DOCTORAL THESIS

The Use of Technology to Improve Swimming Performance

Skill focus

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Table of Contents

List of figures

List of tables

Glossary of terms

BF	Butterfly
BK	Backstroke
BR	Breaststroke
CFD	Computational fluid dynamics
CG	Centre of gravity
DPS	Distance per stroke
FFT	Fast Fourier transforms
Fps	Frames per second
FR	Freestyle
GUI	Graphical user interface
Hz	Hertz (frequency)
ITC	Intensive training centre
LED	Light emitting diode
Psi	Pounds per square inch (pressure)
RTT	Round trip time
SSC	Stretch-shortening cycle
SL	Stroke length
SPM	Strokes per minute
SPS	Seconds per stroke
SR	Stroke rate
TTL	Transistor-transistor logic
UUS	Underwater undulatory swimming
WSN	Wireless sensor network

Abstract

When working with elite swimmers, it is necessary to determine areas in which small changes can result in improved performances during the pinnacle events each year as a culmination of improvements within the daily training environment. The swimming skills of starts and turns comprise approximately 30% of the total race time in events with distances up to 100m (Thayer and Hay, 1984) indicating the importance of skills to overall race performances. Data from the 2011 World Championships is presented to highlight the percentage of race time spent in the start and turn phases for all events.

The starting technique of 48 elite swimmers was investigated to determine the optimal starting position based on the forward leg, width of stance and position of the wedge on the starting block. Ongoing monitoring within the training environment has indicated continued improvements to start times at 15m distances as measured during competitions.

Slawson (2010) showed that a 1% improvement in turn times in the 100m and 200m events at the Beijing Olympics would have resulted in changes to the podium positions, highlighting their importance during competitions.

The development of a waterproofed turn pressure mat throughout the research enabled information on the position and time on the wall for the separate legs to be measured on 33 university level swimmers. Testing was conducted on all swimmers performing maximal freestyle turns during the initial testing session followed by their preferred stroke during testing the following month. Comparisons were made between the four swimming strokes for parameters measured during the wall contact phase although large standard deviations would indicate the need for larger sample sizes to gain a better understanding of the data.

Future research should examine the underwater phase of both the start and turning skills.

Key words: swimming, competition analysis, starts, turns, pressure mat

Publications arising from this work

Conference papers

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Journal papers

Slawson, S.E., Conway, P.P., Cossor, J., Chakravorti, N., West, A.A., 2013. The categorisation of swimming start performance with reference to force generation on the main block and footrest components of the Omega OSB11 start blocks. Journal of Sport Sciences, 31(5), pp. 468–478.

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Cossor, J., Slawson, S, Conway, P., West, A., 2014. Improvements to the start and turn components of the race at international swimming competitions. In development.

Cossor, J., Slawson, S, Conway, P., West, A., 2014. Determination of optimal starting position of elite swimmers using the Omega OSB11 block. In development.
Cossor, J., Slawson, S, Conway, P., West, A., 2014. The effect of foot position during the wall contact phase on swimming turn performance. In development.

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Chapter 1 – Introduction

Information presented in this thesis describes the use of technology within the sport of swimming so that improvements in performance could be made both within the training and competition environments.

1.1 Motivation

Swimming performances continue to improve with world records being set each year. This is as a result of increased training volumes, more swimmers within each event as well as improvements to the environment that the swimmers compete in. Technologies used to monitor swimming performances both in training and competition have evolved with the greatest improvement resulting in more immediate feedback to the swimmers and coaches so that changes to technique can be made in real time.

During the 1912 Olympic Games the swimming events took place within the sea whereas they now take place in controlled environments where the air and water temperatures are set along with the filtration systems used to maintain the water quality. The dimensions of the lane ropes used within the competition have evolved from sporadic buoys along the length of rope to 6mm diameter buoys that restrict the flow of water between one lane and the next. Starting blocks must be within a 30cm height range above the surface of the water with a maximum platform size of 530mm x 530mm and set at 10° to the perpendicular base of the block. The material and design of the swimming suit continues to change and this had a large impact on the performances between 2008 and 2010 when the rules for the manufacturers were changed.

Previous research examined the performances of the elite level of swimmer during major international competitions and the first stage of the current research was to examine the competition performances of this level of swimmer so that trends in each event could be monitored. A more detailed race analysis system needed to be developed so that comprehensive information could be provided on the start and turn phases of the races such that specific improvements for each athlete could be made between each competition.

The next stage of the research was aimed at determining the optimal starting position for each individual when using the latest design for the starting block. A multi component approach was used that incorporated vision systems, force parameters as well as a wireless sensor node.

The final component of this thesis was the investigation of swimming turn performance. Phases measured within the competition environment could be monitored within training on a regular basis. All previous literature on swimming turns used force platforms rather than pressure mats during the wall contact phase where the body was treated as a whole. The use of pressure mats during turns enables comprehensive data to be measured on the positioning of the left and right foot in both the vertical and horizontal positions on the wall. Orientation of the feet in comparison to the surface of the water and the side wall can also be measured automatically through the use of a pressure mat. Coaches and scientists have discussed optimal positions of the feet as they contact the wall during the turn and this research aimed to provide quantitative measures so that objective suggestions could be made to improve turning performance.

1.2 Research objectives

The aim of the research presented within this thesis was to determine the effectiveness of technology to improve swimming performances.

Objective 1

To monitor the performances of swimmers during the major international competition each year and to determine the relative strengths and weaknesses of the British swimmers within these competitions. This would include comprehensive information on the skill phases (starts and turns) of the race which accounts for 30% of the 100m long course[1] events. The ultimate purpose was to improve the swimming times and rankings of the British teams throughout the research period.

