-off. This swimmer produced a peak push-off force of 1074 N with a push-off time of 0.27 s, leading to a peak drag force of only 235 N. As a result of the low peak resistance, the final push-off velocity reached 3.03 m/s. In addition, this swimmer spent a very high percentage (90%) of his total wall contact time generating push-off force. This swimmer applied the push-off force in a more gradual, controlled manner so that the peak push-off force occurred closer to when the feet left the wall and the swimmer was in a more streamlined position. An excessive push-off force was not developed early in the push-off and resistances remained low.

An optimal balance is therefore required between the amount of peak push-off force, time spent pushing off the wall and the amount of peak drag that is produced as a result. Also, the timing of the peak drag force is a factor that plays a major role in determining the final velocity. If the peak propulsive force is developed early in the push-off, peak drag could also occur early and decelerate the swimmer prior to the feet leaving the wall. It may be advantageous for swimmers to plant the feet after the forward somersault and gradually develop a moderate, rather than maximum, force. Then, the peak force is achieved closer to when the feet leave the wall without excessive drag being developed prior to this point (See subject C, Figure 2). An advantage of the peak drag occurring closer to toe-off is that the swimmer is in a more streamlined position and is therefore subject to less form drag (Clarys, 1979).

Hence, minimising resistance is as important as increasing propulsion. Knowing the hydrodynamic drag at various depths and velocities assists coaches to change technique to reduce drag. Swimmers have been towed underwater at various velocities to assess resistance (Karpovich, 1933; di Prampero et al., 1974; Jiskoot & Clarys, 1975), either while prone (passive drag) or while moving (active drag). Only Jiskoot & Clarys (1975) analysed underwater drag and found it was 20% higher 0.6 m underwater than the surface.

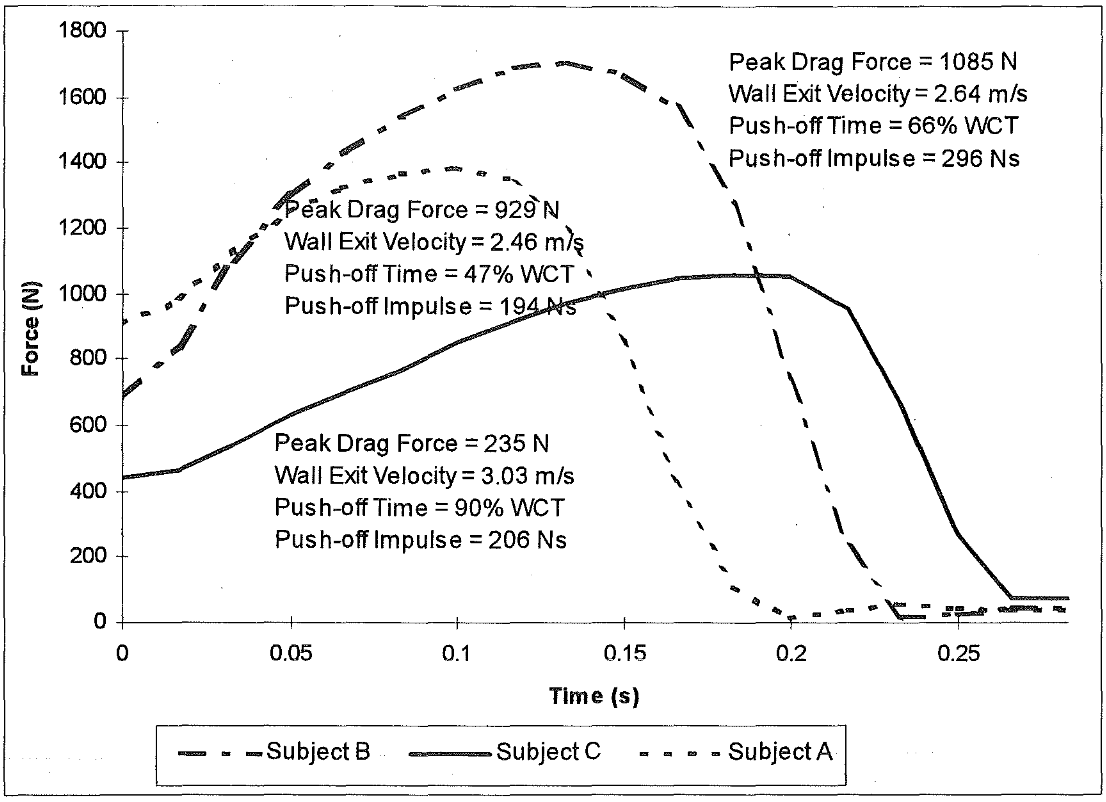

Figure 2 - Push-off force profiles for subject A, B & C

Other fluid dynamics studies showed greater drag immediately under the water surface but the least drag at a depth equivalent to a depth-to-length ratio of 0.2 to 0.4 (Hertel, 1966; Larsen et al., 1981). For a 1.8 m tall swimmer, this is the equivalent of about 36-72 cm below the surface. As the mean chest depth for elite male swimmers is 21.2 cm, and females 18.8 cm, this is about 2-3 body depths below the surface (Mazza et al., 1994).

Figure 3 outlines the experimental set-up used when towing forty experienced male swimmers of similar body size 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). 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 covered the actual velocities experienced by club to elite level swimmers during the push-off and glide after a turn. Swimmers held a prone streamlined position with hands overlapping, head between the extended arms, and feet together and plantar flexed.

A 2-way ANOVA revealed significant depth-by-velocity interactions. The interactions (Scheffe Post Hoc tests) 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 covariates 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 covariate demonstrated no significant influence ($F=0.59$; $p=0.441$) on the outcome of the analysis.

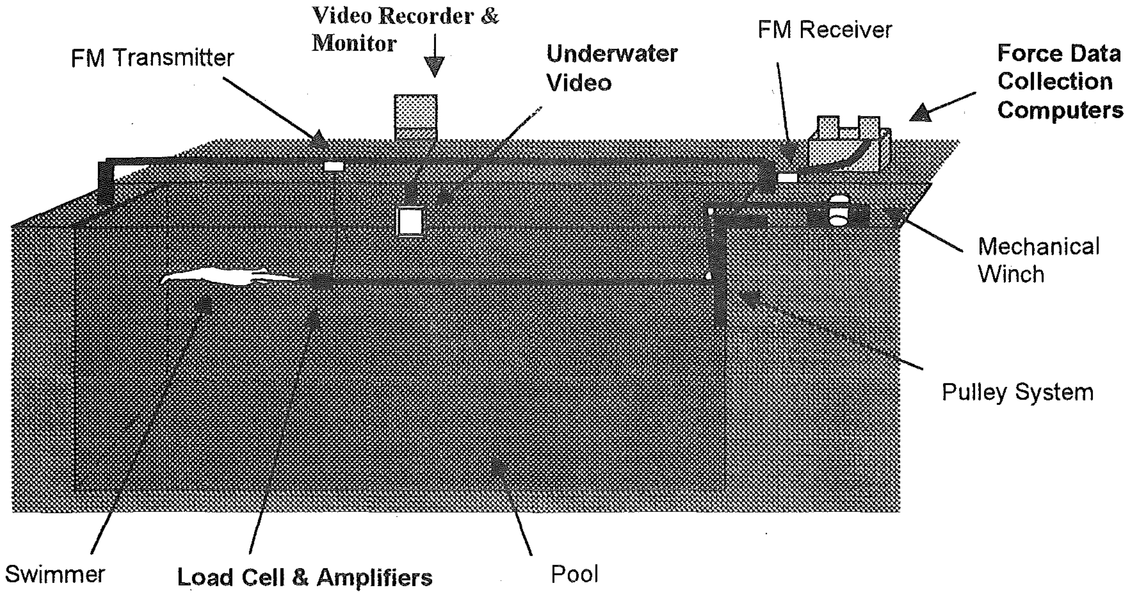

Figure 3 - Testing set-up for quantifying hydrodynamic drag.

Because push-offs are generally at these velocities, swimmers should glide at approximately 0.4 m underwater. Drag reductions of 15-18 % below those at the surface were found for all velocities above 1.9 ms^{-1}. Other fluid dynamic studies have demonstrated that the coefficient of drag decreases rapidly as the body increases in depth due to a decrease in wave drag (Hertel, 1966; Larson et al., 1981). Jiskoot & Clarys (1975) found higher drag forces 0.6 m under the water than at the surface. Perhaps their lower glide velocities of 1.5-1.9 ms^{-1} were insufficient to produce a substantial wave drag.

Table 2 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 %)

Although the body size range of the swimmers was controlled, 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 and supports 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 (Clarys, 1979). 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. 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.

Generally, swimmers should approach and hit the wall hard, maximise the push-off phase of a low wall contact time, develop a moderate force steadily in a streamlined position, exit the wall at 0.4 m under the surface and resume swimming at slightly higher than free swimming velocity. An examination of turns and drag profiles of female swimmers is continuing. Subjective observation of the video film reveals that some swimmers who are close to national selection could turn more effectively.

For example, one tall swimmer kept a straight line from the armpit to the knee when performing a tumble turn. He landed with the back arched, pushed off towards the bottom of the pool and was forced to make an almost vertical 'break out' to resume stroking. That swimmer was only 0.5 s away from making a national 4 x 200 m national relay team. Another national swimmer tumbled onto the wall quite well but, once the legs were positioned, 'sank' into the wall to a 'scrunched up' position and then gave a strong push away from the wall. Video of an Olympic 1500 m final reveals a competitor outswimming his opponents but losing significant distance at each turn. He is quite close to the wall, swivels partly sideways, pushes off at the interface of the water and air, and resumes stroking virtually before the feet have left the wall. Another national selection 1500 m trial revealed two world class swimmers in close competition. One was significantly taller than the other and turning further out from the wall which decreased his swimming distance. His opponent, although not as tall, also tucked up quite tightly, and was forced into 'catch-up' swimming each lap. Hence, as Thayer & Hay (1984) wrote, turning takes up a considerable proportion of race time and can be responsible for winning or losing important events. Special arrangements are necessary to view swimmers underwater to note specific details but coaches are reminded that it is worth doing because of the valuable contribution an improved turn can make.

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SPOTTING TECHNIQUE FAULTS: BELOW AND ABOVE THE WATER

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Due to the highly technical nature of swimming, the technique that a swimmer uses is vital to maximising their performance. The difficulty with analysing swimming technique is that it takes place in two mediums, air and water. Due to the effects of refraction as light passes through water, it is difficult to identify technique flaws by looking from the pool side alone. In order to get around this problem coaches and researchers have turned to examining swimmers both, visually through underwater windows or with underwater video/film cameras, which provide non-distorted views of the athletes' technique, and indirectly with other types of equipment. This presentation discusses most of the current methods used for technique analysis, both above and below the water surface and outlines the advantages and disadvantages of the various techniques.

KEY WORDS: swimming, underwater videography, motion analysis, technique analysis

INTRODUCTION:

Due to swimming's highly technical nature, the determination of faults in technique (according to the prevailing theory of the time as to what technique is actually correct) has always been of great importance when trying to improve swimming performance.

Although swimming has been performed in regular competitions dating back to the mid 1800's in England, there were no real scientific investigations into how people moved through the water until the 1920's. At this time the Japanese, in order to improve their performance at the 1932 Olympic Games, began to examine swimming stroke techniques and realised that they could apply principles of mechanics to the swimming strokes ((Counsilman, 1968)). Until then the techniques which were used had been based on relatively simplistic guesses as to how humans propelled themselves through the water. With the success of the Japanese innovations in swimming technique there was a wider realisation as to the importance of analysing swimming technique both above and below the water surface in order to maximise performance. Around the same period others, such as David Armbruster, then coach of the State University of Iowa swimming team, were also beginning to analyse the basics of swimming technique by means of film analysis both above and below the water surface. To date there have been several methods which allow for swimming technique analysis. These can be roughly divided into two general categories, visual observation methods and more indirect methods that use equipment other than a coach's eyes or a video camera. During this session the various methods of swimming technique analysis will be discussed with regard to their respective advantages and disadvantages.

VISUAL OBSERVATION METHODS: POOL SIDE OBSERVATION:

To this day the most common, and most basic, method of analysing a swimmer's technique is for the coach to stand on the side of the pool and watch the swimmer as they pass by in the water. The obvious advantages of this type of analysis is that it is cheap, no special equipment is needed to perform the analysis, and most people familiar with the basics of swimming technique can perform this type of analysis. There are a couple of additional aspects of this method that can be considered positives. The first of these is that, for experienced coaches, they can make estimates of what the swimmer's technique is like under the water based on certain aspects of what is happening out of the water. While this is by no means an exact science it can at least detect some major technique flaws that may be present. The final positive is that the coach can give virtually instantaneous feedback to the swimmer thereby allowing technique alterations to be more easily made.

While this is the most common method of technique analysis it is also by the far the least effective due to several factors. The biggest reason is that because the coach is looking from above the swimmer they are unable to see exactly what the swimmer is doing when their arms are underneath the body. While, as stated previously, experienced coaches can infer what the swimmer is doing during this unsighted period it is still only a guess. In addition, as with virtually all forms of swimming technique analysis, the coach's view is also obscured by bubbles created by the swimmer's body moving through the water. When this obscured view is combined with the refraction caused by light passing through the boundary layer of air and water it is exceptionally difficult to make accurate technique suggestions because what positions are visible from the surface are greatly distorted. In the following picture you can see just how much the swimmer's body is distorted by this light refraction. Also note the effects of light reflecting off the water surface and how that also obscures the view of the swimmer.

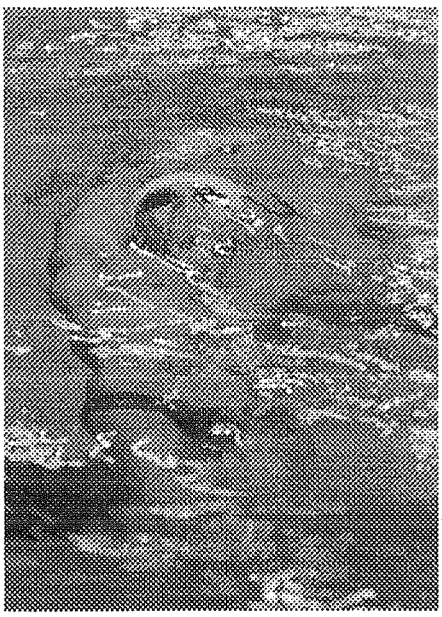

Figure 1 - Image distortion due to refraction

Since this is a common viewpoint for a coach it is not surprising that many coaches, and researchers, can miss some fairly significant aspects of the swimmer's technique which may be affecting his/her performance.

STROKE RATE / STROKE LENGTH: Due to the distortion caused by the bending light rays and bubbles most pool side analysis has been concerned with what can be seen above the water surface. Therefore, the primary aspects of technique which have been studied from by using pool side analysis have been stroke length and stroke frequency. Although not technically a visual analysis due to the use of stopwatches etc, for the purposes of this discussion it will be considered a visual observation due to its common use among coaches today. One of the first research papers to describe this type of analysis in swimming was presented by David East (East, 1970). This study was conducted by filming swimmers during competition from a single film camera, at a frame rate of 16 frames per second (fps) (We currently use frame rates of 25 or 30 depending on where in the world you are). The camera was positioned parallel to the direction of motion of the swimmers at the turning end of the pool. From the film data he determined stroke length (SL) and stroke frequency (SR) according to the following equations:

$$SL = \text{Distance Travelled} / \text{Total Number of Cycles} \quad (1)$$

SR = Total Number of Cycles / Stroking Time (2)

This is somewhat different from the later work of several researchers (Arellano and Pardillo, 1992; Chatard, Collomp, Maglischo, & Maglischo, 1990; Craig and Pendergast, 1979; Craig, Skehan, Pawelczyk, & Boomer, 1985; Grimston and Hay, 1986; Keskinen, 1993; Keskinen, 1994; Keskinen and Komi, 1988; Keskinen and Komi, 1989; Keskinen and Komi, 1993; Keskinen, Tilli, & Komi, 1989) in that these researchers conducted analyses from multiple cameras positioned perpendicular to the line of motion of the swimmers. Similarly to the later studies, East analysed the swimmers during each individual length of the pool during a race in order demonstrate changes over the course of a race. From all of his data East came to the conclusion that, for freestyle swimming in males, improved performance came from increasing stroke frequency. This is the exact opposite of most of the later works that determined that the important factor in improving performance is increasing distance per stroke (stroke length). This is just a small example of how the theories behind swimming have changed relatively recently. The relationship of SL and SR has also become a useful method in analysing swimming technique based on the characteristics of the curves generated from data sets. An example is given below.

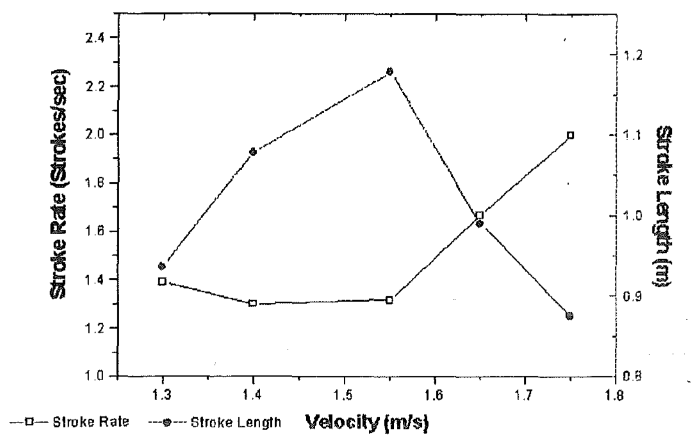

Figure 2 - Typical stroke rate / stroke length graph

As you can see, in this typical graph, most swimmers can increase their distance per stroke without an increase in stroke rate as velocity increases. They then reach a point where they can no longer increase velocity by increasing stroke length and must generate any increases in velocity by increasing their stroke rate. From this type of analysis a coach is able to monitor the effectiveness of technique alterations by noting where the stroke frequency starts to rapidly increase and stroke length falls off. The higher the velocity at which this occurs the more effective the technique.

Although SL/SR analysis can provide useful information and is relatively easy to perform, particularly the SR, it also has some inherent deficiencies that make it of limited value as an indicator of technique flaws. Chief among these factors is that SL and SR give no actual description of the movement patterns. Therefore, it is feasible that an athlete who is instructed to make a change in their technique may exhibit a change in their SL but the coach cannot know for sure whether or not the athlete is actually doing what he/she instructed the swimmer to do. In fact the swimmer may have made a completely different technique change than what was instructed. However, because the coach can't see what the athlete actually did to their stroke he/she may assume that the instruction they gave the swimmer was correct and then may instruct other swimmers to execute a technique modification that may or may not improve performance. This is a common flaw with all

methods of above water observation and is easily overcome by combining SL and SR with underwater video thereby allowing the coach to see exactly what the swimmer is doing under the water. Another factor which limits the usefulness of SL/SR as a technique evaluating tool is that in order to calculate distance per stroke accurately it is necessary to know the velocity at which the swimmer is travelling. For the average coach this can be a little tricky because it is necessary to time the swimmer over a defined distance in the middle of the pool while getting an accurate time for each stroke cycle. This problem can be addressed by utilising the techniques of the aforementioned researchers by using a video camera to record the swimmer during their performance. By doing this the coach is then able to get quite accurate times over a given distance by counting the number of frames it takes the swimmer to cover the distance. However, there is also a problem with this method in that it is very time consuming and does not allow for rapid feedback to the swimmer. Given the difficulty of calculating SL it is probably better for coaches to concentrate on the number of strokes per lap than the actual SL. Technique enhancements can then be detected when a swimmer is able to complete a length in a similar time but with fewer strokes. Because of the very close relationship between SL and SR coaches should still monitor SR and compare it swimming velocity so that they can see at what swimming pace the swimmers SR starts to climb.

Recently, more automated systems have been developed in Japan, Australia, New Zealand, and the US which allow for much more rapid feedback by using instrumented camera mounts that allow computerised tracking of the swimmers motion during the performance thereby allowing for very quick feedback to the athlete.

UNDERWATER WINDOW OBSERVATION:

As evidenced by the solutions to some of the deficiencies of the above methods one of the best ways to analyse technique is from below the water surface. The easiest way to do this is to use either an underwater window (if the pool being used has one) or for the coach to actually get into the water and watch the swimmers from below the surface. This type of observation has the obvious advantage that the coach is then able to see exactly what the swimmer is doing underwater without the view being effected by refraction. Underwater viewing also allows for immediate feedback to be given to the swimmer, which as stated earlier, makes technique modification much easier to do. The following figure shows a typical view from an underwater window. Note the enhanced clarity of the swimmer's body orientation as compared to Figure 1 when refraction is not an issue as it is with pool-side observation.

Figure 3 - Underwater view of swimmer

As with the other methods there are characteristics of underwater windows that are not optimal for providing technique feedback to the swimmers. The first of these is that you can get only one view of the swimmer at a time (either side on or head on) so some aspects of technique may be missed. Also, since virtually no pools have windows which run the full

length of the pool the coach has only a very brief period of time to get a look at the swimmer as they pass by the window. Due to technique variations which occur between breathing and non-breathing strokes, and similar variability of most swimming strokes, simply watching through a window is not sufficient to detect these types of differences in most cases. Additionally, as with virtually all methods of analysing swimming technique, underwater windows still don't get around the problem of dealing with bubbles caused by air entrainment into the water. Again, if you look in the above figure you can see that, even while in a streamlined position there is still the potential for numerous bubbles which may obscure the swimmer's body.

VIDEOTAPING:
As you go through the above methods of analysing swimming technique you will hopefully notice that many of the deficiencies in those techniques can be compensated for by simply using a video camera. Preferably this camera should be positioned under water for reasons laid out in the underwater window section above.

The most significant advantage of using video is that it provides a permanent record of the swimmers movements so that they may be compared more easily to other swimmers or to the same swimmer at different points during the season or during their career. This way the coach and athlete can monitor any changes that may occur and correlate them to the swimmer's performance at that particular time by watching it together. By providing the opportunity for this communication between the coach and swimmer, the video allows for enhanced understanding by the swimmer also allows the coach to get a better impression of how the swimmer actually modifies their technique. An additional advantage to video analysis is that, in most cases, using videotape allows slow motion analysis of the swimmer's technique. Especially when sprinting, the swimming motion can be quite fast, with a complete stroke cycle taking place in less than a second. Due to this high turnover it is often very difficult for coaches to see the finer details of what the swimmer is doing. By utilising slow motion this problem is eliminated by allowing the smallest characteristic of technique to be isolated and corrected if necessary.

Greater analysis opportunities are provided by video when more than one camera is used and, ideally, when the multiple views can be seen simultaneously on a screen by using a splitter. Multiple cameras allow a three-dimensional view of the swimmer's technique that is not possible with the naked eye or with a single video camera. For coaching purposes these cameras should be set perpendicular to and directly ahead of the swimmer. If underwater windows are not available then a periscope system or underwater camera housing can be used. In fact these later two ways of videoing are probably preferable due to their portability which allows for a more detailed analyses of the swimmer by keeping the swimmer in view for a greater period of time. If you are in a pool situation the ideal method of filming is actually a tracking camera that runs along the side of the swimmer and offers extended view of the swimmer's technique from the optimal viewpoints of side on and head on. For researchers, the underwater cameras, especially when combined with above water cameras, also allow for the digitisation and three-dimensional computer modelling of the swimming stroke. Once captured onto the computer these models provide the bases for much more detailed investigations into the dynamics of the swimming stroke. These will be discussed later in the indirect analysis section.

As valuable as video analysis is it still has similar problems to normal underwater observation in that when a single camera is used through an underwater window only one view of the swimmer is possible and the swimmer is also only visible for a brief period of time. These problems can all be taken care of by using multiple cameras and or underwater housings as described above.

FLUME OBSERVATION AND VIDEO ANALYSIS:

As a sort of bridge between the visual and indirect analysis methods we will now look at the use of swimming flumes. Flumes have been used in swimming research since the late 60's and early 70's by researchers in Scandinavia. Flumes are now slightly more widely available although flumes specifically designed for swimming analysis are still relatively rare. The unique thing about a flume is that the swimmer is kept in a relatively static position while the water flows around them. This is essentially the same as a runner running on a treadmill and allows for extensive prolonged analysis of the swimmer both biomechanically and physiologically. By having a swimmer perform in a flume the problems with brief viewing periods are eliminated due to the lack of movement of the swimmer. The flume also allows for precise control of the intensity at which the swimmer is performing. This allows for analysis of the swimmer's technique at different velocities and intensities. As with normal video analysis a flume provides the opportunity to use multiple cameras, both above and below water, simultaneously in order to provide a kind of three dimensional picture of the swimmer's technique. If the flume has enough observation windows, it is possible to set up cameras at several different underwater viewing locations by videoing through the windows. This limits the need for true underwater cameras when analysing technique. When a proper biomechanical analysis is being conducted, however, underwater cameras are preferable to viewing windows because of the extreme refraction that can occur when shooting through a thick glass window.

A flume allows the coach to stop the swimmer at any time to give instruction. Conversely, in a pool situation coaches often have to wait until the swimmer reaches the end of the pool before instruction can be given. This very rapid feedback allows for quicker adaptation to technique modifications.

Within the past several years there has been some criticism of flume swimming in that it has been stated that the technique that the swimmer uses in a flume is different to that used in free pool swimming. While this is true to some extent when swimming in a flume for the first time, it has been demonstrated recently (Wilson, Takagi, and Pease, 1998) that, with proper familiarisation of about a half hour of swimming at various intensities in a flume, stroke rate and stroke length are essentially the same as those demonstrated in pool swimming at the same relative swimming velocity. In fact, anecdotal evidence shows that any initial differences in technique are actually due to the initial anxiety about being 'chopped up by the propellers' rather than any actual dynamic difference in the swimmer-water system. It is because of this anxiety that swimmers tend to spin through their stroke quicker than they normally would at that same velocity in a pool. We have found that if the swimmers are given enough assurance and are shown the safety features of the flume then the familiarisation period can be more rapid allowing for quite valid measurements of their technique. It also appears that once a swimmer becomes familiarised to flume swimming that they do not need to go through the familiarisation procedure again for later sessions other than a normal warm-up period prior to testing.

However, to say that the swimming stroke used in a flume is absolutely identical to pool swimming would not be entirely accurate. There are minute changes in the duration of various phases of the stroke cycle, particularly the catch phase. As with the anxiety caused differences described above, these small technique variations do disappear after a relatively short period of time after the initial familiarisation. Another 'disadvantage' of flume swimming, at least to pool swimmers (as opposed to open water swimmers), is that, due to the lack of walls to do turns at, the swimmers can tire fairly quickly. From a coaching perspective this may actually be an advantage to flume swimming in that it may help the swimmers in training their aerobic energy systems. A final issue that must be addressed with flume swimming is that, because of the constancy of flow velocity of the water, when the swimmer's relative swimming velocity fluctuates they tend to move forward and backward in the flume. This movement, particularly the backward movement can elicit a response similar to the initial

anxiety the swimmer feels the first time in a flume. Again, these factors ease with greater use of the flume but they do have particular importance for breaststroke and butterfly which have greater velocity fluctuations during a stroke cycle than freestyle and backstroke. Unfortunately, many coaches and researchers have used the supposed technique differences to discount the value of using a flume for technique and physiological analysis as well as training. However, due to the extensive advantages of a flume for these type of investigations it is hoped that more coaches and researchers will use flumes in order to improve their swimmers' performance.

INDIRECT METHODS OF TECHNIQUE ANALYSIS: VELOCITY FLUCTUATION:
The first method of indirect technique analysis to discuss is the measurement of velocity fluctuations during the stoke cycle of a swimmer. This type of analysis can provide information on factors such as the generation of greater propulsion from one arm or the other as well as identifying any periods of excessive drag during the stroke by looking for drops in velocity. These are important variables because, from a physics point of view, it is more efficient to move at a constant velocity than with a fluctuating velocity. This is because if there are any slow points during the stroke cycle, in order to maintain an average velocity, the swimmer must compensate by generating extra propulsion in order to attain a velocity higher than the stroke average in order to balance the slower portions of the stroke. The greater the fluctuations the greater the amount of additional propulsion that is required thereby eliciting extra fatigue and potentially decreasing the swimmer's performance.

There are essentially two principle methods of doing this type of analysis. The first method is for the swimmer to be attached to a line which is in turn wound around a flywheel interfaced with a data recorder such as a computer. This method was described by D'Acquisto et al (1987). A diagram of a typical setup is given below.

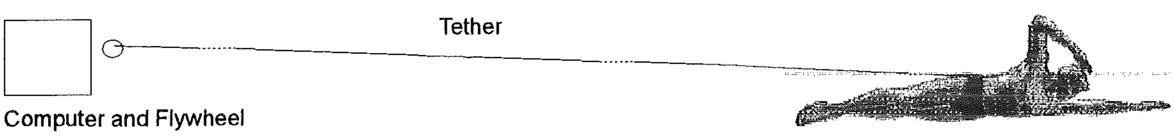

Figure 4 - Velocity measurement schematic

This type of analysis can also be done in a flume when a line is attached vertically to the swimmer and is then in turn connected to a device which measures the movement of the swimmer in all three dimensions over time and from those measures calculates the velocity fluctuation. If the equipment is available these data can then be overlaid onto a videotape of the swimmer so that the video can be matched up to the velocity trace thereby allowing the determination of the weak points in the swimmer's stroke.

The second method of velocity measurement is to videotape the swimmer and, after calibrating the video picture into real life distance, determining the velocity of the swimmer by seeing how far he/she travels for each frame of video and then plotting these velocities and determining the magnitude of any fluctuation. Even though these methods are tedious, especially the video system, the data can be valuable to the swimmer in detecting faults and giving the coach an idea of the relative efficiency of a given technique or efficacy of technique alteration.

In terms of the disadvantages of this type of analysis the biggest one is that the equipment is not widely available to do the tethered type of testing and the video option is very tedious and does not lend itself to rapid feedback to the athletes. There is also a problem with the tethered option in that due to bounce in the tether line the data is sometimes not so accurate and therefore can limit it's usefulness. A final problem with this type of analysis is that it does

not really give any information on the underlying movement patterns unless it is synchronised with a video tape, and the equipment to do this is also not widely available.

TETHERED SWIMMING:

Another popular method of analysing technique is by the use of a tether attached to the swimmer. This tether can either be a dynamic one, where the swimmer is still moving but with resistance, or a static one where the swimmer is kept stationary in the water while swimming in a pool. From these types of analysis it is possible to measure the propulsive forces generated by the swimmer if the tether is instrumented with a load cell or some other such device; or, in the dynamic situation (usually a piece of surgical tubing) by how far the swimmer can travel down the pool with ever increasing resistance from the tubing. Again, these analyses can give a very rough idea about the effectiveness of the technique being used by the swimmer without giving any specific information on the movements themselves. As with the velocity measurement the synchronisation with video may help, particularly in the static tether situation. However, there is another problem in that it has been shown that the technique used by swimmers when tethered is significantly different to that used during free swimming (Maglischo, Maglischo, Sharp, Zier, & Katz, 1984). Due to Maglischo's findings it seems somewhat superfluous to use tethering as an indicator of swimming technique.

HAND FORCE PATTERN ANALYSIS: DIRECT AND INDIRECT:

The most complex method of swimming technique analysis is by means of analysing the propulsive forces generated by the swimmer. At the moment this type of analysis is generally only done on the hands and sometimes the forearms. By determining the pattern of propulsive force production throughout the swimming stroke it is possible to pick out points in the stroke where the swimmer is losing propulsion and therefore not performing to the optimum. While this is, on the surface, a very valuable method of technique analysis it is also one of the most controversial methods.

This is particularly true of the indirect method which was first described by Schleihauf (Schleihauf, 1979). In this method it is necessary to video the swimmer underwater with at least two synchronised cameras. The video pictures are captured into a computer and digitised and then combined using an algorithm called the Direct Linear Transformation or DLT which allows for the creation of a three dimensional image from two or more two dimensional images, such as a video frame. Once the three dimensional model has been established it is then possible to determine the propulsive force generated by the hand based on it's orientation and velocity through the water at each point during the stroke cycle. The problem lies in the calculation of forces based on orientations. The early model of Schleihauf is inadequate due to certain limitations of data collection and mathematical model. There have been a few studies more recently (Sanders, 1999; Berger, Hollander, & de Groot, 1993) which have addressed some of these issues but the entire procedure is still fairly controversial. However, even if the absolute propulsive force values are not correct the pattern of force production may be informative. Therefore, it is possible to use this indirect method to look at relative differences in technique and to detect any flaws which may cause a loss in propulsive forces generated by the swimmer. It is also interesting to note a recent debate regarding the relative contributions of lift and drag forces to total propulsion. This has centred around the hand force patterns produced by this type of analysis. This seems like a somewhat dangerous step considering the ramifications to the coaching of swimmers. When Counsilman first theorised that swimmers were primarily using lift forces generated by the sculling motion of the hand as it moved through the water (Counsilman, 1969) the theory was adopted by virtually all coaches throughout the world and performances have continued to improve ever since. The recent move back to a predominantly drag oriented theory of propulsion seems like somewhat of a backwards step and could cause a reversal to older styles of swimming which were shown to be less effective as early as the 1950's (Counsilman, 1955).

Some of these problems with indirect force measurement are overcome by another method of determining propulsive forces involving the placement of pressure sensors on the swimmer's hand and getting a direct force measurement from these. This method is applied by Takagi (1998). This method is especially suited to a flume testing situation where the swimmer is stationary. This allows for the wire leads, which come off the sensors, to be adequately tethered in order to avoid any interference with the swimmer. This method also has the advantage that it is faster than the indirect measure due to not having to digitise any video data.

As is demonstrated by the above discussion both of these methods are not very easy to utilise due to the need for highly specialised equipment and a relatively long analysis period in order to give feedback to the swimmers. The lack of coefficients of lift and drag for the rest of the body is also a serious deficiency when looking at whole body technique. Additionally, in the pressure sensor method, there is again the problem of matching the force data with the actual movements of the swimmer unless the data are somehow synchronised with a video of the swimmer's technique. However, if we are ever to be able to understand exactly how a swimmer propels him/herself through the water this type of analysis is going to be vital and therefore any inadequacies in the methodology need to be overcome in the future.

OTHER METHODS:
Finally, I would like to briefly address some additional methods which have been used or which may be used in the future to analyse swimming technique. The first of these is the use of long mirrors on the bottom of the pool or on the wall of the pool so that swimmers can watch themselves swim. While this is a somewhat useful tool it is also worth noting that a problem may arise from the change in the swimmer's head position and amount of body roll which need to be altered for the swimmer to maintain a view of the mirror. However, this type of instantaneous feedback to the swimmer as to what they are actually doing can be invaluable when trying to make technique corrections.

Another method of giving instantaneous feedback to swimmers is a biofeedback system integrated to hand pressure sensors by emitting a tone with a frequency linked to the magnitude of the propulsive forces of the hand. This is an intriguing method that has only been reported once (Chollet, Micallef, & Rabischong, 1988) but it is an intriguing option as a tool for technique analysis by the swimmer, coach, and researcher and should be investigated further.

Finally, another method recently used to analyse technique efficiency is quantification of active drag. This is an even more controversial area of study than the indirect hand force measurement in that there are many different methods of determining active drag. The basic idea is that, as the swimmer is moving through the water while swimming, there is a resistive force (active drag) acting on his/her body. By modifying their technique they should be able to reduce active drag by maintaining a more streamlined position and having less of their body moving against the relative flow of water. In order to be truly useful there needs to be agreement as to which method should be used. Options include the MAD system of Toussaint et al (Hollander, Toussaint, de Groot, & van Ingen Schenau, 1985; Toussaint and Beek, 1992; Toussaint and Vervoorn, 1990; Ungerechts et al., 1994); the added mass method of Kolmogorov (Kolmogorov and Duplishcheva, 1992); or one of the more recently proposed methods such as that of Wilson et al, 1999; (Nomura, Goya, Matsui, & Takagi, 1994; Ungerechts and Niklas, 1994). If a method can be agreed upon then the determination of active drag could be extremely valuable in the analysis of swimming technique.

SUMMARY: In summary, swimming is an extremely complicated motion which has several unique characteristics which make it more complicated to analyse than virtually all other sporting activities. The fact that it is also one of the most competed in sports in the world indicates that the study of swimming technique both above and below the water surface is a

very important area of study for all those concerned. Unfortunately all of the methods mentioned in the previous discussion are not available to the entire swimming community. This is particularly the case of swimming flumes which, in my opinion, are one of the most valuable tools available to modern swimming analysis. Therefore, if a coach or a swimmer has the opportunity it is highly recommended that they try to undergo some testing in a flume facility so that they can get an accurate description of their swimming technique under all sorts of conditions. Even if this isn't possible all coaches should at least try to find some way to look at their swimmers from below the water surface so that can get a clearer picture of what the swimmer is really doing than what they can see from the pool side.

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WHAT ARE THE BEST BREASTSTROKERS DOING NOW?

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The purpose of this study was to analyse the styles of the best breaststrokers, taking into account their body characteristics, to allow a kinesiological diagnosis. The styles of 65 breaststrokers at international level were digitised and the body characteristics of 574 swimmers of at least national level were tested. The styles were grouped into five variants. Because undulation, consisting of upper trunk rotations above the water and body waving, was chosen as criterion for style, concepts from animal locomotion were derived. As criterion for efficiency, the velocity variation of the body centre of mass (CMbody) was chosen. In the most undulating variant, extreme CMbody velocity variations are avoided thanks to a velocity variation of the counter-acting body segments above the water, and a high and even velocity is obtained during body waving, thanks to accelerating water backward. For the education of experts in diagnosing swimmers of various performance levels, multimedia are a necessity because written outputs are not sufficiently visual.

KEY WORDS: kinesiology, breaststroke, undulation

INTRODUCTION:

In breaststroke at international level very different styles occur. Above the water surface, one can observe an almost stable trunk position or a large back- and forward upper trunk rotation; below the water surface, one can observe a predominantly horizontal or vertical leg kick and arm pull, and between the kick and pull a flat or a waved body position. Because most competitive swimmers do not find their best style, since the seventies technique and dryland training advice were offered in a Kinesiological Research and Evaluation Centre in Leuven (Persyn et al, 1982).

Even a leading physiologist, like Costill (1988), is convinced that the difference between international and club level swimmers has more to do with skill than with physical ability, and that a swimmer has to concentrate every day on technique. To obtain a database for technique advice, the styles of 65 breaststrokers at international level were analysed (100m time women:71.3sec; men:62.8sec). Because amplitudes of upper trunk rotations and eel-like body waving (the so-called undulation) became progressively larger, the application of concepts from dolphin and eel locomotion became more appropriate than from ship locomotion. Maglischo (1982) and Troup (in Rutemiller, 1990) did not find statistical relationships between joint flexibility or muscle strength and swimming performance. But, when relationships between body characteristics and amplitude of undulation were studied, a kinesiological database was obtained allowing to improve swimming performance.