Objective 2

To determine the optimal starting position of elite level swimmers training at the five Intensive Training Centres (ITCs) based around the United Kingdom. The best starting position for each individual would result in the highest take off velocity from the block, maximum flight distance and the fastest time to reach the 15m distance from the block. The timing of the peak vertical and horizontal forces on the front and rear legs would also be used with the assessment of the starting performance.

Objective 3

To determine the position of the feet on the wall that resulted in the fastest turn times as measured from the head passing the 5m distance in to the wall and back to the same position after the swimmer had completed the turning motion. There is currently no research to suggest that the foot position effects turning performance but it is an assumption made by swimming coaches.

[1] Races that occur in a 50m pool are referred to as long course events while those conducted in a 25m pool are short course events.

1.3 Thesis outline

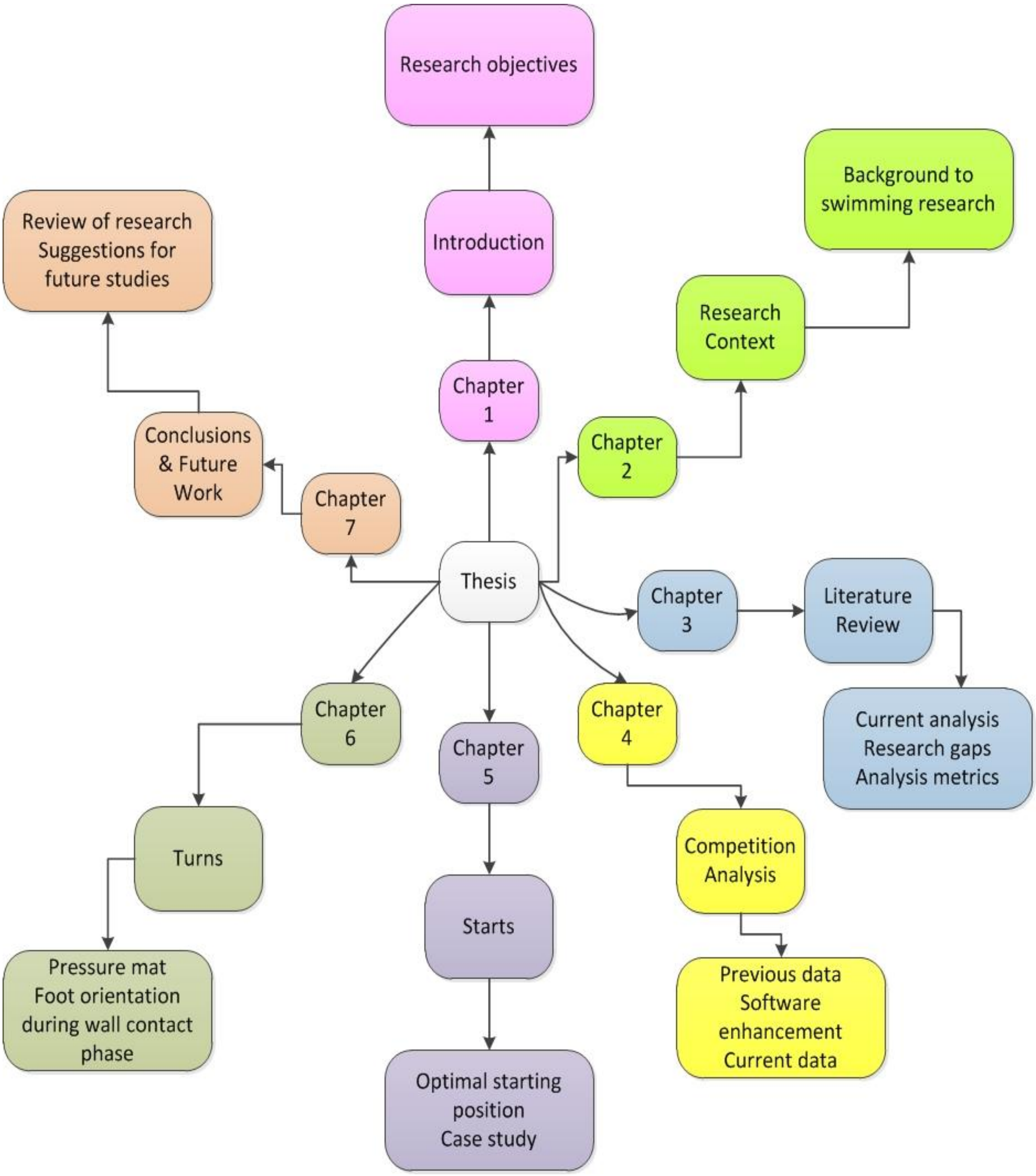

Figure 1: Thesis outline including contents for each chapter

1.4 Research questions answered

Objective 1

Swimming performances were monitored at the 2010 Commonwealth Games, 2011 World Championships, 2012 Olympic Games and 2013 World Championships. Results showed that the fastest swimmers tended to have the fastest starts and turns with one exception observed in the women's 100m butterfly world record set during the London Olympics.

The software used to analyse performances within a competition was improved through collaborative work with UK Sport and Sheffield Hallam University. Race analysis was provided to the coaches more quickly than previous software and in a format that was suggested by the British coaches. Start and turn performances of the British swimmers competing in these events improved over the 4 year period as observed in the more detailed analysis that included a number of phases within each skill component.

Objective 2

An instrumented starting block was designed that enabled vertical and horizontal forces to be measured during the block phase of the start. Measures were separated in to the front and rear legs with the design of experiments incorporating narrow and wide stances, wedge positions 3, 4 and 5[2], as well as the right and left legs placed at the front of the block.