Because stroke mechanics in the very different styles, as well as follow-up studies of style changes, could not effectively be described in written documents, the implementation was made via interactive multimedia (Figure 1). This was an appropriate output of research and expertise to familiarise swimming experts (at the university or in the club) with the various steps of a kinesiological expert system for diagnosing and advising, which is being developed.

The objective of this paper is to give an introduction in the kinesiological research strategy and in applications of concepts from animal locomotion in different style variants (unfortunately much less visual than when using the CD-Rom). The content of this paper was collected from various (multimedia) presentations at the congresses of 'Biomechanics and Medicine in Swimming', before and after the rule change.

METHODS:

1. A Criterion for Style and for Efficiency:

At the congress of 'Biomechanics in Swimming' in Brussels (1974), attention was paid to undulation (body waving and trunk rotations), used by finalists at the Olympics in Munich (1972). In the folder of the congress, striking similarities were drawn between body waving in butterfly and in eel swimming, as introduced by Gray in 1933 (Persyn et al, 1975). One female breaststroke finalist, using an extreme upper trunk rotation and head movement, obtained a much more even velocity of a fixed point on the trunk than the others with an almost stable trunk position. It was concluded that 'retarding movements or positions are not exclusively hindering' (Persyn et al, 1976). When more exactly the velocity of the centre of mass of the body (CMbody) remains even, the swimmer must not lose extra energy in overcoming the inertia of the body in addition to hydrodynamic drag forces (Persyn, 1969).

The conclusion of this study is still up-to-date: "although the body positions and velocity fluctuations can be measured in the stroke cycle, it remains a formidable task to quantify the forces affecting these resultants, considering the body with its multi-link system moving in both air and water, in addition to the water being extremely discontinuous." (Persyn et al, 1976). Even when pulling with only one arm, while the swimmer was lying on a force platform just above the water surface, large differences were found between the propulsive forces measured and those calculated from film analysis (Van Tilborgh et al, 1988). Such a calculation remains difficult because in addition to the lift and drag forces, generally studied in the literature, inertial effects must be considered. These are created by the mass of the displaced arm as well as by a so-called added mass of water accelerated behind the arm. In fact, propulsion and drag forces are as inseparable as Siamese twins.

In the whole swimming stroke, inertial effects are also created by body segments accelerated above the water surface. In this multi-link system moving in the two media, only the difference between global propulsion and drag forces can be calculated, the so-called resultant impulse. Therefore, the horizontal velocity of the CMbody had to be calculated (Figure 1a). In this paper, this velocity was chosen as a global criterion for mechanical efficiency, while the amplitude of undulation was chosen as a criterion for style (Colman et al, 1992).

It was assumed in the Kinesiological Research and Evaluation Centre that more flexible swimmers should undulate more and could obtain a more even velocity of the CMbody by using their whole body, and that more inflexible swimmers should use the muscle strength of their limbs in flatter styles, despite more velocity variation of the CMbody (Figure 1g).

B. A System for Movement and Body Analysis and for Diagnosing:

To quantify the amplitude of undulation and the velocity of the CMbody, at least a side view video recording was required. To record the swimmer, moving below and above the water surface, with one camera, a periscope was used, and to obtain the largest image possible, the camera and periscope were rotated (Colman et al, 1990; 1993, 1998). The problem was to reconstruct the disturbed image of the swimmer (using often extreme trunk flexion and extension and shoulder girdle movements) and to calculate correctly the CMbody and the CM of the body segments above the water surface. Therefore, a video-analysis system specific for swimming was developed (on an Amiga-computer).

To derive and compare stroke mechanics per phase in the very different styles, typical instants had to be defined clearly in the cycle. This was not only necessary for the leg kick, the arm pull and the recovery, but for body waving and trunk rotation as well. For a fast digitising, only 12 instants were selected from side and front view recordings. Now nine instants have to be digitised at least for diagnosing (Figure 5).

To score individual body characteristics, profiles had to be constructed. Based on observations of typical instants in the strokes of the finalists in Munich (1972), measurements of body

structure, flexibility and isometric muscle strength were made (Persyn, 1974). 34 body characteristics, significantly correlated with performance in at least one swimming stroke or style variant, were retained (Figure 1h-i) (Vervaecke and Persyn, 1979; Persyn et al, 1980).

C. Concepts from Animal Locomotion:
Because in 1972 the trunk position was almost stable in breaststroke, applications of concepts from ship locomotion could be derived, such as a propeller-like propulsion with the hands and feet during arm and leg squeezing (Persyn et al, 1975). Because already much attention has been paid in the scientific literature to the hand and foot concept (Sanders, 1998), and because of the increased participation of the whole body in the locomotion when undulating (above as well as below the water surface), it was preferred to stress here applications of concepts from eel or dolphin locomotion (e.g., Gray, 1933; Ungerechts, 1986):

More propulsion can be obtained:

1. When a mass of water is displaced backward in the curves of a body (Figure 1, d2).
2. When the tail fin is moved in a more vertical plane (instead of backward or forward) during the straightening of the tail (Figure 1, d2).
3. When the inertia of a mass of water, accelerated forward behind a body, pushes the decelerating body in the back.
4. When a body section is accelerated forward above the water surface (and more drag can be obtained when accelerated backward) (Figure 1, e).

Less drag can be obtained:

5. When the mean propulsion is directed through the CMbody.
6. When the CMbody is maintained in the same horizontal plane.
7. When the front part of the body counter-acts the tail kick (Figure 1, d2).
8. When the body passes through a small pipe (Figure 1, f).
9. When a part of the body glides above the water surface (Figure 1, f).

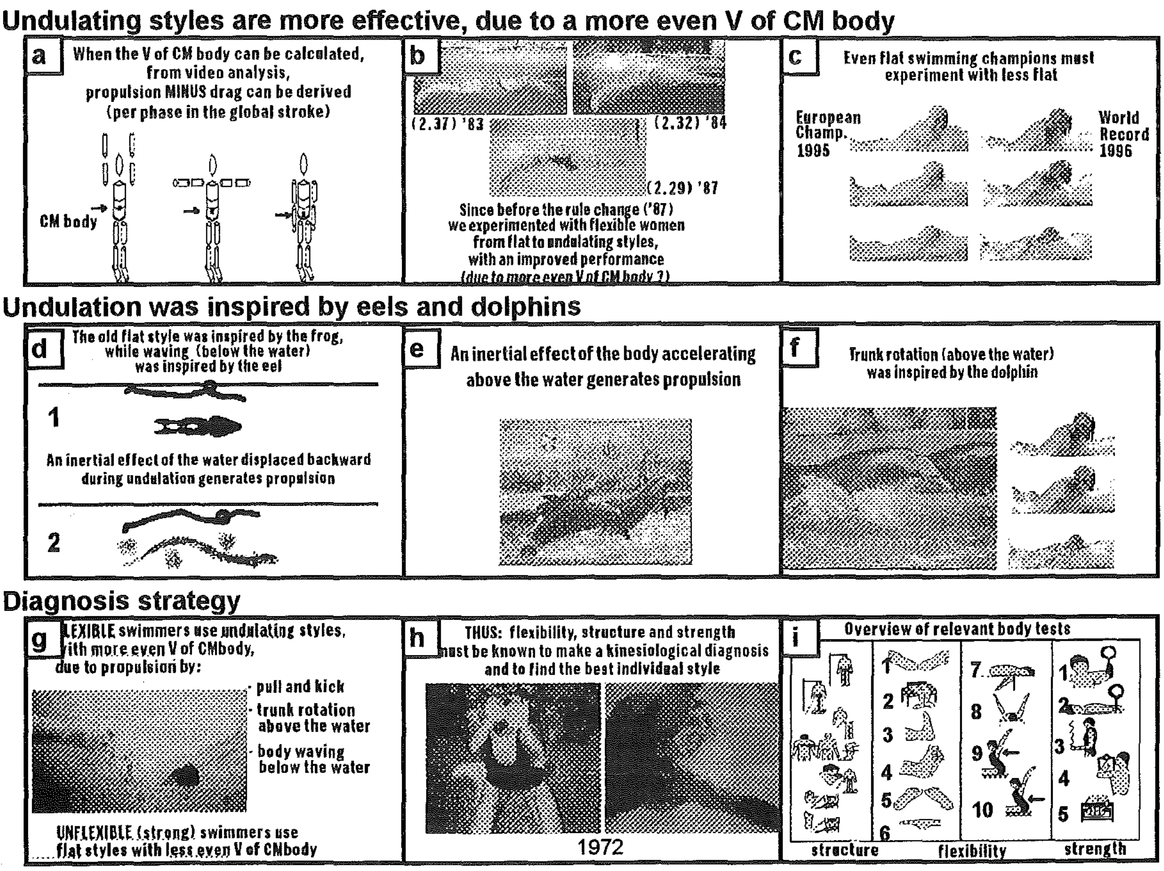


Figure 1 - Some screens from a multimedia CD-Rom on kinesiology of breaststroke

PILOT STUDIES:

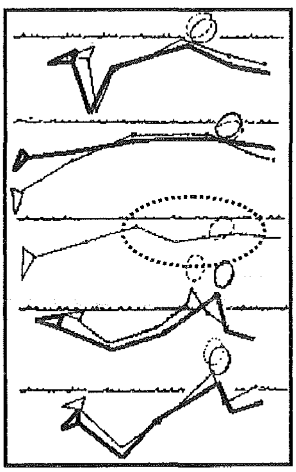
At the congresses of 'Biomechanics and Medicine in Swimming' in Bielefeld (1986) and in Liverpool (1990), respectively before and after the rule change (allowing to dive the head below the water surface), a co-worker of the Kinesiological Research and Evaluation Centre received the Archimedes Award. At each congress, on the one hand, a successful experimental case study, changing to more undulation, was presented (Figure 1b). On the other hand, the findings of statistical analyses of kinesiological data, related to undulation, from a large group of high level breaststroke swimmers were visualised, using multimedia.

A. BEFORE THE RULE CHANGE:

1. Experimentation with Undulation:

At the congress in Bielefeld (1986), a breaststroke swimmer was presented who changed her flat to an undulating style, in combination with a specific dryland training (Figure 2) (Persyn et al, 1988). After nine months, she improved her 200m performance from a national level (2min 37sec) to an Olympic medallist level in Los Angeles 1984 (2min 32sec).

Before the rule change swimmers risked to be excluded during competition when they undulated too much, due to the immersion of the head. However, despite this limitation, some applications of the previously mentioned concepts from eel and dolphin locomotion could already be derived. In Figure 2, five instants visualise style changes typical for undulation (for the phase definition: see Figure 5.):



a. a trunk position kept uphill when the leg kick starts (resulting from a specific recovery) (CONCEPT 9)

b. a dome-shaped body position (resulting from the downward leg squeezing)

c. a waved body position, and a still limited downhill trunk position (resulting from a flexed hip and still limited upward arm spreading) (CONCEPT 1, 6)

d. a cambered body position and an uphill trunk position (after the arm squeezing)

e. a trunk position kept uphill half way the recovery (resulting from a still extended hip) (CONCEPT 3).

Figure 2 - The change from a flat to an undulating style (respectively dark and thin lines) of an 'experimental' swimmer (I.L.), before the rule change. Undulation was limited because part of the head had still to be kept above the water surface (Persyn et al, 1988). Despite this limitation, for each of these instants a statistical relationship was already found with resultant impulse (Van Tilborgh et al, 1988) (for the phase definition: see Figure 5).

2. Statistical Study of a Movement Analysis:

At the same congress, Van Tilborgh received the Archimedes Award by visualising, via Amiga-computer animations, how large the velocity variation was and how undulation required less mechanical work due to a more even velocity (Van Tilborgh et al, 1988). Statistical findings were presented of an analysis of 18 German national level swimmers.

a. Average results related to the velocity variation of the CMbody

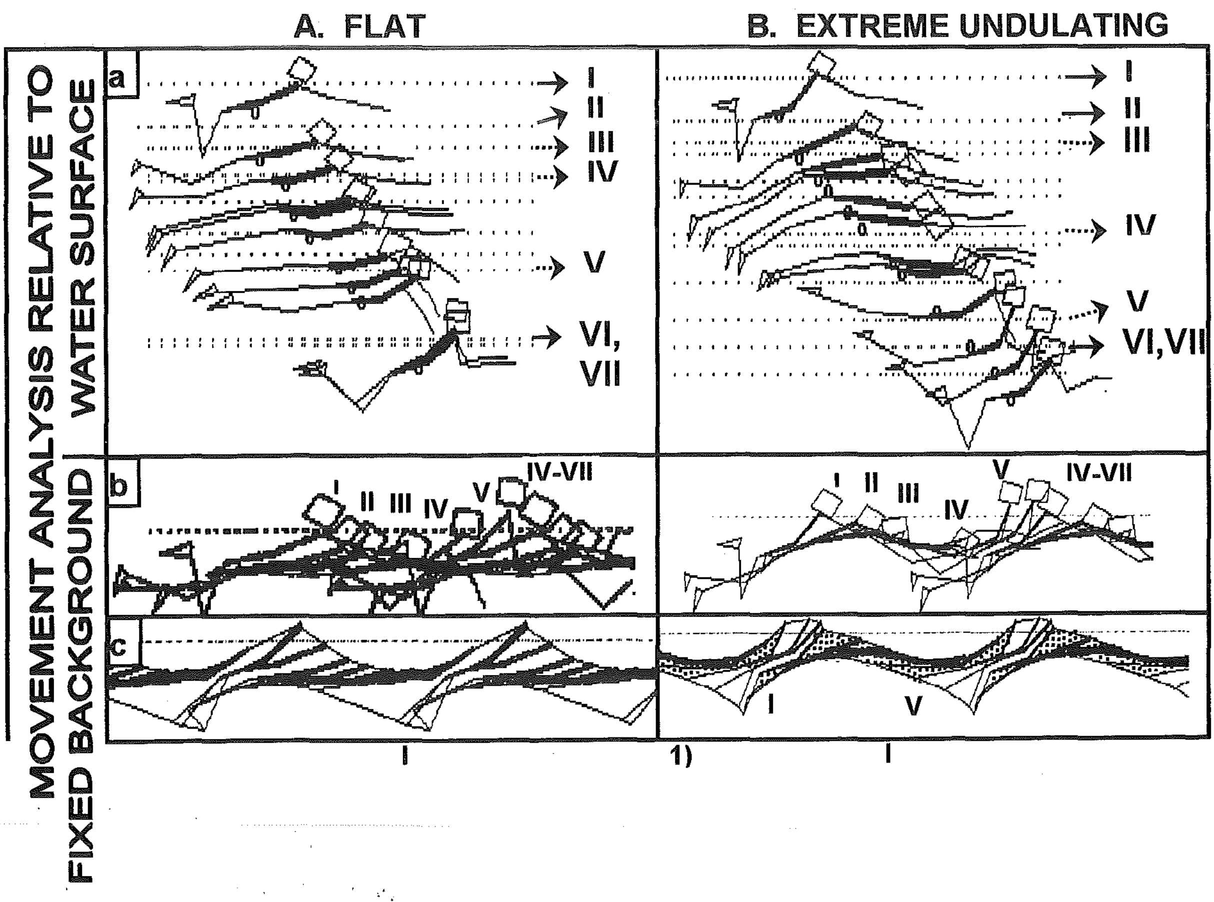
- The difference between the highest and lowest velocity peaks (respectively between the arm squeezing and the leg spreading) amounted 77% of the swimming velocity.
- The work needed to accelerate the body was 92 J; namely a loss of 80 Watt (which is 25% of a total work of, e.g., 320 Watt).

- The resultant impulse during arm squeezing was four times larger than during arm spreading and during leg squeezing three times larger than during leg spreading.
- 75% of the total resultant impulse was, however, generated by the leg kick. But when a simplified correction could be made per phase for hydrodynamic drag (correcting by the square of the velocity and considering the body position), the arm pull becomes as propulsive as the leg kick (when the swimmer is strong enough).

b. More undulation corresponded with a more even velocity of the CMbody:
In this group it was found that more undulation during the very accelerating arm and leg squeezing phases corresponded with lower resultant impulses (thus with less acceleration due to respectively a more cambered and a more dome-shaped body position) (Figure 2: b,d). In most other decelerating phases, more undulation corresponded with a higher resultant impulse (Figure 2a, c, e). Thus, more undulation resulted in less than the average 77% velocity variation of the CMbody and, consequently, in less loss than 25% of the total work.

B. SHORT AFTER THE RULE CHANGE
1. Experimentation with Extreme Undulation:
When short after this congress, the breaststroke rules were changed (1987), allowing unlimited undulation, the same 'experimental' swimmer (from Figure 2) was ready to use an extremely undulating style, improving her 200m performance once more (to 2min 29sec). At the congress in Liverpool (1990), this new style was compared to her original flat style (Persyn et al, 1992). The applications of concepts of eel and dolphin locomotion became more evident:

- Larger down- and uphill trunk rotations were combined with a larger down- and upward leg kick and arm pull (seen relative to a fixed background in Figure 3, d); the movement amplitude of the limbs in the hip and shoulder joints was much wider (seen relative to a fixed trunk in Figure 3, e) (CONCEPT 2).



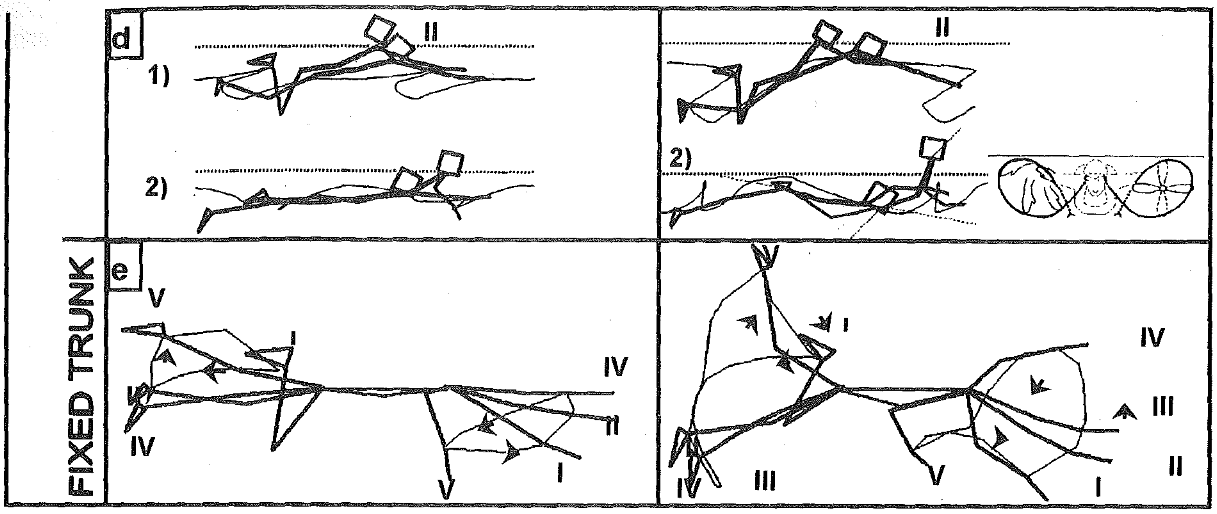


Figure 3 - The original flat style (1983) and the extreme undulating style (after the rule change in 1987) used by the same Olympic medallist as in Figure 2. Different references are relevant for the analysis:

* relative to the water surface (dotted lines): a) 12 instants digitised and VII representing undulation:

- Trunk rotations, quantified from the angles between the trunk and the water surface: max. tilted trunk = VI; ½ leg recovery (knee 90°) = VII; begin leg spreading = I; max. leg spreading = II.
- Body waving, quantified from the angles between the limbs and the trunk in the hip and shoulder joints, and between the upper and lower half of the trunk, in 3 typical body positions: most dome-shaped = III; most S-shaped = IV; most cambered = V.

* relative to a fixed background: b) the VII undulation instants; c) only the trunk and the thigh (for interpretations of drag); d1-2) the path of the ankle and the wrist, including rear and front view (for interpretations of propulsion); d2) the extreme trunk positions (for interpretations of balance)

* relative to a fixed trunk: e) the path of the ankle and the wrist (for interpretations of flexibility

- Larger body waving allowed a smooth transition between the down- and uphill trunk rotations; the whole body was now able to pass through a small sinusoidal pipe, except during the recovery (seen relative to a fixed background in Figure 3, b-c) (CONCEPT 8).

2. Statistical Relations between Style and Body:
At the same congress, Colman received the Archimedes Award by visualising, via Amiga-computer animations, how and why the amplitude of undulation was chosen as a criterion for style and that this amplitude was significantly related with body characteristics (Colman et al, 1992). Statistical results were presented of a movement and body analysis of 35 breaststroke swimmers at international level.

a. The amplitude of undulation as a criterion for style
On the one hand, even before the rule change, various changes from a flat to an undulating style were successful, as shown for one swimmer. On the other hand, even when undulation had to be limited, instants typical for undulation corresponded with less excessive resultant impulses. Therefore, the amplitude of undulation was chosen as the criterion to distinguish styles. The two styles in Figure 3, used by one swimmer, are still now representative for the two extreme style variants at international level (Figure 5), and were taken to indicate striking differences in each of seven typical instants chosen to quantify undulation, more precisely:

- body waving, the most dome-, S-shaped and cambered body positions (instants III to V)
- trunk rotation, four trunk positions relative to the water surface (instants I-II and VI-VII).

To score the amplitude of undulation of an individual, seven percentile scales were constructed from angles measured at each of the typical instants (Figure 3,a). Three years after the rule change, the swimmers undulated significantly more; women more than men did, mainly due to 8 degrees more backward trunk rotation.

b. Relation between the amplitude of undulation and body characteristics:
Because of the increased variation in amplitude of undulation, the statistical relations between body characteristics and performance in 'the' breaststroke became less evident. But, many statistical relationships were found between this amplitude and body characteristics. This criterion of amplitude of undulation was thus a good choice to optimise the individual style and dryland training advice.

Some statistical findings for body structure, strength and flexibility will now be specified:
A more undulating style occurred in smaller and leaner women.
High scores for latissimus-pectoralis-triceps muscle strength (devided by body weight) were important to use a flatter style in men, but a more undulating style in women. These muscles must, indeed, be strong during the arm squeezing phase:

- in flat swimming men, to accelerate the body,
- in undulating women, to tilt part of the body above the water surface (CONCEPT 4).

In fact, the average strength score of the triceps muscle of women at international level was higher than of men at national level.
Concerning flexibility:

- the use of a flatter style, in men, was positively related to the capacity:
- to flex the ankle, as well as to rotate the knee outward and the hip inward, allowing the sole to function as a propeller blade with an optimal range, pitch and speed, during the first part of the leg squeezing (CONCEPT 5) (Vervaecke & Persyn, 1979).
- to extend the ankle, allowing to streamline the legs and to raise them behind the trunk, during the leg squeezing (Figure 4A).
- the use of a more undulating style, in men and women, was related to the capacity:
- to extend the trunk and the shoulder upward, required for body waving and upper trunk rotation (Figure 3B, a IV).
- to rotate the hip outward and to supinate the ankle, required to orient the sole like a dolphin tail fin, during the downward leg spreading (CONCEPT 2).
- to hyperextend the knee backward (sabre position), during an additional upward leg kick (Figure 1b; Figure 4B,c) (CONCEPT 2).

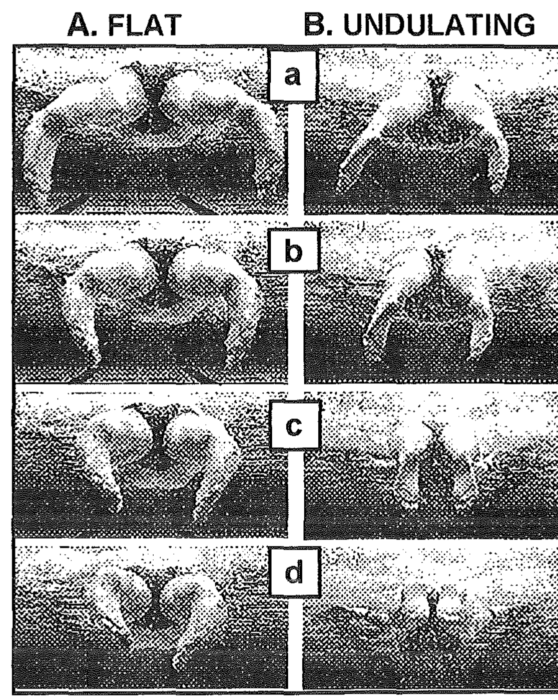


Figure 4 - Second part of the leg squeezing in the flat style (A); second part of the downward leg squeezing and upward leg kick in the undulating style (B).

RECENT RESULTS AND DISCUSSION:
At the congress of 'Biomechanics and Medicine in Swimming' in Jyvaskyla (1998), style variants of the best breaststrokers now, 10 years after the rule change, were visualised, via a multimedia CD-Rom. Digitised data of 65 breaststroke swimmers and 59 butterfly swimmers at international level were available, in addition to test scores of body characteristics of 267 women and 307 men of at least national level. Based on the amplitude of undulation (Colman

et al. 1992; 1993), the styles of almost all the breaststroke and butterfly swimmers could be grouped into five variants.
To show how much mechanics can differ in 'the' breaststroke, first, a comparison was made between two extreme style variant groups, consisting of the five most undulating women (variant 5) and the five flattest swimming men (variant 1). In Figure 5, the two style variants are visualised in nine selected mean stick figures and the mean velocities of the CMbody per phase are specified. As mentioned earlier, the two styles in Figure 3, used by one swimmer, are still now representative for the two extreme style variants.

A. DIFFERENT STROKE MECHANICS IN THE MOST UNDULATING AND THE FLATTEST VARIANTS:

In the flattest style variant, the highest CMbody velocity peak occurs during the second part of the arm squeezing (Figure 5A, 7-8) and the lowest during the leg spreading (1-2). The difference amounts 77%, which is still the same as found in the German group at national level studied by Van Tilborgh before the rule change. In the most undulating variant, deceleration occurs only during the recovery (Figure 5B, 8-1), when the swimmer is unable to pass through a small sinusoidal pipe (Figure 3, b-c). Consequently, the velocity variation of the CMbody amounts only 59.2%. The highest peak, during the second part of the arm squeezing, is avoided because body segments are decelerated above the water surface; the lowest peak, during the leg spreading, is avoided because these segments are accelerated (CONCEPT 4).

1. Balance Mechanics Causing Upper Trunk Rotations

In the most undulating variant, an extreme upper trunk rotation of 63° with the horizontal (versus 34° in the flattest style) allows the deceleration and acceleration of the body segments above the water surface (up to 29% of the body mass versus 21% in the flattest variant). The balance mechanics causing the upper trunk rotations (and other body movements) above the water surface consist of inertial effects and force couples:

- Inertial effects are created independently from the water, and result from a flexion or extension of the whole body (Figure 5B, 2-4 and 6-7), of the limbs or of the neck.
- Force couples result from:
  - The distance between the downward directed gravity force (acting in the CMbody) and the upward directed force (acting in the centre of buoyancy).
  - Hydrodynamic forces (acting up- and downward on the front or rear body parts).

The very precise co-ordination, allowing the extreme upper trunk rotations in the most undulating variant, will now be specified, as an example:

- The up-backward upper trunk rotation results from a swing-like body movement, created by:
  1. an inertial effect from an extension of the whole body (Figure 5B, 6-7),
  2. a lift force acting on the hyperextended body,
  3. a forearm squeezing like a propeller blade of an helicopter (Figure 5B, 7-8).
- The uphill trunk position can be maintained by surfing during the recovery, because the hip and the trunk remain extended (cambered) while the forearm is inclined upward and displaced with high velocity at the water surface. When the leg spreading starts, still 21% of the
  body mass remains tilted above the water surface (Figure 5B, 1).
- The last part of the down-forward upper trunk rotation results from a trunk flexion (kyphosing the back) combined with a force couple acting on the whole body. This is obtained from the downward leg spreading, from the late downward orientation of the arms and from the gravity force on the head and shoulder girdle (Figure 5B, 1-2). (In the flattest variant, the forward trunk rotation is completed during the recovery, because of an early hip flexion and an early downward orientation of the arms, Figure 5A, 9-1.)

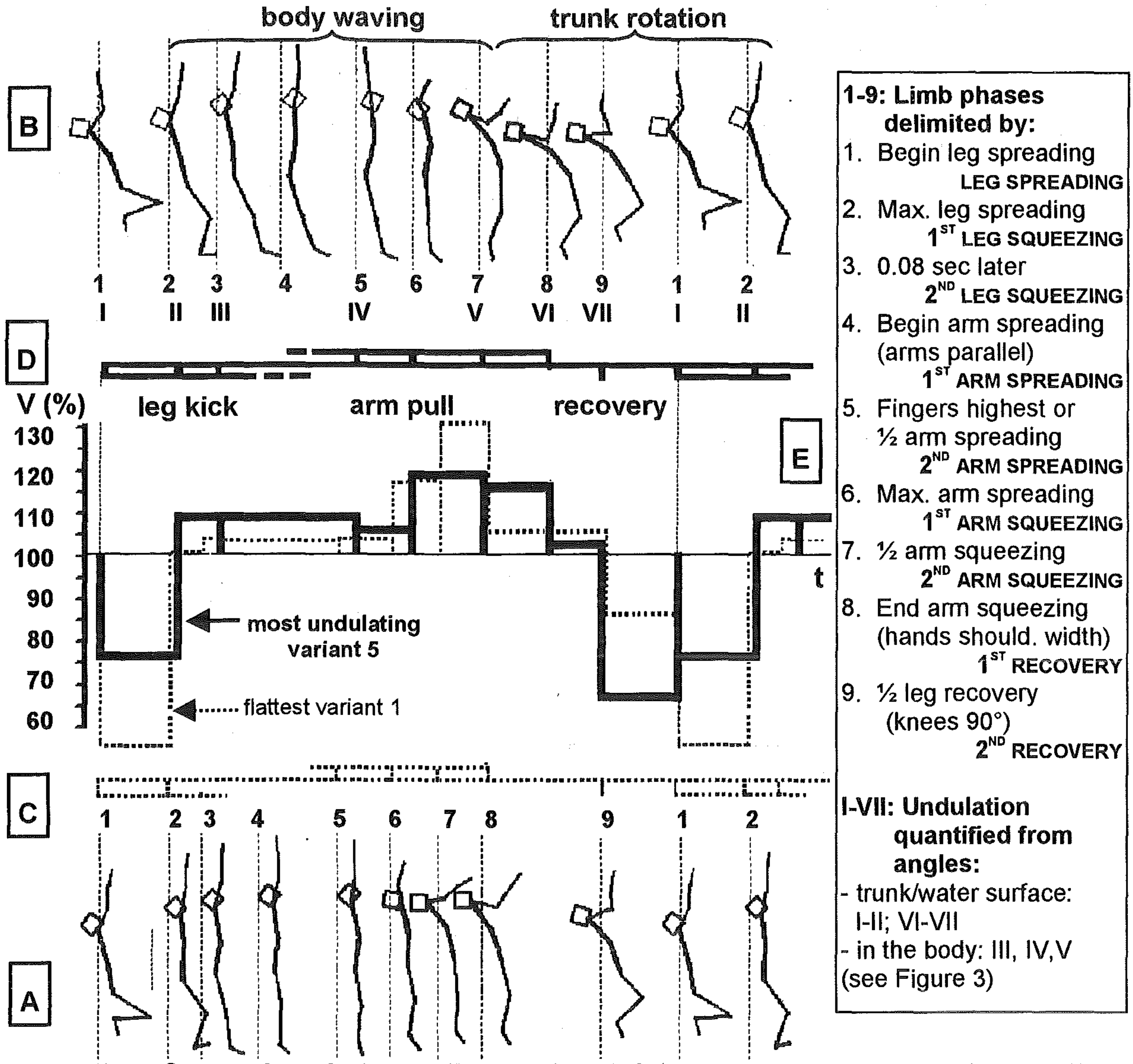


Figure 5 - Comparison between the most undulating style variant (5) and the flattest style variant (1):

A and B. **Mean stick figures, calculated from the mean lengths of the body segments and from mean angles (between the limbs and the trunk and between the trunk and the water surface)**

C and D. **Mean duration of selected limb phases**

E. **Mean percent of the horizontal velocity of the CMbody per phase; to compare the velocity of the CMbody between individuals of the two sexes, the mean velocity per phase was expressed as a percent of the mean swimming velocity during the stroke cycle. (When the mean velocity increases considerably from phase to phase, there is an acceleration.)**

2. Propulsion Concepts Related to Accelerations of the Body above the Water Surface

The more even velocity thanks to the upper trunk rotations in the most undulating style variant will now be explained and applications of concepts from animal locomotion will be made:

- During the second part of the arm squeezing (Figure 5B, 7-8), the forearm, functioning like a helicopter propeller blade, is oriented back-downward and can thus still generate propulsion during this apparently recovering phase. But, because the backward rotation of the body segments above the water surface is combined with a forward rotation of the immersed body segments, extra frontal drag is obtained and an added mass of water is accelerated behind the back.

As a result, the propulsion generated by the arms and the drag caused by the trunk allow to maintain approximately the same velocity as in the previous phase (versus an increase of 16.6% to the highest velocity peak in the flattest variant). The energy lost by lifting body segments above the water surface (29%) and by the water accelerated behind the back can, however, be recuperated in the two following critical phases:

- During the first part of the leg and arm recovery (Figure 5B, 8-9), the forward accelerated mass of water, behind a hydroplaning body, could push against the back and help to avoid too much deceleration of the CMbody (CONCEPT 3) (Van Tilborgh et al, 1988). Another phenomenon helping to avoid too much deceleration of the CMbody is the acceleration of the shoulder girdle and the upperarm above the water surface. (During this phase, the forward velocity of the CM of the body segments above the water surface is 59% greater than in the preceding phase.) These segments do not encounter drag, while the immersed body segments are somewhat stabilised by the water medium (CONCEPT 4). Furthermore, because the forearm is already directed forward at the end of the previous squeezing phase, the duration of the first part of the recovery is reduced to only 9% of the stroke cycle (versus 21% in the flattest variant).
  As a result, thanks to the inertia of the water pushing against the back and to the acceleration of body segments above the water surface during this short phase, the velocity decreases only 17% (versus 27% in the flattest variant). In the most undulating variant, the last phase of the recovery remains the main source of deceleration.
- During the downward leg spreading_(Figure 5B, 1-2), the forward velocity of the CM of the body segments above the water surface is 216% greater than in the preceding phase (CONCEPT 4). Moreover, the trunk flexion (kyphosing the back) flattens the under side of the trunk, which reduces the form drag, and causes a high muscle tension in the abdomen and around the pelvis, which consolidates the basis for the downward leg kick. As a result, thanks to the inertia of the forward accelerated body segments above the water surface, the reduced form drag and the strengthened leg kick, the CMbody velocity is increased 9.5% (versus decreased 32% in the flattest variant).

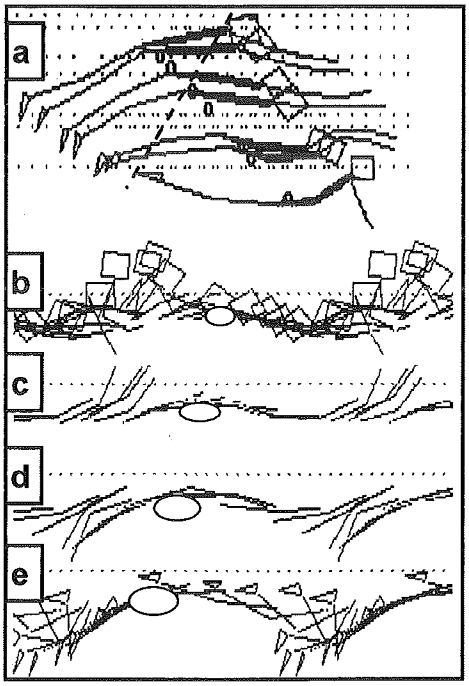


Figure 6 - Eel-like backward displacement of rotating water contained in a curve formed below the swimmer from Figure 3B, a (a), by consecutively:
b. the angle arm-upper part trunk
c. upper-lower part trunk
d. lower part trunk-thigh

3. Propulsion Concepts Related to Body Waving Close to the Water Surface

In the most undulating style variant, body waving (from the most dome-, S-shaped to cambered body position) allows to maintain a relatively high and even velocity (Figure 5B, 2-7).

- During the first part of the downward leg squeezing_(Figure 5B, 2-3), the whole body is flexed and a dome-shaped body position is obtained. Due to this body position, the velocity increases only to 34% (versus 45.5% in the flattest variant, where propulsion is more directed through the CMbody) (Figure 3A, d-e; Figure 4A) (CONCEPT 5).
- During the second part of the downward leg squeezing phase_(Figure 5B, 3-4), a downward extension of the front part of the body (from the midpoint of the trunk to the hands) counter-acts the wide downward leg kick. This is required to displace the body sufficiently horizontally and to decrease drag (CONCEPT 7).

The energy lost by the dome-shaped body position and by raising the hip can, however, be recuperated during the following phases by displacing water backward below the body. This is only possible when the trunk and the knee can be hyperextended to allow a real S-shaped body position. A curve below the body can then be displaced backward as in an eel, from the shoulder to the hip, the knee and the lower leg (Figure 6). An added mass of water contained in this curve could be displaced backward and even be set in rotation, which propels the body forward (Gray, 1933) (CONCEPT 1).

Moreover, when this mass of water leaves the lower leg backward, thanks to straightening the hyperextended knee during the second part of the upward leg kick, the sole of the foot can be moved more vertically. This generates additional propulsion by deflecting water backward during the critical arm spreading phase (Figure 4B, c-d) (CONCEPT 2)
Other advantages of the dome- and S-shaped body positions are that the back and then the buttocks glide above the water surface (Figure 5B, 2-5). As a result:

- Drag is decreased (CONCEPT 9)
- The CMbody is almost not lowered after the trunk rotation (CONCEPT 6).

The CMbody is not displaced more vertically than in the flattest variant (4% of the body length), but the mean mass above the water surface during the cycle amounts 12% (versus 7 % in the flattest variant).

B. THE DIFFERENT STYLE VARIANTS AND SPECIFIC BODY CHARACTERISTICS:
In breaststroke, as well as in butterfly, the styles at international level could now be grouped for men and for women in the same five variants (Figure 7). For about 80% of the swimmers at this level, the fastest style variant can be calculated from body characteristics (based on determining the smallest difference between the individual body scores and the mean scores of the body characteristics specific per style variant). In addition, the mean error of the performance calculation from body characteristics amounts only 3% (Zhu et al, 1997).