Optimal starting positions were recommended to each of the swimmers and these were compared to their preferred starting positions in the second phase of testing. Ongoing monitoring of the starting performance, as measured from the starting signal until the swimmer's head reached the 15m mark from the wall, was measured three times over a 12 month period. A case study was also presented for the swimmer whose preferred and suggested starting position differed by the largest amount and he has qualified for the 2014 Commonwealth Games using the proposed stance.

Objective 3

A waterproofed pressure mat was developed that enabled the position of the feet during the wall contact phase of the turn to be monitored. Information included the vertical depth of each foot from the surface of the water as well as the horizontal distance between the centres of the ball of each foot. The orientation of the feet in relation to the surface of the water and the side wall was measured and differences in techniques employed in each of the four strokes were observed. Greater subject numbers in future research will enable more accurate interpretations to be made for each of the swimming strokes.

[2] The OSB11 starting block includes a wedge towards the rear of the block and can be moved between five fixed positions ranging from 350-530mm from the front of the block.

Chapter 2 – Research context

Swimmers are judged on their race performance at international competitions each year with the Olympic Games being the ultimate event within each four year cycle. At the elite level, small changes in performance can have a significant effect on the outcome of the race (Slawson, 2010). Physiological changes can be made through each training cycle[3] but the most easily attainable improvements to swimming performance are made through the improvement of skills. The skill components of a swimming race include the start, turns and finish, with the starts and turns being the most significant contributors to success (Maglischo, 2003). The final 5m of the race is referred to as the finish and is a relatively small component (average 5.17% of the race time in the male 100 m freestyle final at the 2011 World Championships) and as such was not the focus of this research.

Analysis at the 2011 World Championships was undertaken to determine the contributions of the starts and turns in all events from 50m through to the 1500m. Starts within a swimming race are the time that it takes for the swimmer's head to reach the 15m distance after the starting signal while the turns are measured from the swimmer's head passing the 5m mark on the approach to the wall until they reach the 10m distance after the change in swimming direction. The percentage of race time for the starts and turns for all events in all strokes at the 2011 World Championships can be seen in Figures 2 and 3 for male and female swimmers respectively. Within the figures, the blue shading indicates the events where the start is important (50m and 100m events), the green shaded area covers the events where both the starts and turns impact on the result (200m events) and the yellow shaded area is for the distance events (400-1500m) where turns are the most significant skill component. The starts have a greater contribution to the overall performance in the sprint events (~25% for 50m and ~10-15% of 100m events) while the turns are important for the distance events (~24% of 400m, 27% of 800m and 1500m events). Both starts (~5% of race time) and turns (~21% of race time) are important for the middle distance (200m) races.

Figures 2 and 3 show that the percentage of race time in starts and turns is similar for both the male and female events with the only slight exception observed in the freestyle long distance event. This is due to the fact that males compete over a distance of 1500m while the females have a maximum race distance of 800m in the Olympic Games. These comparisons were used rather than all events swum at the World Championships where the females are able to compete in the 1500m freestyle and males can compete in the 800m freestyle, as the Olympic Games are the definitive event for a swimmer during a four year cycle.

[3] Training cycles allow athletes to work to different physiological constraints in order to improve both the aerobic (endurance) and anaerobic (speed) abilities (Maglischo, 2003). These are undertaken in a structured manner and tend to be repeated every 15 weeks in swimming. The different training phases enable the body to recover from the additional loads generated within the pool and land sessions.