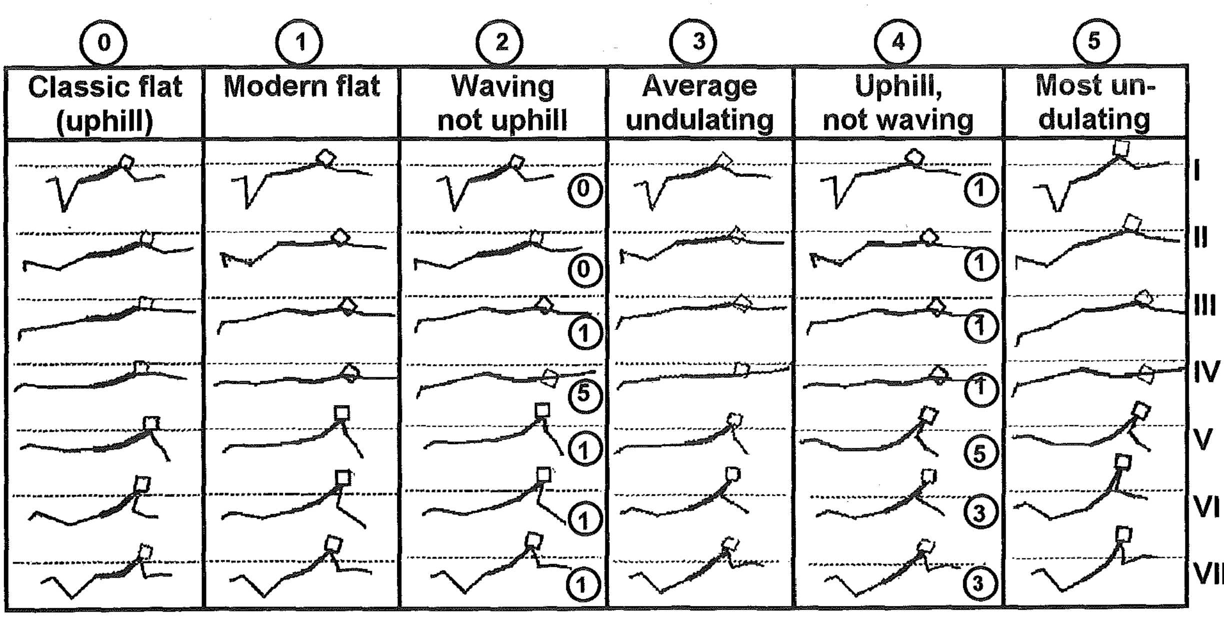


Figure 7 - Different style variants in breaststroke. Definition of undulation instants I-VII: see Figure 3

Some particularities per style variant (Figure 7):

- Style variant 5, most undulating, is used primarily by women in butterfly and breaststroke, wherein similar scores occur for flexibility, except for hip inward and outward rotation.
- Style variant 3, average undulating, must be situated between variant 1 and 5, and is used by men and women. Although their swimming velocity differs 10%, the velocity variation of the CMbody is almost identical in the two sexes (Colman et al, 1993). In addition, in this style variant the flexibility scores in the two sexes are very similar.
- Style variants 2 and 4 are composed by a mixture of the other variants, as specified in Figure 7. Variant 2 is predominantly flat, but shows an S-shaped body position (IV) as in variant 5, and is primarily used by men; variant 4 is predominantly flat, but shows a cambered body position (V) as in variant 5, and is primarily used by women.
- Style variant 0, classic flat, is disappearing from the international level. This variant was popular before the rule change and was typified by a stable uphill trunk position, a deep arm recovery and a downward arm spreading, which frequently caused a deformation (kyphosis; but lordosis problems could be caused by hyperextension in variants 4 and 5).

Women use 8 degrees more trunk rotation than men, who could, apparently, compensate a less even velocity of the CMbody by higher resultant impulses during the leg and arm squeezing, thanks to more muscle strength.

The precise co-ordination during the recovery above the water surface of the upper trunk, the shoulder girdle, the (upper) arm and head is typical and critical in each style variant. Apparently, many swimmers do not yet profit sufficiently from diving the head and launching the arms actively forward, to use their inertia during a slow phase, nor from gliding with the back and the buttocks above the water surface, even in the flatter style variants (Figure 1, c).

In the flatter style variants or when a glide occurs (e.g., in 200m events), the arms are, first, raised from deep in the recovery during the leg kick and spread afterwards. In the more undulating variants and in sprint events, the arms are raised and spread simultaneously and overlap with the leg squeezing (Figure 3Bd2). In fact, the arms are rotating in the opposite direction than in the classic variant (0) with a downward arm spreading (Figure 3B, c II-V).

CONCLUSION:

Thanks to the research steps described in this paper, a kinesiological database is progressively more supporting pure experience in guiding a swimmer to his optimal style and body characteristics (Colman & Persyn, 1994). Even when expert systems will become available, the coach and the swimmer still have to continuously experiment with various styles. The swimmer must thus be able to combine different amplitudes of trunk rotations and body waving.

General dryland training from the age groups must enlarge the range of experimentation. Specific flexibility in the hips, knees and ankles is to a large extent congenital and must be maintained. However, specific flexibility and strength in the shoulder girdle are more trainable but still not sufficiently developed, even not in many swimmers at international level. But, increasing the body mass by a general strength training hinders the swimmer more than in other strokes because of the energy lost due to velocity variation. This variation is not the only criterion but remains important in the experimentation. One cannot expect that one decade after the rule change the style variants are stabilised. An exceptional combination of body structure, flexibility and strength could still allow to evolve to a new and faster style variant.

For the continuing education of the swimming expert (at the university and in the club) in diagnosing and advising, the European Research and Evaluation Centres have organised

modules. Each module was dealing with one or more areas of the sport sciences: the kinesiological, physiological, psychological, ... area, and consisted of two parts: distance learning (CD-Rom) and a residential short course. The next steps must be the development of expert systems for diagnosing and advising and, most importantly, the integration of the specific areas. Governing and non-governing bodies should support the universities in starting more interdisciplinary research and in the development of multimedia and expert systems, because this is not yet rewarding for the staff in most universities (Martens, 1990).

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THE ROLE OF THE THORACIC SPINE & SCAPULA IN SHOULDER IMPINGEMENT

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WHAT IS SWIMMER'S SHOULDER?:

Shoulder pain is the most commonly reported injury in swimmers and swimmer's shoulder is associated with pain at the front (anterior) aspect of the shoulder (Bak, 1996). Ultrasound imaging of this region shows occasional inflammation of the biceps tendon but more commonly inflammation of the supraspinatus tendon which has a stabilising effect for the shoulder especially as it moves through elevation (Gold, et al 1993). The problem with early detection of the condition is that the symptoms are often vague and non limiting to begin with and a gross change in the athlete's pattern is not noted until several months later when even non swimming movements are painful (Bak, 1996).

CAUSES OF SWIMMER'S SHOULDER:

The main factors associated with shoulder pain include swimming experience, faulty stroke technique and training errors (Bak and Fauno, 1997).

THE IMPORTANCE OF CENTRAL CONTROL:

For the shoulder (glenohumeral joint) to function optimally it relies on a muscular balance not only at the shoulder but at the scapula (scapula) and the thoracic spine (Bak and Fauno, 1997). The aim is to begin with good central control, that is a stable and correctly positioned scapula so that maximal transition of energy can occur from the large back and arm muscles during the swimming stroke. Weakness of the scapulothoracic muscles leads to an abnormal positioning of the scapula into an upwards and forwards position. This causes a narrowing of the subacromial space, the area where impingement of the supraspinatus tendon occurs (Figure 1)(Kamkar, et al, 1993).

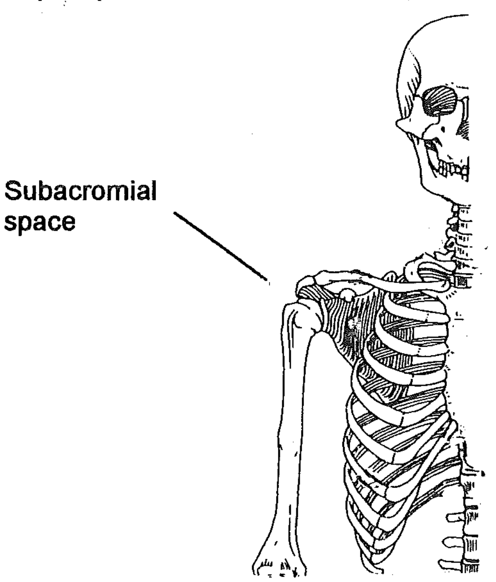


Figure 1 - Shoulder girdle (McMinn and Hutchings, 1985, p.2)

THORACIC SPINE KYPHOSIS:

The excessive rounding of the middle spine has a detrimental effect on the shoulder by affecting the position of the scapula and the length of the posterior arm muscles (Allegrucci, et al, 1994). In this position the scapula becomes abducted and therefore the muscles holding it close to the spine become lengthened. An imbalance occurs which allows the

shortened muscles to be activated more easily causing an abnormal pattern of movement around the muscularly controlled shoulder (glenohumeral joint) (Sharman, 1990).

WHAT HAS THIS GOT TO DO WITH SWIMMING?:
To achieve the optimal power for swimming it would make sense to recuit muscles that offer large mechanical advantage for little work. Examples of these muscles include; latissimus dorsi, serratus anterior, pectoralis major and deltoid (Figures 2 &3). These are used effectively in the normal, non painful shoulder but in the painful shoulder there is a notable decrease in the use of anterior deltoid and serratus anterior (Figure 4) (Scovazzo et al 1991). The other interesting points of note were that although there was no noticeable difference in the latissimus dorsi it was misfiring at different ranges of the stroke in the painful shoulder and never reached the maximal amplitude of the non painful shoulder (Figure 5a). Also there was an abnormal increase in the activity of the rhomboids in the painful shoulder which would exacerbate the impingement of the shoulder because it causes a downward tipping of the scapula (Figure 5b).

That is useful if there is access to electromyograhic equipment to record these differences but what does this mean to the observer? In the painful shoulder hand entry is further from the midline with the arm lower to the water (dropped elbow). This is commonly mistaken for fatigue or laziness (Scovazzo et al 1991). The hand exits the water early because of the lack of propulsion available from the serratus anterior due to the poor position of the scapula. The rhomboids also contribute to the early exit of the hand, that is it leaves the water before it has reached the thigh and with the elbow still bent (Scovazzo, et al 1991). Another observable strategy to avoid the impingement pain is for the swimmer to increase their body roll which increases the drag, slowing them down (Beekman and Hay 1988).

From the perspective of visually identifying and understanding the causes of swimmer's faults it becomes easier to correct. Although the above examples have been given due to research done with painful shoulders, if a swimmer lacks flexibility through the thoracic spine and control of the scapula these faulty stroke techniques will still occur and hopefully can be corrected before they become painful.

STRATEGIES FOR A BETTER SWIMMING STYLE:
The solutions to correcting the identified faults begin centrally. The thoracic spine must have good mobility as well as resting posture. To obtain a maximal reach of the arm the thoracic spine needs to extend and side flex away from the elevating arm (Stewart, et al, 1995). This is impaired if there is an abnormal rounding of the thoracic spine (Crawford, and Jull, 1993).

Next, the scapula resting position needs to be observed and corrected if the inside border is sitting more than three fingers from the spine. Observing the way the scapula moves during the swimming stroke identifies if there is a part of the range that the muscles have decreased control on the scapula thus making it susceptible to contributing to impingement (McConnell, 1994).

The over-training of the pectoral muscles may lead to them shortening and therefore contributing to rounded shoulders or thoracic kyphosis. Maintain a good pectoral length as well as strength in the posterior shoulder muscles such as middle and lower trapezius avoids this problem (Figures 2 and 3)(Allegrucci, 1994).

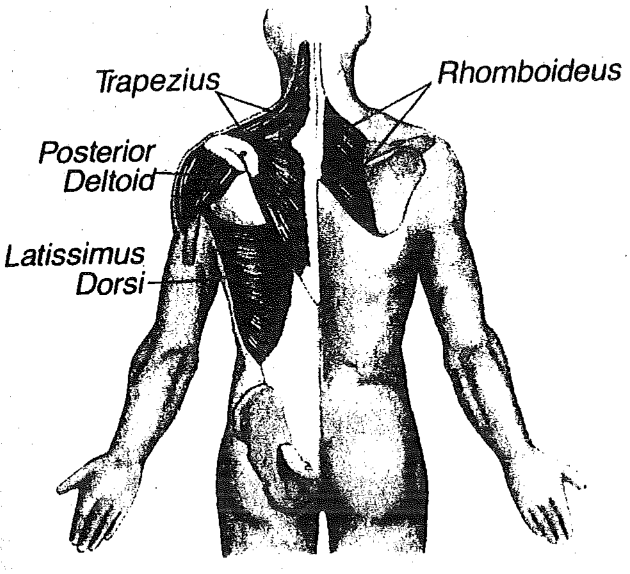


Figure 2 - Muscles in the back.

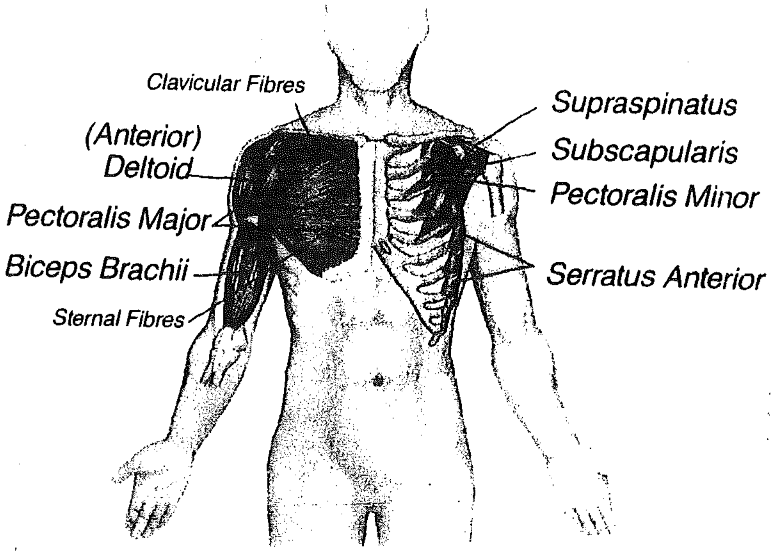
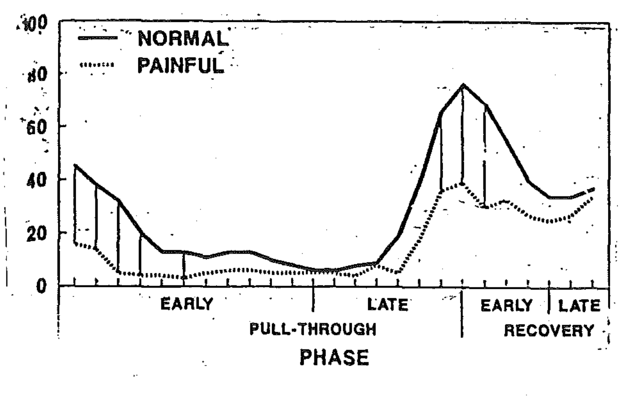


Figure 3 - Muscles in chest and shoulder.



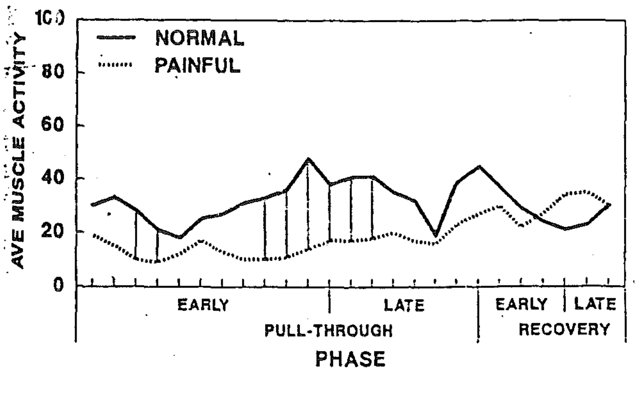
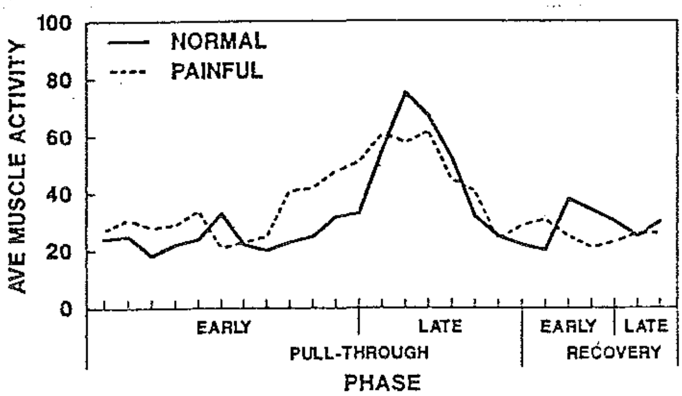


Figure 4(a) - Anterior deltoid muscle activity
(Scovazzo, et al, 1991, p 579)

(b) Serratus anterior muscle activity

(Scovazzo, et al, 1991, p 581)



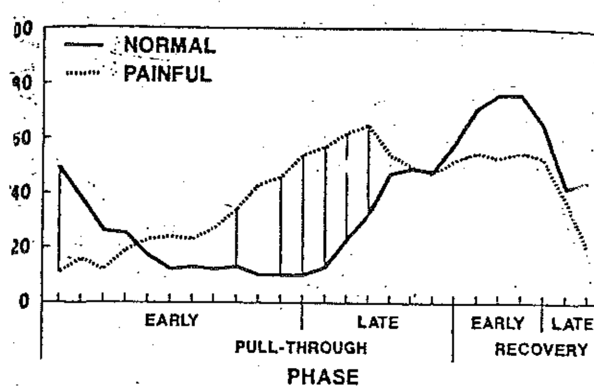


Figure 5a - Latissimus dorsi muscle activity **Figure 5b - Rhomboids muscle**
activity
(Scovazzo, et al, 1991 p 581) (Scovazzo, et al, 1991 p 581)

Motor control is often overlooked but the fine coordinated pattern of muscle recruitment is crucial for an efficient swimming stroke. It prevents energy wastage from unnecessary muscle activity (McConnell, 1994). Having an awareness of the arm and scapula position decreases the likelihood of instability and coupled with training which mimics the swimming patterns reinforces to the brain the exact patterns of movement required (Allegrucci, 1994). Gaining control in the normal swimming pattern can allow for more challenging tasks such as paddle training and increased distances without risks of impingement.

CONCLUSION:

Training often centres around improving power, strength and increasing distances while stability and motor control are forgotten. This generally happens because the stability muscles are deep and close to the joint which makes them hard to identify and observe (See Figure 3). Their training is also based on slow, controlled patterns of movement which does not seem as rewarding as 'hard and fast'. However, 'hard and fast' is not effectively possible if the 'slow and controlled' is not in place first. Tuning a radio can be done with large turns of the dial but perfect sound comes when the dial is turned in a slow, controlled manner. Likewise gross movements of large muscles around the shoulder will still allow for movement to occur but couple this with the slow and controlled action of the deeper, smaller stabilising muscles and there is a perfect harmonious stroke.

DEFINITIONS:

Thoracic spine:	Middle area of the spine where the ribs are attached.
Scapula:	Shoulder blade.
Kyphosis:	Forward rounding of the spine.
Scapulothoracic muscles:	Muscles that attach the scapula to the thoracic spine.
Shoulder:	Glenohumeral joint where humerus (arm bone) attaches to glenoid cavity of scapula.
Electromyographic equipment:	Measures electrical activity in muscles.
Anterior:	Front of.
Posterior:	Back of.
Flex:	To arch forwards.
Extend:	To arch backwards.
Side flex:	To arch sideways.
Abducted:	Away from the middle.