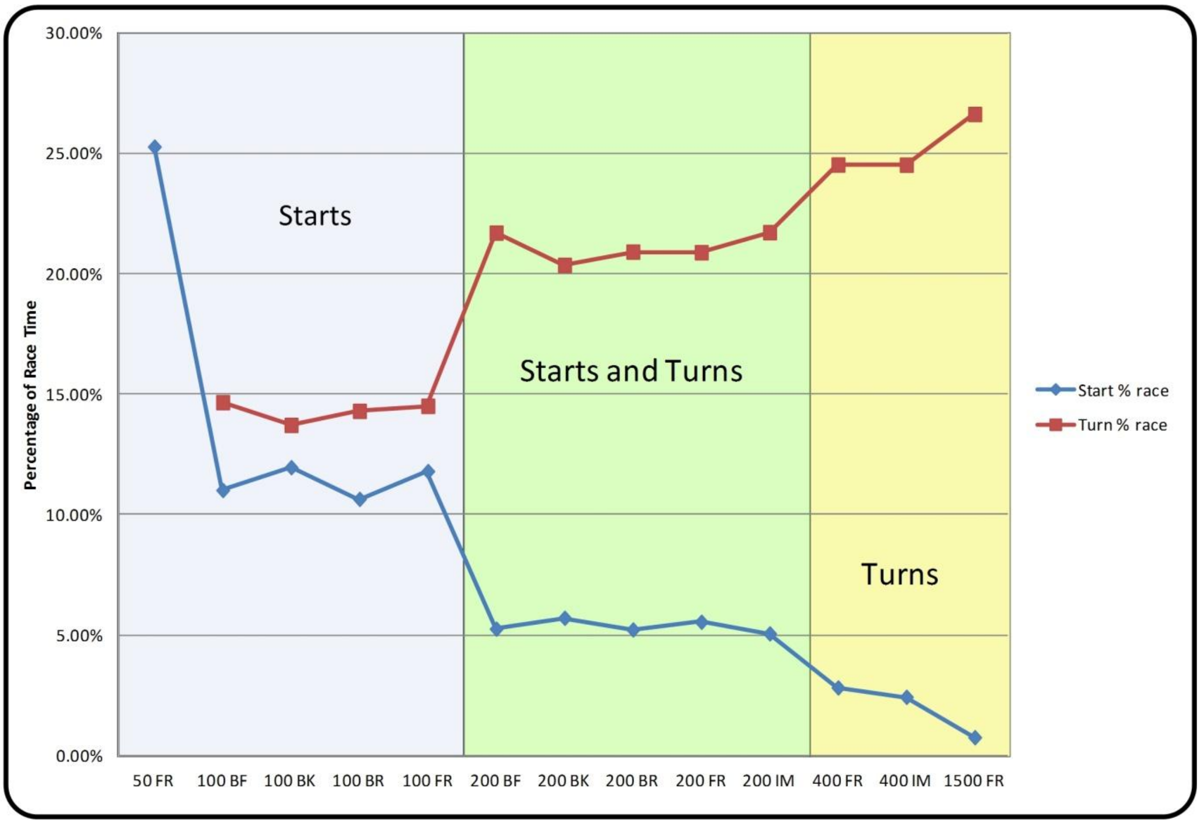

Figure 2: Percentage of race time for starts and turns in all male events at the 2011 World Championships

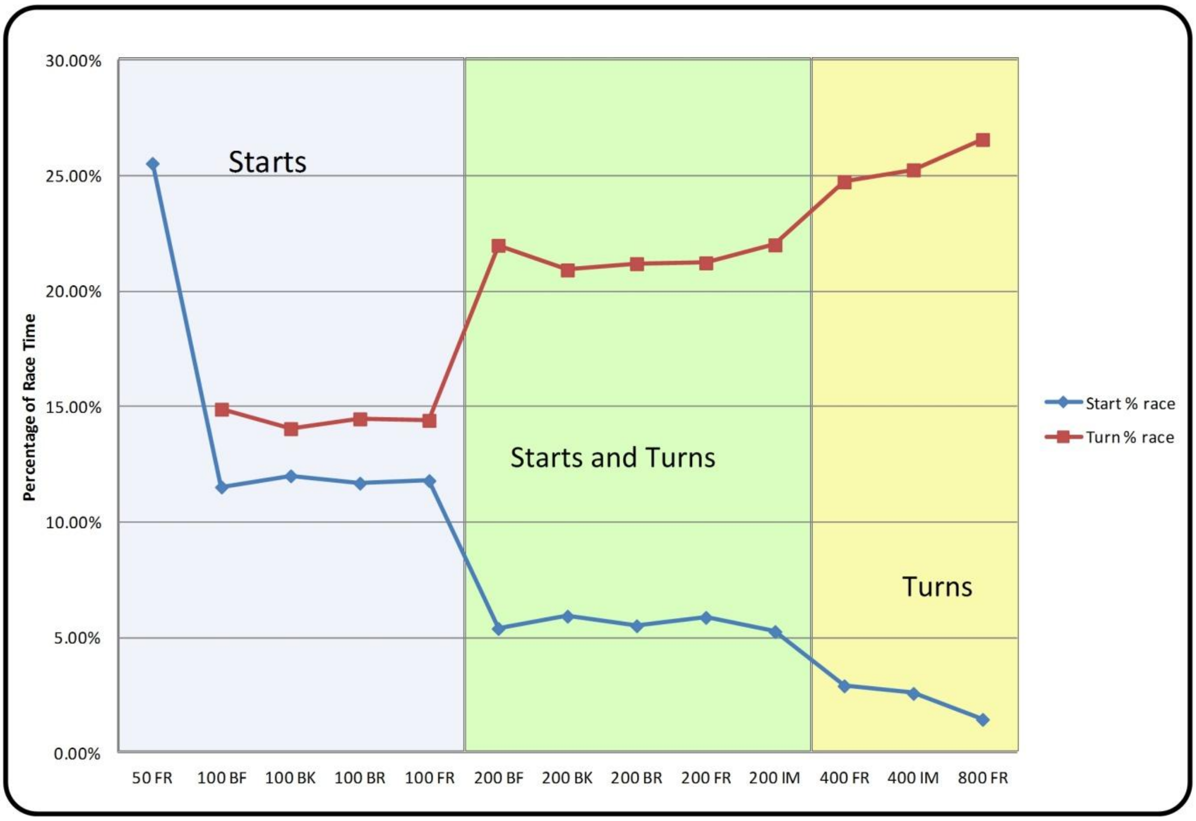

Figure 3: Percentage of race time for starts and turns in all female events at the 2011 World Championships

The swimming race can be divided into a number of phases including starts, free swimming and turns as displayed in Figure 4. The governing body for swimming, Federation Internationale de Natation (FINA) have ruled (FINA SW 5.3, 6.3 and 8.5) that swimmers must break the surface of the water by 15m for both starts and turns in all strokes except for breaststroke. Breaststroke is the only stroke where swimmers are allowed to complete a stroke during the underwater phase (FINA, n.d.) resulting in some swimmers travelling further than the 15m distance prior to reaching the surface of the water during starts and turns. Outside of the starts and turns, the swimming technique is monitored and this is referred to as the free swimming phase. The parameters measured include the velocity for each 25m race segment, the stroke rate (SR) measured in strokes per minute (SPM) or seconds per stroke (SPS), and stroke length (SL) that is also referred to as distance per stroke (DPS). As velocity is the product of stroke rate and stroke length, a change to either of these parameters influences the speed of the swimmer.

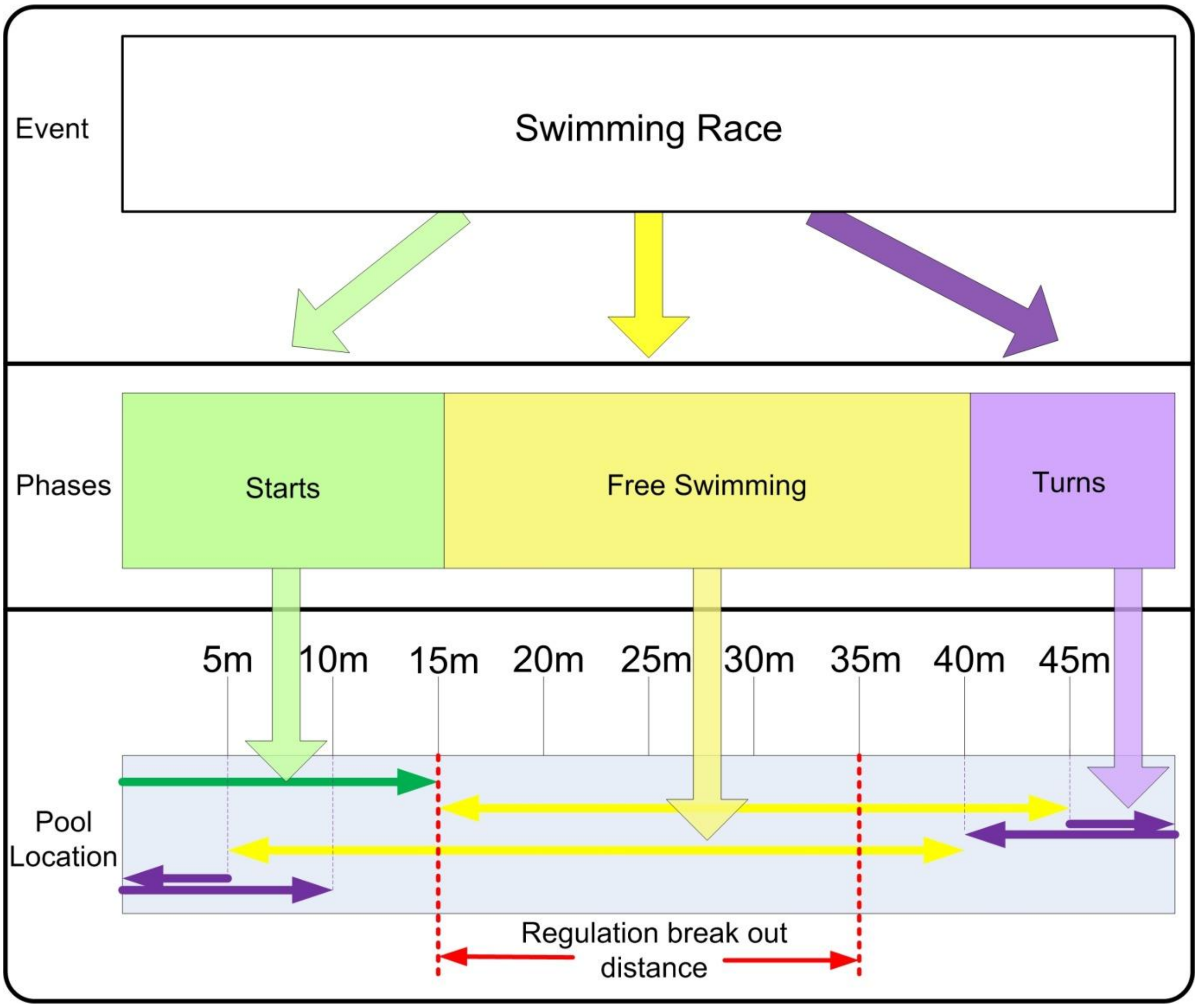

Figure 4: Components of a swimming race including starts, turns and free swimming

By performing race analysis at the major interntational competitions each year it would be possible to monitor the progression of swimmers within each event so that trends could be examined. This would enable more accurate tracking of younger swimmers and their potential to final or medal in future Olympic Games based on previous data as a potential tool to direct resources for future success. The relative strengths and weaknesses within the race could also be highlighted so that the British swimmers could improve on their performances both within the competition as well as on an annual basis. The initial research question was: **Can competition analysis improve the performance of British swimmers?**

In 2008, Omega introduced a new design to the starting block and this has been phased-in to all international swimming competitions. The Omega OSB11 block displayed in Figure 5 has two major differences from the earlier OSB7 block. These are the slope of the block (10° instead of the previous 5°) and the inclusion of a wedge to the rear of the block.

The wedge may be moved to one of five fixed positions that are in 45mm increments (Figure 6) and is inclined by 30° to the main plate of the starting block. If the wedge was placed in the last position, the remaining exposed area of the block is the same dimension (53cm x 53cm) as the OSB7 block.