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VORTICES AND PROPULSION

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A review of the general theory of swimming propulsion is presented relating this with knowledge about vortices in steady and unsteady flow conditions. Three methods of flow visualisation have been used in the experiments: a) injecting air bubbles close to big toe during undulatory underwater swimming and breaststroke kick; b) putting reflective particles in water to see hand short movements and; c) injection of air bubbles in the swimming pool creating a 'bubble wall', making it possible for the swimmer to cross and to swim along it. The results of the experiments showed that: a) vortices are generated during different phases of the stroke and during the downward kick in undulatory swimming, flutter kick and breaststroke kick; b) when the hand suddenly changes the direction of its movement the starting vortex is detached from the hand and; c) the size and movement characteristics of the vortex seem related to propulsion obtained by the hand and foot movements.

KEY WORDS: swimming propulsion, vortex, flow visualisation, bubble wall.

INTRODUCTION: THE BASICS OF SWIMMING PROPULSION: The total mechanical power (Po) produced by the swimmer (assuming a constant velocity) equals the power to overcome active drag (Pd) plus power expended in giving masses of water pushed away a kinetic energy change (Pk) (Toussaint, 1992): Po = Pd + Pk (1) (Counsilman, 1971) stated that efficient propulsion is obtained by pushing a large mass of water a short distance without much acceleration. Greater efficiency in water is achieved by moving a large amount of water a short distance than by moving small amounts of water a great distance. These statement were developed after observing how good swimmers pull in the water with complex 3D trajectories that show continuous changes of the direction of the hand's pulling path. Later, Martin (1989), speaking about the fundamental principles in swimming asserted that swimming by propelling water, one may achieve a given amount of thrust either by accelerating a large mass of water to a small velocity or vice versa. It turns out that the former choice is more efficient. The thrust is equal to the momentum, mv (the product of mass and velocity) of water that is propelled backwards each second. The energy required to accelerate this water is proportional to mv^2 (2). One sees that the thrust is independent of the relationship between m and v, but the energy required is less if v is small. Thus it is more efficient, mechanically speaking, for a swimmer to move a large tail (or flipper or hand) slowly than a small one rapidly. (Butovich & Chudovskiy, 1968) in a very interesting book written in Russian about front crawl biomechanics explained graphically the differences between planar and 3D curvilinear pulling paths. The second path illustrates better the previous statements (Figure 1).

Vogel (1997), speaking about the propulsion of bivalve molluscs, stated that the problem is that thrust is produced most efficiently by giving as large a mass of water as possible the smallest incremental speed, just the opposite to what a jet does. An expert in water animal propulsion obtained the same conclusion as our swimming experts. It is necessary to make a brief remark now, about how this force is produced by the swimmer and the implications on the propulsion theory. The hand displacement is the result of a muscle contraction. Muscles such as latissimus dorsi, pectoralis major, teres major and deltoids are mainly responsible for arm pulling (Hamill and Knutzen, 1995).

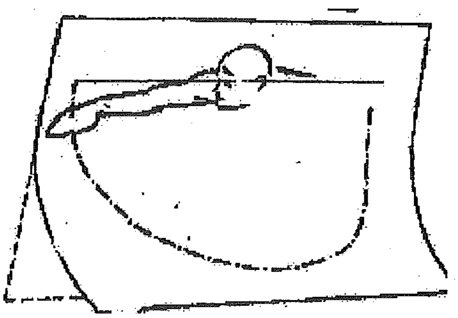

Figure 1 - Graphical explanation of differences between a planar and a 3D curvilinear pulling path in freestyle (Butovich & Chudovskiy,1968).

Therefore, the swimming propulsion is the result of a muscular force applied by the hand, forearm and arm to the water (Figure 2). Shortening the muscle impels the body displacement forward while the hand "seems" to be in a fixed point. Conceptually we can set up differences between two forces: muscular force and applied force. Swimming training attempts to develop muscular force and muscular endurance but is this muscular development useful directly to improve swimming speed? In our studies, we recorded propulsive force during tethered swimming at velocity equal to zero (Arellano, 1992). We found that after a cycle of training oriented to improve muscular force out of the water, the improvement of recorded force was near 15% ($p<0.01$) but the swimming velocity in short distances did not improve. This situation can be explained because, while the muscular force increased with weight training the applied force did not follow in the same way. It is necessary to train more specifically (in the water) to transfer this muscular force to applied force. Applied force involves a development of the feeling of water in a specific kinesthetic and tactile sense. The development of modern training in swimming has to be oriented to improve applied force and this force can only be developed inter-acting directly with the water. This situation explains how many world-ranked swimmers do not do power training out of the water, yet they are very fast swimmers and they have in some cases less muscular force but much more applied force.

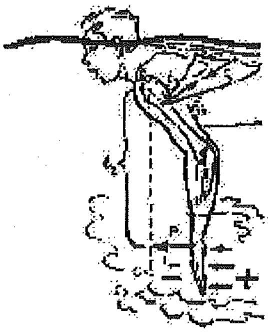

Figure 2 - Graphical explanation of how the propulsion is generated by a muscular contraction in freestyle swimming (Makarenko, 1975)

The next problem is to explain how the swimmer generates applied force. For many movingobjects, the surrounding fluid (air or water) can exert a sideways force that is subtler than the drag force. The forces that can make a spinning ball swerve or produce lift in an aeroplane are produced by a common cause: a net circulation of the fluid around the object. This flow can be separated into translating and circulating components. In the case of a ball the reason for this circulation is clear: the fluid in contact with the ball rotates with it (Figures 5a and 5b). The force perpendicular to the flow is directly proportional to the rotation rate, and can be explained in terms of Bernoulli's law, which relates flow rate and pressure.

The fluid moves faster on one side of the object than the other, and the resulting pressure difference exerts a force that can lift the ball or cause it to swerve. Although an aeroplane wing or airfoil does not rotate, its shape and/or the angle of inclination in the flow produce the same effect on the fluid (Figures 6a and 6b). In this case the fluid circulation around the wing is not known. However, it can be determined by the Kutta-Zhukovski theorem, which states that the circulating component around the airfoil is matched so that the flow field continues smoothly past the back edge of the wing (Belmonte and Moses, 1999). The circulation concept and others such as lift and drag were cited for first time in a Biomechanics book by (Hochmuth, 1973) in 1966.

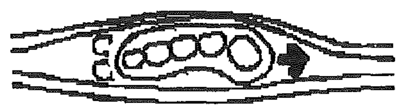

Figure 3 - Flow behaviour during a linear hand's movement with an attack angle of 0° and a sweep-back angle of 0°. The drag and lift components of the propulsive force are small. Two stagnation points are located rear and forward where the flow velocity is equal to zero (Marchaj, 1988).

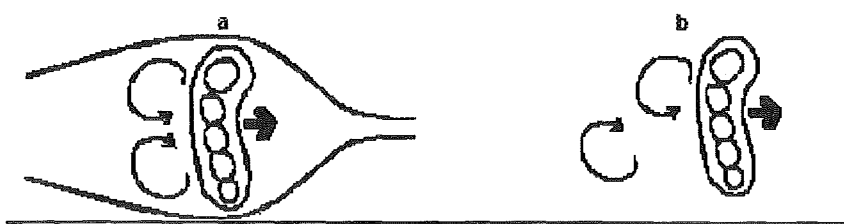

Figure 4 -Flow behaviour during a linear hand's movement with an attack angle of 90° and a sweep-back angle of 0°. The drag component of the propulsive force is high and the lift component is small. Two big vortices are created on the back of the hand inside the wake. There is a considerable relationship between the boundary layer separation and the formation of the wake. The size of the wake and the pressure within it determine the magnitude of the pressure drag (Douglas et al., 1995) (a). These vortices are unstable and a vortex street is developed. This situation makes difficult to keep the pulling path straight, feeling lateral oscillations on the hands (b).

Figure 7a shows an hand section and some of the most important terms related to it: a) leading edge or edge facing the direction of flow; b) trailing edge or the rear, downstream, edge; c) chord line or a straight line joining the centres of curvature of leading and trailing edges; d) camber line or centreline of the hand section and; e) angle of attack or angle between the direction of the relative motion and the chord line (adapted from (Douglas, Gasiorek, and Swaffield, 1995). To define the real position of the hand in the water another term plays a roll the sweep-back angle. This angle defines the leading edge of the hand relative to the fluid flow and is found by projecting the hand velocity vector onto the plane of the hand (Payton and Bartlett, 1995). Similar variables can be applied to know the feet position (Sanders, 1997).

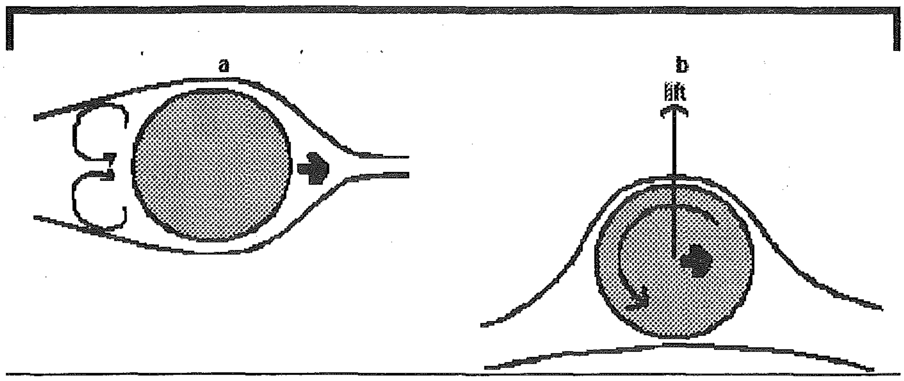

Figure 5 - A ball without rotation only develops aerodynamic drag and some instability if a vortex street is created (a). The same ball with rotation mimics a airfoil by distorting the flow field in a way that creates aerodynamic lift. Because of the rotation the air flowing over the top of the ball is accelerated to the rear and the air flowing under the ball is retarded (Larrabie, 1980). The velocity differences results in an imbalance of forces (according Bernoulli's Theorem) that pushes the ball upward (b).

The variations on the angle of attack produce a modification in water behaviour in the wake generated on the back of the hand (Figures 3, 4, 5 and 6). Two different forces are generated with different values related to the attack angle and their vector addition is the resultant force or net propulsive force. Schleihauf (1979) investigated lift and drag forces on hand models in an open-water channel at certain steady-state flow conditions. His experiments showed a specific relationship between drag and lift coefficients and the attack angle (Figure 9). The Schleihauf experiments were replicated by (Berger, Groot, & Hollander, 1995) and she stated in her conclusions: a) It has been shown from a theoretical point of view that propulsive forces during human swimming can be more efficiently derived from lift forces then from drag forces. At high lift forces the loss of energy will be minimal. Consequently, a proper technique should generate as much lift as possible; b) The data obtained indicate that the optimal orientation of the hand with respect to the direction of motion of the hand would be about 55º for a thumb-leading orientation and 25º for a little finger-leading orientation. The lift force will be as high as possible at these orientations of the hand; c) Swimming with a sculling motion in which the hand velocity is always higher than the velocity of forearm might be much more efficient than swimming with a 'push-pull' stroke, in which the hand and forearm velocity are much more similar. Using three pressure force transducers on the palm and three more on the back of the hand (Redondo & Cano, 1979; Redondo, Morris, & Cano, 1981) and calculating the lift force from the Kutta-Zhukovsky equation, he found that the lift and drag forces were both responsible for swimming propulsion during the propulsive movements in freestyle.

But, a big controversy was developed over the last decade about the importance of each force component. Sprigins and Koehler (1990) recommended using a Newton's model instead of Bernoulli's model to explain dynamic lift in sport. Rushall, Holt, Sprigings, and Cappaert (1994) stated "if lift forces were working fully in the Bernoullian mode, the flow of water across the back of the hand would be undisturbed, ... When observation of turbulence and bubbles are made, lift forces will not be dominant in contributing to propulsion". These authors in their practical implications recommend "swimmers should be taught or encouraged to feel that they are pushing against the water in a predominantly backward direction". Another well-known author Ernie Maglischo showed in his opinions an evolution from lift to drag and he said: 1) "Once the principles of using lift to generate propulsion are understood, coaches and swimmers can apply them to improve the stroke mechanics of competitive

swimmers" (Maglischo, 1982). 2) "The theory subscribed to in this text is that the most important propulsive principle they are applying is Newton's third law of action-reaction, not Bernoulli's theorem (Costill, Maglischo, & Richardson, 1992). 3) "...sculling is the central propulsive mechanism regardless of the theory you select. Whether swimming propulsion is drag-dominated or lift-dominated does not change the fact that the majority of world-class swimmers are using sculling movements to propel themselves forward" (Maglischo, 1995). 4) "... I think I've been wrong, and I've provided you with a lot of misinformation over the years....Now, a little later on I came along and because I was disenchanted with the Bernoulli theorem, I tried to come up with another idea for propulsion. And, I went back to Newton's third law of motion, that if you're pushing water backward you'll go forward.... I now believe that propulsion is drag dominated..." (Maglischo, 1999).

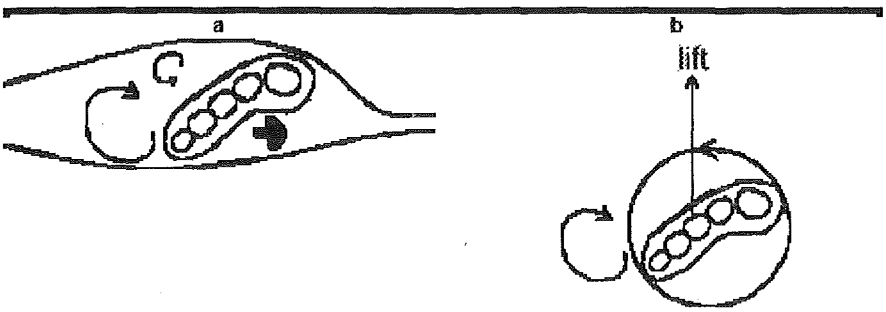

Figure 6 - When the hand is moving with an angle of attack bigger than zero the fluid has a tendency to go around the trailing edge of the hand. The flow breaks away from the edge and so-called starting vortex begins to operate between the trailing and the rear stagnation point that is now situated on the upper surface (back of the hand) (a). As the starting vortex rotates, a counter-rotation develops round the foil in the opposite direction to that of the starting vortex because the rotation of the starting vortex (angular momentum) cannot be created in a physical system without reaction: circulation. (Marchaj, 1988). The circulation around the hand develops as the ball of in Figure 6b, a lift force perpendicular to the direction of the hand's movement.

lift

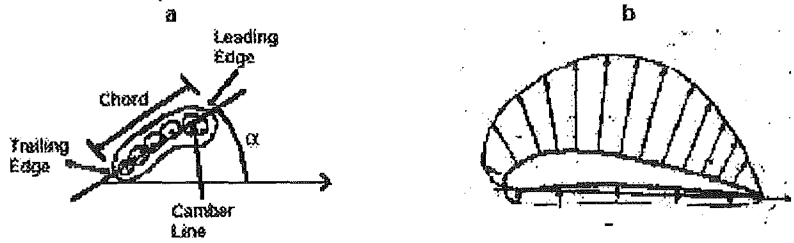

Figure 7 - Basic terminology utilised in fluid mechanics to describe the different parts of propulsive element (Douglas et al., 1995) (a). Pressure distribution around an airfoil according (Butovich and Chudovskiy, 1968) (b).

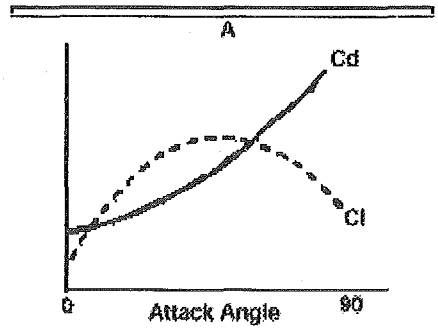

Figure 8 - Drag and lift coefficients obtained changing the angle of attack of a flat plate from 0° to 90° (Hochmuth, 1973). The lift and drag coefficients increase from 0° to 50° in a similar value and from 50° to 90° as drag increases and lift decreases (a).

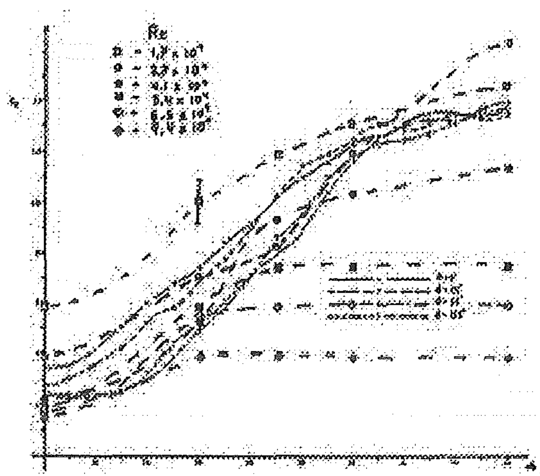

Figure 9 - Hand drag coe-fficients obtained experimen-tally at different water speeds by (Redondo, 1987) related to the Reynolds number (Re) and compared with those obtained by (Schleihauf, 1979). The drag coefficient decreases when the Reynolds numbers increase. The values of the drag coefficient reach similar values from 20 ° to 90° when Re is high (9.4×10^4)

Personally, I don't think Mr Maglischo was so wrong before and nor is he so totally right now. Many of the "new theories" are based in the forces shown by using underwater video-recording where the average errors in lift- and drag-coefficients could become 27% and 20%, respectively (Payton & Bartlett, 1995). When you are increasing the speed of the hand, the drag coefficient is not increasing linearly because is affected by Reynolds' number (criterion which determines whether flow is viscous or turbulent). The drag coefficient is considerably smaller during the turbulent boundary layer than for the laminar boundary layer because the wake is narrower (Douglas et al., 1995). In experiments developed by (Redondo, 1987) he measured the drag coefficients in a water channel of models of hands at different velocities of flow. When the drag coefficient (α = 90°) was related to the Reynolds number, at high values of Re the Cd decreased until values similar to attack angles were close to zero (Figure 9). Thus, knowing the water is mostly turbulent when the hand is moving in the water, is it exactly correct to tell swimmers they have to move the hand directly backwards? Moreover, in some cases the propulsive theory is being explained in a very analytical way, for example saying there is four theories for explaining propulsion: drag theory, lift theory,

vortex theory and sculling theory (Maglischo & Maglischo, 1995). But this is not true, there is only a theory of the propulsion that includes drag and lift components, flow circulation, starting vortex, bound vortex, Bernoulli's principle, Magnus' effect, Kutta-Zhukovsky's theorem, steady and unsteady flows and so on. Or as Colwin (1999) said "instead of belabouring the lift versus drag argument, we need to move on and learn more about the way the water reacts when we swim". New observations on unsteady effects have shown, for example, that hydrofoils with an impulsive start and high angle of attack can produce significant transient lift force. This finding suggests that the application of unsteady fluid dynamics to competitive swimming may rejuvenate the debate on the nature of thrust forces DeMont (1999). In the next pages we will try to give information about how the water reacts during the hand and foot movements in the water.