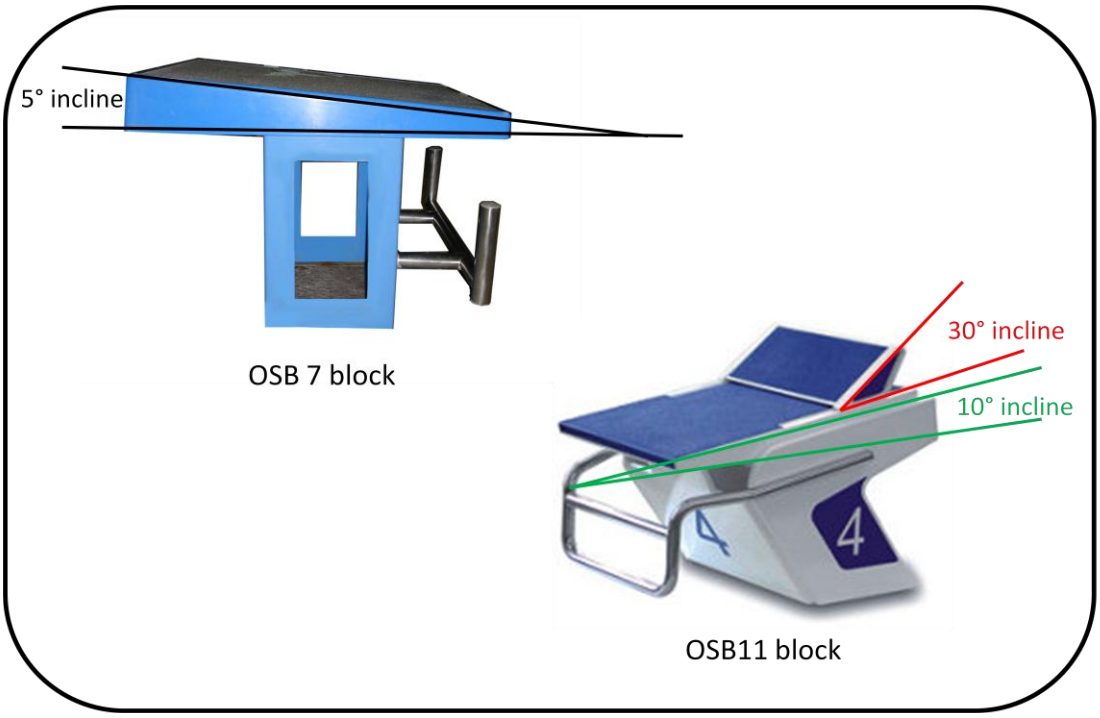

Figure 5: Omega OSB7 and OSB11 starting blocks

With the inclusion of the wedge, swimmers should be able to generate more drive from the rear leg compared to previous starting blocks. The change in block design has resulted in more swimmers using the track style (one foot placed towards the front of the block and the other towards the rear of the block) starting technique in competitions as observed during international competitions. Issurin and Verbitsky (2003) noted that half of the swimmers in the men's 100m freestyle semi-finals and finals and 8 of the 15 swimmers in the women's 100m freestyle events used the track starting technique at the Sydney Olympic Games. Images displayed by Rein Haljand on www.swim.ee show that all of the finalists in the men's and women's 100m freestyle finals at the 2010 European Championships used the track start.

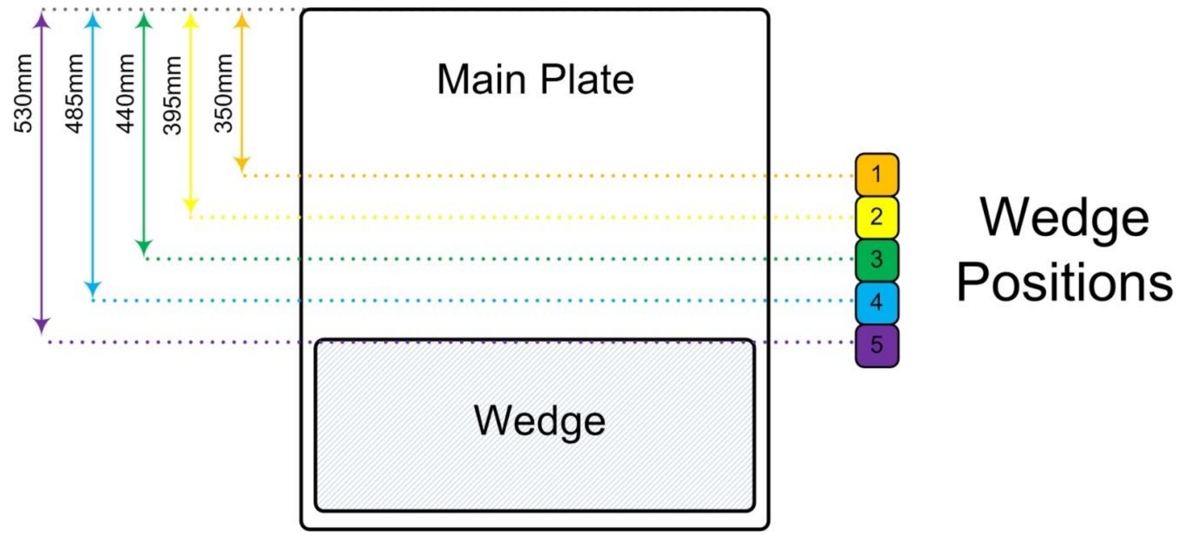

Figure 6: Positions of the wedge from the front edge on the OSB11 starting block

Swimming start techniques have included track (one foot placed in front of the other), grab (both feet at the front of the block) and swing (includes arm rotation and is generally used in relay events).

The start can itself be divided into a number of phases for further analysis including the block, flight, underwater and stroking phases (Figure 7). The block phase is defined as the time from the starting signal until the swimmer's feet leave the block and the flight phase is from this point until the head enters the water. From the time when the head enters the water until the hand breaks the surface of the water is defined as the underwater phase and the stroking phase includes any surface swimming through to a distance of 15m from the starting wall.