WHAT IS A VORTEX? In common usage, by vortex we usually mean a whirlpool, or a circular cavity formed by a liquid in rotation. Vortex in fluid mechanics means a region of fluid bounded by the so-called vortex lines, whose tangents at all points are parallel to the local directions of vorticity. The vortex lines, which are the axes of rotation, have to be either closed lines, or begin and end on the boundaries of the fluid or on the points in regions of infinite vorticity. A vortex induces an external fluid motion. (Tokaty, 1994). A vortex is a form of kinetic energy, the energy of motion. A shed vortex represents the energy produced by the swimmer and "given" to the water. In fact, when you see the vortices produced by the swimmer in the water, you are actually looking at the swimmer's propulsion. Without the resistive friction provided by vortex turbulence within a fluid, no tractive force would be provided.(Colwin,1999). The theories applied to develop mathematical models of the vortex behaviour come from the Kutta-Zhukovsky Theorem: When a vortex (or equivalent rotating body) of circulation Γ moves in a uniform fluid of density ρ with the velocity v_∞, it produces a force $\rho\, v_\infty\Gamma$, per unit length,perpendicular to the direction of v_∞ and to the axis of the vortex.

$L = \rho\, v_\infty \Gamma$

The Zhukovsky theory of conformal transformation shows that when a flow with circulation around a circle (vortex) is transformed into a flow past an airfoil, the circulation remains the same. A circle and a wing can replace the airfoil by a circular cylinder (long vortex). A bound vortex is imagined to be inside the wing, and confined to the wing. Because the aircraft wing can ever be infinitely long, the bound vortex too, must have an infinite length, or span. Zhukovsky suggested that his bound vortex twists at the tips of the wing and thus a horseshoe vortex system is formed (Tokaty, 1994).

In steady-state situations, such a aeroplane cruising at constant speed and altitude, the Kutta-Zhukovski theorem has been shown to be correct. But what about an unsteady situation where the wings move vertically or flap (Belmonte & Moses, 1999). Many studies in the animal world show how vortices are generated during the flight of birds and the propulsion of fishes. In more simple situations such as a sheet of paper falling through the air or metallic plates through water we can observe how vortices are created at the end of their lateral movements while they are changing their falling direction.

Three different vortices can be observed during the propulsion of the hands: starting vortex, tip vortex and hub vortex. The starting vortex is produced as it is explained in the Figures 6a, 6b, 10a, 10b, 10c, 10d and 14a. In these cases the sweep-back angle is 0°. The starting vortex is generated during all the propulsive movements including all the sweep-back angles (Figure 14b). This vortex is easily visible during suddenly changes of the hand movement direction because the sweep-back angle changes and a new starting vortex is created. The starting vortex after the change of the hand movement direction is detached and it keeps rotating in the water during a short time. The starting vortex can be study on infinite wings or hands, but the swimmer's hand has a finite span. The difference in pressure between upper and lower hand produces vortices that are shed from the hands tips as the water from below

turns upward. These hand-tip vortices can be observed during real swimming when the swimmer traps bubbles during the hand entry. A line of bubbles shows the swimmer's pulling path (Figure 11). The hub vortex is created in a screw propeller from his centre of rotation. This type of vortex is observed in small propulsive movements of the hands featured during synchronised swimming. This vortex is perpendicular to the propulsive hands (∞) path and created a whirlpool in the water surface. Starting and tip vortices can be observed during the propulsion of the feet in breaststroke as well (Figure. 12).

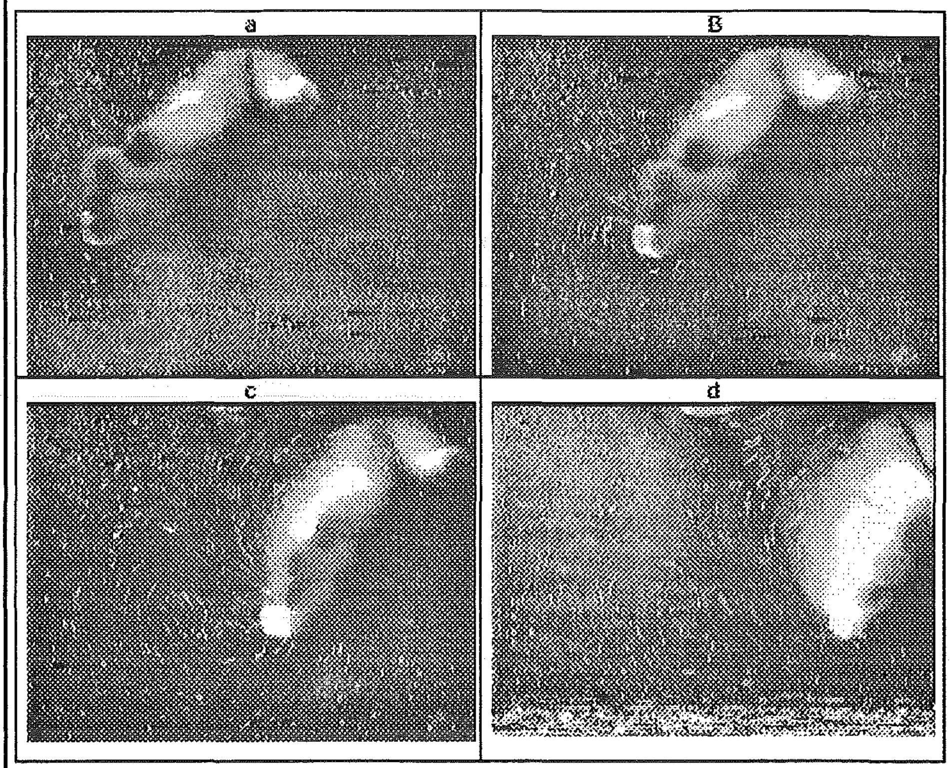

Figure 10 - Development of initial vortex in a rectilinear movement of the hand. Thanks to the flow visualisation you can see both vortices and how different in size they are (Redondo and Arellano, 1998).

During flutter kick and underwater undulatory propulsion one different type of vortex is created. Gray (1968) explained the vortices generated by the fishes: "when a flexible undulating body acquires forward momentum, a corresponding amount of backward momentum must be acquired by the water; this backward momentum is concentrated in a vortex wake and appears in the form of a jet of fluid expelled from the wake". The propulsive capabilities of this vortex propulsion can be higher than screw propeller in underwater vehicles. After the down-kick a vortex is generated as described in the Figures 13a and 13b. This vortex is the bigger and it is named main vortex. In some cases, we found a small vortex after the upward kick, this vortex is named secondary vortex. These vortices rotates around one horizontal axis perpendicular to the swimmer's displacement.

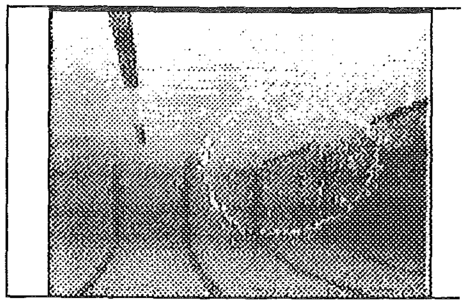

Figure 11 - Tip vortex kept in the water after a freestyle arm pull.

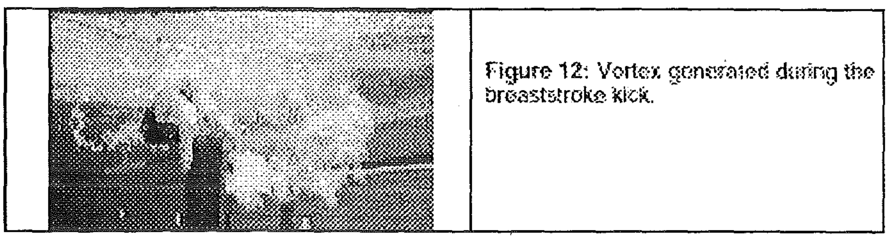

Figure 12 - Vortex generated during the breaststroke kick.

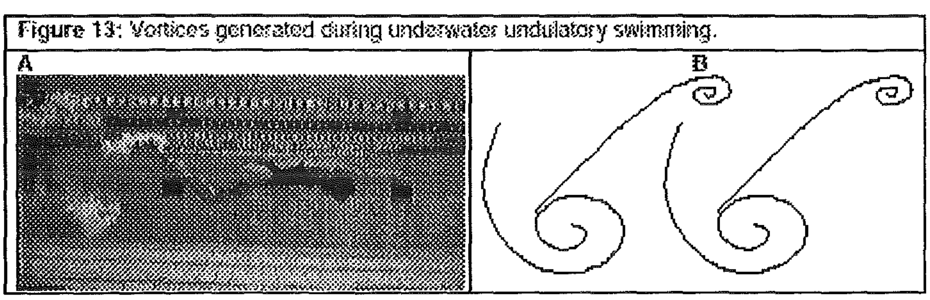

Figure 13 - Vortices generated during underwater undulatory motion.

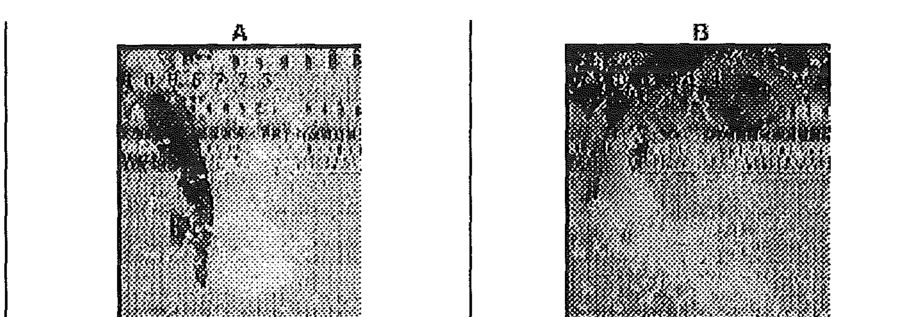

Figure 14 - Vortices generated during the end of in-sweep (a) and at the end of the up-sweep (b).

FLOW VISULISATION TECHNIQUES:

Most of the methods used in visualising streamlines require the experimenter to inject some foreign material into the flow that makes the particle, or path, or surface visible. The one major requirement an experimenter must keep in mind is that the material injected should reach the flow velocity as quickly as possible (Granger, 1995). Leonado da Vinci was the first researcher to publish drawings representing observed vortices. The materials used are: dyes, smoke, tufts, small particles, solids, liquids, gas bubbles, air bubbles and optical set ups. The new computer technologies are letting the researchers make simulations of the flow behaviour around a moving object in a flow (Moin & Kim, 1997). Lists of some research developed about human swimming using flow visualisation techniques are summarised in the next table.

Table 1: Studies Developed Applying Flow Visualisation Techniques in Swimming

Year	Author	Technique utilised
1985	Colwin	Bubbles
1986	Hay & Thayer	Tuft Method
1989	Hay & Thayer	Tuft Method
1992	Colwin	Bubbles
1993	Nakayama	Tuft method
1996	Bixler & Schloder	Computer simulation
1997	Persyn & Colman	Injected dye
1997	Arellano, Gavilán & García	Injected bubbles
1998	Arellano & Redondo	Reflective small particles
1999	Colwin	Bubbles, shadowgram
1999	Arellano	Bubble wall

Our research was oriented during recent years to attempt to visualise the flow during swimming. We developed three different systems to observe vortices: a) vortices generated during undulatory underwater swimming and breaststroke leg kicking injecting bubbles; b) vortices produced by the hand in analytical situation in the lab using reflective small particles and; c) vortices created during analytical situations in the swimming pool and in real freestyle swimming and kicking using a bubble wall.

Experiment 1: Flow visualisation injecting bubbles: A plastic tube was connected from an air compressor to the body of the swimmer until the big toe. The tube diameter was 0.5 cm. The air compressor injected air through the tube and a bubble trace of the big toe trajectory was easily observed during underwater body gliding. Without feet movement and during horizontal gliding, the bubbles draw a line parallel to body displacement until they start going up thanks to the flotation force. This trace was maintained more or less a couple of seconds.

When the feet started to flutter kick or breaststroke kick the bubble trace followed the big toe in a laminar path in some phases, but in other phases the bubbles started rotating and kept rotating stationery in the space where they were created and they did not follow the path. We observed during underwater undulatory prone swimming:

- The swimmers generated a big vortex at the end of the downward kick. This vortex started during the initial phase of the downward vertical movement, in the wake behind the feet.
- If the swimmer is kicking from left to right the water rotation is anticlockwise.
- In good swimmers we found the vortex rotated in the same place without displacement, for longer than whit slower swimmers. In some cases the vortex rotated for more than five seconds.
- Some slower swimmers pushed the vortex directly downward.

- We found in some very good swimmers a small vortex at the end of the upward movement rotating clockwise (Figure13.a) .
- In most cases during the upward movement the bubbles follow a linear path upward and forward similar to the big toe trajectory.
- The previous remarks were observed also in freestyle kicking on the surface with kickboard, in freestyle kicking during full stroke swimming, butterfly kicking on the surface with kickboard, and in butterfly kicking during full stroke swimming. In these cases we videotaped normal swimming without bubble injection. The bubbles were captured by the swimmer from the surface air. Using the same procedure we had the opportunity to observe a case of an international female champion swimmer practising breaststroke.
- From the lateral view a vortex similar to that created in undulatory kicking was observed but the size was smaller in the same swimmer. From this point of view we saw a small quantity of anticlockwise rotation.
- Observing the breastroke kick from behind a considerable starting vortex was created at the beginning of the downward kick increasing in size until the end of the inward kick.
- At the beginning of the upward kick the vortex kept rotating in the same place and did not follow the feet.
- The axis of this rotating vortex was nearly vertical. Observing the rotation above the rotation was anticlockwise (right foot).

Experiment 2: Flow visualisation using small particles: A small aquarium was utilised in the lab. Small reflective particles were placed in the water with density similar to the water. A big lamp projected light inside the aquarium. The light permitted us to observe easily the position of the water particles. A video camera was placed perpendicular to the aquarium. The shutter speed was low to see easily the path of the particles. The hand made short movements (aprox. 0.30 m) in a rectilinear path. Only attack angles between 40° - 70° were used (Figure 10).

- When the hand started the movement, the thumb being the leading edge (sweep-back angle of 0°), a vortex begun to rotate near the little finger. The water separated near the little finger and returned to the back of the hand over the fingers, creating a vortex.
- When the speed of the hand increased the vortex increased in size and a small vortex was created behind the thumb with opposite rotation to the starting vortex.
- Later the hand suddenly stopped the displacement and the starting vortex kept rotating for a while without horizontal displacement.
- The same situation occurred with a sweep-back angle of 180°.

Experiment 3: Flow visualisation using a bubble wall in analytical situation: A plastic tube, 2 cm diameter, two meters in length and with a line of holes of 2 mm diameter every 5 cm, was connected to an air compressor. The tube was placed in a swimming pool 1.5 m deep, parallel to the water surface, 20 cm in front of an underwater window (4 x 1.5). When the air begun to go up, parallel vertical lines of bubbles (bubble wall) was created moving up with a average speed of 0,68 m/s. A subject located verticaly or horizontaly in front of the underwater window started to make different propulsive movements. When the hand or feet crossed the bubble wall, it was possible to see whether the water was moving or not around the propulsive element.

- Case 1: Long diagonal movements. These movements are similar to those used in freestyle when the pulling path is observed from the bottom. The angle of attack is nearly 50°. We found similar vortices to those created in experiment number two. When this diagonal movement was followed by a sudden change of direction (close to 90°), the previous starting vortex finished its displacement behind the hand and it kept rotating in this position. Immediately, another starting vortex begun rotating in the opposite direction and following the new displacement of the hand.

- Case 2: Rectilinear movements with an angle of attack of 90º. A big wake followed the hand. A vortex street was created and perpendicular oscillations to the hand displacements were observed.
- Case 3: Short-sculling movements similar to those used in synchronised swimming. The situation is similar to case 1, after the sudden change from left to right for example, the starting vortex was detached. The path of tip vortex was observed very clearly and sometimes a vertical whirlpool was created (hub vortex)
- Case 4: Flutter kick: a starting vortex began in the sole of feet during the first part of the down-kick. At the end of the down kick a large vortex was detached. The rotation was anticlockwise if the swimmer was moving from left to right.
- Case 5: Analytical movements related to the breaststroke kick. A clear tip vortex path was shown when the foot was moving with a sweep-back angle of 0º.

Experiment 4: Flow visualisation using a bubble wall in real freestyle swimming: The system used was the same as in experiment 3 but positioned in the middle of the pool lane nearest to the underwater window. Many trials were necessary to get the movement of hand crossing the bubble wall in the correct moment to show a vortex.

- Case 1: Initial down-sweep of freestyle pulling. One small starting vortex was generated during this phase. This vortex was clearly observed when the hand changed from down sweep (with a small out-sweep component) to in-sweep. The rotation axis of this vortex was nearly horizontal at the beginning, it finished this phase with the axis more horizontal.
- Case 2: In-sweep of freestyle pulling. A bigger starting vortex was observed. The starting vortex in this phase was similar to that shown in the Figure 6a. The axis of rotation is nearly vertical in this phase.
- Case 3: Up-sweep of freestyle pulling. After finishing the in-sweep the swimmer changed the direction of the hand and started a nearly horizontal out and backward sweep. A small vortex was observed in this moment. When the hand started to move upward the biggest vortex of the pull was observed. The axis of this vortex was horizontal.

CONCLUSIONS:

The flow behaviour observed during the different experiments agrees with the general theories of flow dynamics. The several propulsive movements analysed (arm pulls and leg kicks) generated large or starting vortices during linear movements that agree with the theories of steady or quasi-steady flow conditions. When the hands or feet accelerated or changed the direction suddenly the vortex was detached and theories of unsteady flows explain better this situation. At this moment, it is difficult to state teaching cues for the swimmer and coach. It does not seem correct to tell swimmers things like "try to rotate the water", because water rotation is produced automatically in a correct propulsion. Besides, it is not possible to feel the water rotations because the flow movement occurs an instant after the hand passes through the water volume. Only in straight hand movements with attack angles of 90º are the vibrations felt which are produced by a vortex street. What does the swimmer feel? The answer is pressure and differential pressure. The swimmer can not feel the differences between lift or drag forces, the swimmers feel only the resultant force. This is a complex perceptive situation, where the swimmer receives information through the tactile and pressure sensitive cells and, kinaesthetic propioceptive system of the pressure drag, skin friction drag, circulation, wake lower pressure and so on. All this means that some swimmers can apply their propulsive force better controlling the direction of the resultant force (as parallel as possible to swimmer's body displacement: neat effective propulsion). This propulsive feeling is mixed with the perception of the total body drag in each phase that makes the situation much more complex. The problem is to be able to feel the difference between pushing water and applying effective force.

Some situations observed in our experiments such as keeping the vortex rotating stationary after the kick and to develop larger vortices during the hand pull seem related to higher propulsion. Incorrect propulsive movements are when the vortex is pushed away after the kick or when the vortex is small especially during the up-sweep. Swimmers, especially the beginners, have to play with water trying to feel the water movements. Cues, as proposed by Colwin (1992,1999), seem the most logical way to improve the generic swimming propulsion. However, after all our work, there still seem to be more questions than answers when trying to understand swimming propulsion.

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TALENT IDENTIFICATION: WHAT MAKES A CHAMPION SWIMMER?

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The utility of talent identification programs for predicting swimming performance is assessed using data gathered in recent research studies. Evidence is assembled to determine whether elite swimmers differ from the normal population on strategic variables that are not easily modified through training. Further, the data clearly demonstrate that these attributes may be used to discriminate between elite performers in various strokes and event distances, as well as between the best performers and the rest of the field. The research also supports the notion that an effective talent identification program may be formulated for the sport of swimming.