Changes to any one of these phases can impact on the time to 15m, the distance that starts are measured to in competitions. Intuitively, making adaptations within the initial block phase will impact on the flight phase via the take-off angle and velocity respectively, and then the underwater phase via the entry angle and velocity respectively. The second research question was therefore: **What is the optimal starting position for each swimmer using the OSB11 block?**

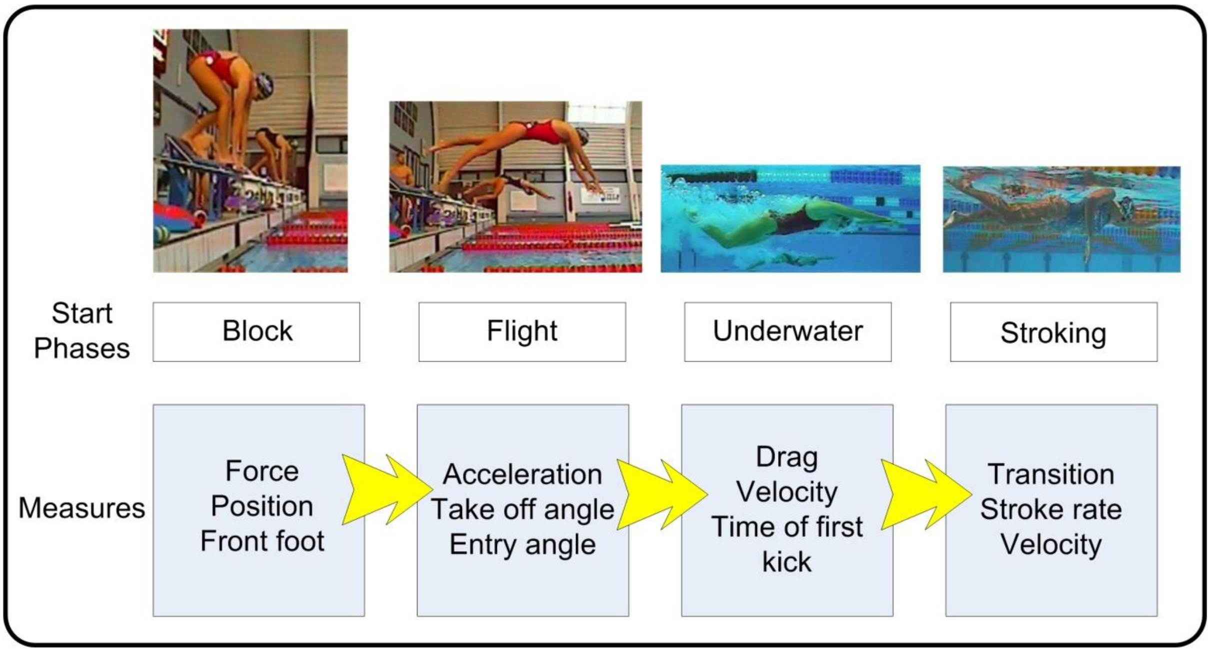

Figure 7: Swimming starts phases and the measures that are used in each phase

The importance of turns is significant in the longer races where a greater percentage of the race time is comprised of turns (Figure 2 and Figure 3). Observations by British Swimming board members at the 2010 Commonwealth Games indicated that the British team were slower in the turns when compared to the Australian swimmers. Dennis Pursley, the British Swimming head coach at the time noted the following in his review report in October 2010 "Our team is as good as any between the walls, but we are clearly disadvantaged on the starts and turns against our toughest competitors. I would encourage all of our coaches to incorporate more start and turn work into their weekly training plans. As is the case with swimming on the surface, it all begins with proper technique."

Board members also noted that the greatest weakness in turns by British swimmers was in the underwater phase after the turn rotation and suggested that the Australian swimmers travelled further than the British swimmers. Competition data showed that the Australian males were breaking the surface of the water after the turn on average 7.93m from the wall compared to the British 6m, while the Australian women travelled 8.15m underwater after the turn compared to the British 5.2m. Competition analysis measures the turn from the 5m distance into the wall to 10m out from the wall for a total of 15m. This distance therefore includes some swimming in most events where the swimmer surfaces prior to the regulation 15m distance, resulting in more than just the skill of a turn within the rotation, wall contact and underwater phases illustrated in Figure 8.

Turns can be divided into a number of phases including the approach (In), rotation, wall contact, underwater and stroking phases (Lyttle and Benjanuvatra, 2007). The approach phase is defined as the period from the swimmer's head passing the 5m distance into the wall until their last hand entry in freestyle and backstroke or the hand touch on the wall in breaststroke, butterfly and individual medley turns. The rotation phase is from this point until the feet touch the wall, whilst the wall phase encompasses the swimmer's leg and foot positioning whilst in contact with the wall. The underwater phase covers the period from when the feet leave the wall until the first hand breaks the surface of the water and the stroking phase is any swimming that occurs prior to the 10m distance after pushing off the wall.