KEYWORDS: talent identification, swimming, anthropometry.

INTRODUCTION:

Many sport scientists and coaches from relatively small nations believe talent identification to be an essential component of their elite sports development programs. These countries, it may be argued, do not have sufficient population to rely on a trial-and-error approach which eventually allows some athletes to reach the elite levels in sport by a process known as natural or self selection (Bloomfield, et al., 1994). Commenting on this natural selection process, Bompa (1985) suggested that the development of talent evolved slowly and often resulted in incorrect sport selections. That is, many young athletes may compete in sports and events for which they may be ill suited or worse still, not compete in activities for which they possess a natural advantage due to some inherent physical or physiological capacity.

Rather than relying upon junior athletes with a strong potential for success to simply emerge from the population, a number of sporting associations now adopt a talent identification and development program. Children and adolescents with certain physical characteristics are sought and then persuaded to try these activities. In other words, there is a system of active recruitment based on a set of predetermined criteria that may relate to structural, physiological and/or psychological capacities.

If an effective talent identification program for swimming were to be formulated, it would require that the majority of the following statements hold true.

- The elite group must be consistently different from the normal population, and these differences in physique, physiology, psychology or technique must provide a logical advantage.
- It is doubly beneficial if these characteristics are predominantly inherited traits that cannot be easily modified with training.
- These attributes can discriminate between various positions or events within the sport.
- These attributes can discriminate between the best performers and the rest of the field within the sport at an elite level.

We must, however, acknowledge that there will exist 'exceptions to the rule' – people without all of the prescribed characteristics who will still achieve success at an elite level.

RELATED RESEARCH: To address these issues we will draw information from a number of studies conducted at The University of Western Australia.

National Age-Group Swimmers (Blanksby et al., 1986)
Eighty-two competitors aged 9-13 years, who were finalists or reserve finalists in the WA State Swimming Championships were measured on a battery of structure and function tests. Individual measures were correlated with a performance ratio based on the swimmer's

elapsed time and the appropriate state record. The aim of this research was to investigate the relative importance of those anatomical and physiological characteristics that were thought to contribute to high level performance in 100m freestyle and 100m butterfly events.

The UWA Growth and Development Study (Bloomfield et al., 1985)
Rated by pubescent assessment as being at maturity stage-1, data for 202 pre-adolescent children were selected for analysis from the UWA Growth & Development Study database. Differences in body size, shape, composition, strength, flexibility and fitness were sought for these competitive swimmers (n=37), competitive tennis players (n=61) and normally active controls (n=104).

The KASP Study (Carter & Ackland, 1994)
During the Sixth FINA World Aquatic Championships held in Perth in January 1991, an international team of researchers measured physical dimensions on 922 elite aquatic athletes across four disciplines. This project was named KASP (The Kinanthropometric Aquatic Sports Project).

Athletes, wearing a lightweight swimsuit only, were landmarked by a criterion anthropometrist and sent to the measurement stations where body size, shape, proportionality and composition were assessed. With an estimated 1050 athletes in attendance, this sample represented 88% of the competitor population which is far in excess of samples for previous surveys of a similar nature. Competitors from 52 countries were measured with the majority from Europe, Australasia and North America. Most athletes in the KASP sample were Caucasian with mean ages of 20.9 years (female) and 23.0 years (male).
Table 1 shows the breakdown of competitors by gender and swimming event. Further evidence of the quality of this sample may be seen under the table headings - percent of total competitors and percent of A and B finalists. For most swimming events some 70 to 80 percent of the all competitors were measured in KASP with a similar, or slightly higher, percentage of A and B finalists measured in these groups. Also, note that the long distance swimming event was a 25 km swim in open water - the Swan river in Perth.

Table 1 Swimming Sample from the KASP Study (Carter & Ackland, 1994).

GENDER	EVENT*	EVENT TOTAL	% OF TOTAL COMPETITORS	% OF A & B FINALISTS
FEMALES (N = 170)†	FR SD	31	79	81
	FR MD	27	83	82
	FR ML	6	83	88
	FR LDS	10	63	40
	BR SD	28	79	85
	BK SD	18	66	66
	FL SD	29	87	81
MALES (N = 231)†	FR SD	47	70	73
	FR MD	34	75	75
	FR ML	10	77	88
	FR LDS	13	48	40
	BR SD	37	70	65
	BK SD	28	71	75
	FL SD	41	76	81

* Where: FS = freestyle; FL = butterfly; BK = backstroke; BR = breaststroke;
SD = 50 + 100m; MD = 200 + 400m; ML = 800 + 1500m; LDS = open water 25km
† Includes individual medley and relay competitors.

THE ELITE GROUP MUST BE CONSISTANTLY DIFFERENT FROM THE NORMAL POPULATION:
There is no doubt that elite level swimmers differ in size, composition, strength, flexibility and fitness compared to the normal population. Selected physical dimensions are shown to reinforce this notion in Table 2, with data from the KASP study (Carter and Ackland, 1994) compared to British norms (Pheasant, 1988). These data show clearly that swimmers (irrespective of preferred stroke or distance) are taller and possess longer body segments than members of the general population who are matched for age and gender.

Comparing age-group swimmers at the state level to non-competitive controls, Bloomfield et al. (1985) reported significant differences for these pre-adolescent children in measures of leg strength, lung capacity and physical exercise capacity. The differences in exercise capacity became more marked when the values were normalised for body mass. No differences were found, however, for stature, body mass or adiposity.

Table 2 Selected Size Differences between World Championship Swimmers and Normal British Adults Aged 19-25 Years.

VARIABLE	Male Swimmers		British Adults 19-25 yrs		Female Swimmers		British Adults 19-25 yrs	
	X	sd	X	sd	X	sd	X	sd
Stature (cm)	183.8	7.1	176.0	7.3	171.5	7.0	162.0	6.1
Sitting height (cm)	96.5	3.5	91.5	3.7	90.7	3.4	85.5	3.5
Arm span (cm)	192.5	7.8	181.5	8.6	176.3	7.0	161.5	7.0
Shoulder width(cm)	42.5	1.9	40.5	2.1	38.5	1.8	36.0	1.8
Hand length (cm)	20.8	1.4	19.0	1.0	19.3	1.0	17.5	0.9
Hand breadth (cm)	8.6	0.5	9.0	0.5	7.7	0.4	7.5	0.4
Foot length (cm)	27.4	1.4	27.0	1.5	24.9	1.3	24.0	1.2

THESE CHARACTERISTICS ARE PREDOMINANTLY INHERITED TRAITS THAT CANNOT BE EASILY MODIFIED WITH TRAINING:
Of the many parameters available for use in a talent identification battery, several may be considered mostly inherited traits that cannot be easily modified with training. These traits would include aspects of body size and proportionality, muscle fibre type (endurance or power), and onset of maturity.

For example, the effect of body segment proportions on our ability to move may be understood through an examination of the mechanical principles of lever systems. Rasch (1989) explained that for any lever with a given force arm (distance from the rotation axis to the muscle insertion for example), a long lever results in a greater resistance arm and therefore a mechanically disadvantageous system, but one which is geared for high velocity movement. In contrast, for any given force arm a short lever results in a smaller resistance arm and therefore, a mechanically advantageous system (ie. one is geared for strength of movement).

Other parameters that may be considered for talent identification purposes may be easily modified with training. These parameters may include strength, flexibility, power and aerobic

fitness. While they are important factors in determining a swimmer's current performance, they may easily modified through specific training programs. Talent identification is about predicting future potential. All too often the proponents of talent identification get confused and rely too much on an athlete's current level of performance.

THESE ATTRIBUTES CAN DISCRIMINATE BETWEEN VARIOUS POSITIONS OR EVENTS WITHIN THE SPORT:

While factors such as strength, power generation and aerobic fitness may clearly discriminate between successful swimmers in each of the events, these capacities may be easily modified with training. As a result, they provide little benefit for use in talent selection. Alternatively, variables that are predominantly determined by genetic inheritance provide a better basis for talent identification. These factors cannot me modified to any great extend through training, and thereby give the swimmer a natural advantage or disadvantage over rival competitors.

The data in Table 3 show significant structural differences between World Championship competitors in each of the four major strokes (50, 100 & 200m swimmers). Generally, it may be seen that breaststroke swimmers (BR) are the smallest group, with freestyle (FR) and backstroke (BK) competitors possessing longer limbs and greater body mass. Proportionally though, BR swimmers are stockier with larger girth and breadth measures relative to stature.

Table 3 Structural Differences between World Championship Swimmers with Respect to Stroke* (from Carter & Ackland, 1994).

VARIABLE	MALE SWIMMERS		FEMALE SWIMMERS	
	Low	High	Low	High
Stature	BR	FR / BK	Nil	
Body mass	Nil		BR	FR / BK
Arm span	Nil		BR / FL	FR / BK
Lower limb length	BR / FL	FR / BK	BR / FL	FR / BK
Transverse chest breadth	BR	FR / BK	BR	FR
Most proportional breadths & girths	---	BR / FL	Nil	
Sum 6 skinfolds	Nil		Nil	

* Where: FS = freestyle; FL = butterfly; BK = backstroke; BR = breaststroke

The data in Table 4 show significant structural differences between FR competitors in each of the distance categories. It is clear that the short distance male swimmers (SD) are the tallest sub-group with the longest limbs. Similarly, the female SD and middle distance (MD) swimmers are the tallest sub-group with the longest limbs, feet and hands. The 25km open water swimmers (LDS), both male and female, are the smallest competitors with the greatest levels of body fat. The latter is presumably an aid to thermal insulation and buoyancy.

Table 4 **Structural Differences between World Championship Swimmers with Respect to Freestyle Distance* (from Carter & Ackland, 1994).**

VARIABLE	MALE SWIMMERS		FEMALE SWIMMERS	
	Low	High	Low	High
Stature	LDS	SD	LDS	SD / MD
Body mass	Nil		Nil	
Arm span	LDS	SD	LDS	SD / MD
Sitting height	LDS	SD	LDS	SD / MD
Lower limb length	Nil		LDS	SD / MD
A-P chest depth	ML	LDS	Nil	
Hand length	LDS	SD	LDS	SD / MD
Foot length	LDS	SD	LDS	MD / ML
Sum 6 skinfolds	---	LDS	---	LDS

* Where: SD = 50 + 100m; MD = 200 + 400m; ML = 800 + 1500m; LDS = open water 25km

THESE ATTRIBUTES CAN DISCRIMINATE BETWEEN THE BEST PERFORMERS AND THE REST OF THE FIELD WITHIN THE SPORT AT AN ELITE LEVEL:
If we were to create a list of attributes that determined a swimmer's success in performance, those shown in Figure 1 would come easily to mind. But what is their relative contribution to that success?

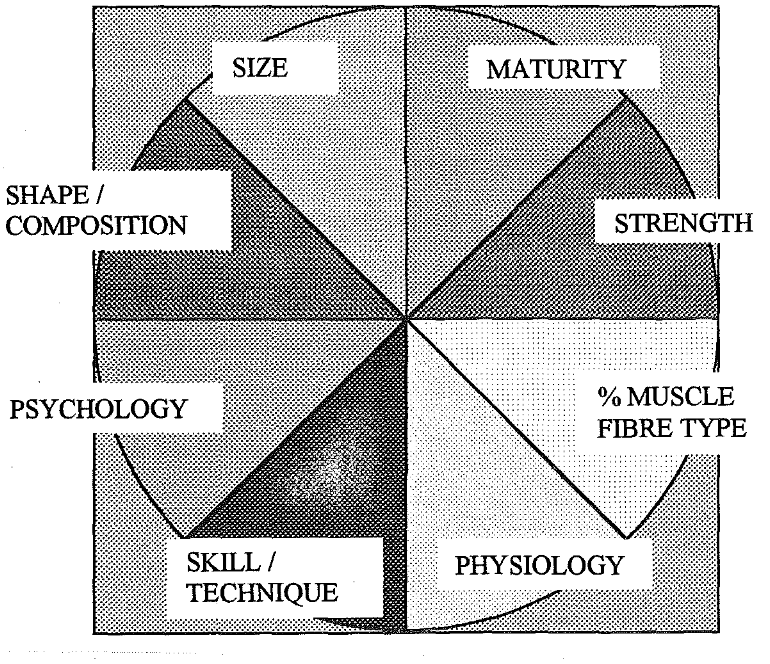

Figure 1 - Factors influencing success in swimming performance.

Data from the research of Blanksby et al. (1986) show many of these factors correlate significantly with 100m freestyle and butterfly swimming performance among state age-group competitors. A performance ratio was calculated for this analysis, based upon the relationship between the swimmer's elapsed time and the state record time (Table 5).

Table 5 Significant Correlates with Swimming Performance among State Age-Group Competitors (from Blanksby et al., 1986).

VARIABLE		FREESTYLE	BUTTERFLY
BODY SIZE	Stature (cm)	-.344	-.377
	Body mass (kg)	-.314	-.302
STRENGTH	Hand grip (kg)	-.355	-.378
	Arm extension (kg)	-.322	-.279
	Leg extension (kg)	-.240	-.291
	Thigh flexion (kg)	-.324	-.306
FLEXIBILITY	Shoulder (deg)	-.240	-.358
LUNG FUNCTION	FVC (l)	-.473	-.398
	FEV_1 (l)	-.429	-.373
FITNESS	PWC_{170} (l/min)	-.260	-.302

Despite the significant correlations noted in Table 5, they do not suggest strong relationships between these measures and the performance criteria. Indeed, when a multiple regression analysis was employed to predict swimming performance, only 20% of the variance was accounted for by these measures. This suggests that the remaining 80% of the variance in swimming performance for this age group must be attributed to other factors. Could this be skill or technique in combination with psychological make-up (Figure 2)?

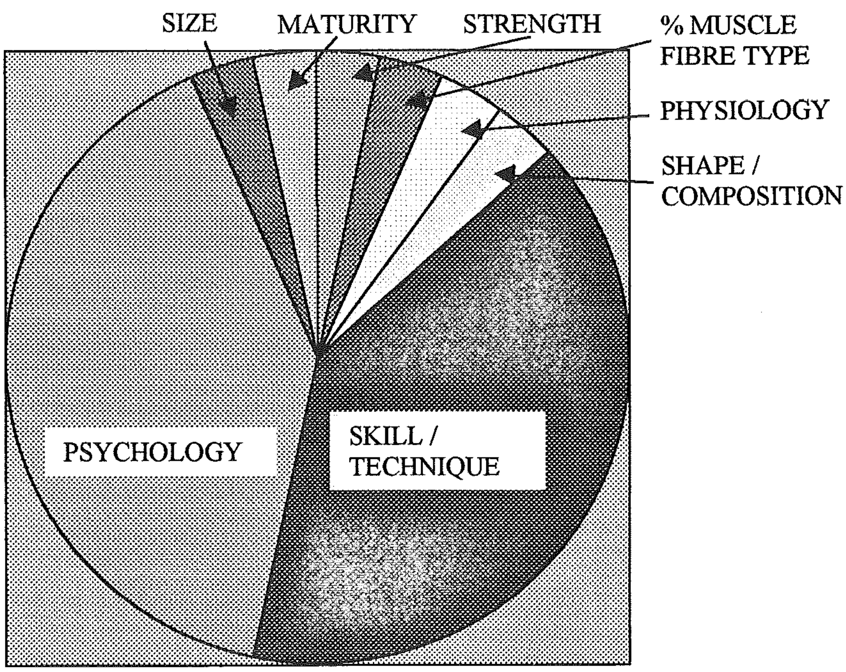

Figure 2 - Only 20% of variance in FR and FL swimming performance Is explained by physical and physiological variables.

At the elite level, we might expect that competitors have been able to maximise their attributes through intensive training, and that they become a more homogeneous group than age-group swimmers. This does not appear to be the case as we see from the KASP data in Table 6 for male competitors. The 'best' versus 'rest' results for the female swimmers were very similar, with the added observation that the 'best' competitors had uniformly lower body fat scores than the 'rest'.

Table 6 Differences between 'Best' and 'Rest' Male Competitors * (from Carter and Ackland, 1994).

STROKE & DISTANCE	VARIABLE	VARIABLE
FS 50 + 100 m	Stature ⇑ Upper limb length ⇑	Lower limb length ⇑ Leg length ⇑
FS 200 + 400 m	Stature ⇑ Body mass ⇑ Upper limb length ⇑ Lower limb length ⇑	Leg length ⇑ Foot length ⇑ Chest girth ⇑ Transverse chest breadth ⇑
BR 50 + 100 m	Stature ⇑ Body mass ⇑ Arm span ⇑	7 x segment lengths ⇑ 9 x girths ⇑ 3 x breadths ⇑
BK 50 + 100 m	Stature ⇑ Arm span ⇑	6 x segment lengths ⇑
FL 50 + 100 m	Stature ⇑	Sitting height ⇑

* Best = ranked in the top 12 finalists; Rest = the remaining competitors.

Three important features are revealed when seeking common traits among the best swimmers in the short distance (SD) events. Despite the mean differences for segment lengths between competitors in the various strokes, the best swimmers possess longer absolute limb lengths, especially foot length. With respect to the model of performance described by Grimston and Hay (1986), the beneficial effects of longer body segments among sprint swimmers would appear to influence the development of propulsive forces to a greater extent than resistance forces.

The best swimmers in SD and MD events are also generally taller than the rest. While this concept is not new, support for these results can be seen from studies which have reported on active drag in swimmers (Huijing et al., 1988; Toussaint et al., 1990). In adult swimmers, Huijing et al. (1988) have shown a high correlation between the cross-sectional area of the body exposed to water flow and active drag. However, when increases in cross-sectional area are combined with increased stature (Toussaint et al., 1990), active drag remains relatively unchanged for velocities of between 0.8 and 1.5 m/s. It was suggested by Toussaint et al. (1990) that increases in stature and the associated decrease in Froude number, serve to reduce wave making resistance. This would presumably counter the increased pressure drag caused by any increase in cross-sectional area, so that the net effect on total active drag was negligible.

Finally, in almost all strokes the best swimmers have lower proportional skinfold thicknesses. Competitors in the 800m and 1500m events (ML) tend to be less robust than SD and MD especially among the males with the former having significantly lower values on three absolute girth measurements. In addition, ML have proportionally smaller neck, arm and thigh girths, as well as lower values on two skinfolds than SD. These structural characteristics will be reflected in lower values for the frontal area of segments as well as affecting the coefficients of lift and drag. The combined effect may be to sacrifice generation of some propulsive force in favour of significant reductions in drag. Thus, if economy of motion is the overriding strategy for success in ML events, these modifications to swimmers' size and shape would appear to adequately serve this strategy.

CONCLUSION:

The data presented in this paper support the idea that an effective talent identification program may be formulated for the sport of swimming. While a junior swimmer's current level of performance may provide a useful starting point, through our understanding that talent identification is about predicting some future potential of this individual, we should therefore seek attributes that will provide an advantage over other competitors. Of special interest are those attributes that cannot be easily modified through training, as they provide a 'natural' advantage for the swimmer when all other factors are equal.

Quite clearly, tall stature and long segment lengths provide a mechanical advantage for short distance swimmers in their development of propulsive force. This tall stature allows the swimmer to increase body bulk through strength and power training, without seriously affecting active drag. Whether the forearm-plus-hand is used as a paddle or foil, it appears that longer segments are a definite advantage, as too are a pair of size 16 feet. The shorter, stockier body builds, on the other hand, appear more suited to breaststroke technique as well as to the open water, long distance events.

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