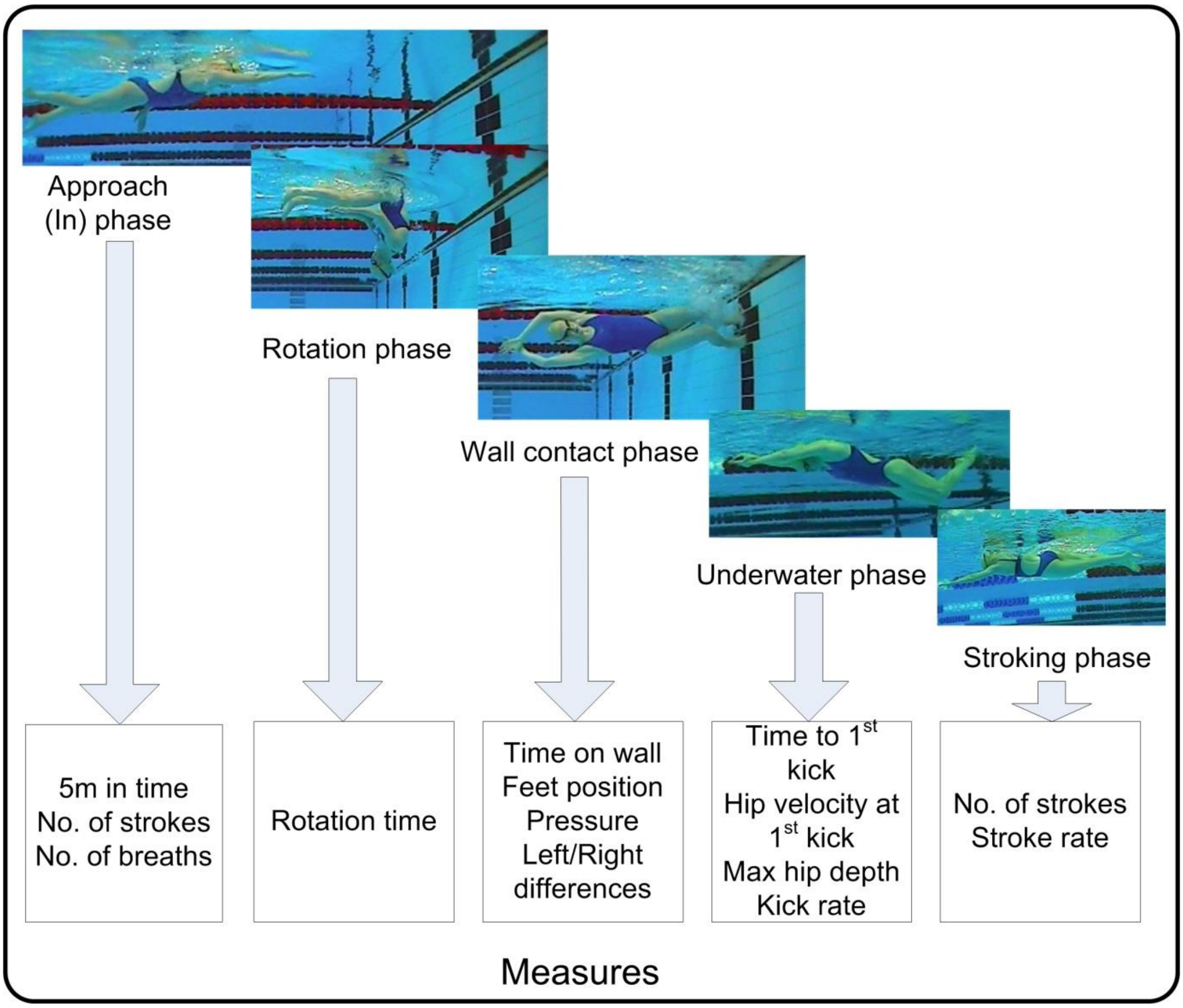

Figure 8: Turning phases and measures that can be used in each phase

The current British race analysis system (Nemo©, Sheffield Hallam University) includes information on each of the turning phases noted in Figure 8. This enables a more detailed analysis of the turns compared with earlier software, within a competitive environment, such that improvements can be specific for each elite swimmer. Comprehensive analysis of the turns at the 2011 World Championships on those British swimers identified as potential medallists for the London 2012 Olympics is presented in Table 1.

Table 1 Turn analysis of selected British swimmers at the 2011 World Championships by phase and compared with the winner of each event

Swimmer	Gender	Event	Position	5m In Time (s)	10m Out Time (s)	Rotation Time (s)	Breakout Time (s)	Breakout Distance (s)	Underwater Velocity (m/s)	5m in/10m out Time (s)
1	Female	200 Free	24	3.33	5.35	1.39	1.95	4.54	2.32	8.68
		400 Free	2	3.44	5.29	1.36	2.19	5.03	2.30	8.73
		800 Free	1	3.49	5.36	1.40	1.97	4.69	2.38	8.85
2	Female	400 Free	15	3.53	5.44	1.31	1.67	4.15	2.48	8.97
		800 Free	16	3.65	5.59	1.39	1.76	4.12	2.33	9.25
3	Female	100 Fly	6	2.78	5.88	0.70	4.84	8.35	1.73	8.66
		200 Fly	2	3.10	6.25	0.71	4.02	6.55	1.63	9.35
4	Female	50 Free	4							
		100 Free	4	2.97	4.87	0.98	2.63	6.03	2.29	7.84
5	Female	200 Free	23	3.30	5.17	1.43	1.91	4.81	2.52	8.47
6	Female	100 Fly	8	2.88	5.74	0.68	4.50	7.85	1.74	8.62
		200 Fly	7	3.05	6.14	0.87	4.43	7.38	1.67	9.19
7	Female	200 IM	7	3.46	6.40	0.69	4.33	6.91	1.60	9.86
		400 IM	2	3.65	6.42	0.88	3.61	5.96	1.65	10.07

Swimmer	Gender	Event	Position	5m In Time (s)	10m Out Time (s)	Rotation Time (s)	Breakout Time (s)	Breakout Distance (m)	Underwater Velocity (m/s)	5m in/10m out Time (s)
8	Female	100 Back	7	3.29	5.09	1.24	7.19	13.55	1.88	8.38
		200 Back	7	3.58	5.14	1.17	6.40	11.84	1.85	8.72
9	Female	100 Back	23	3.34	5.26	1.34	4.76	9.25	1.94	8.60
10	Male	100 Back	6	2.95	4.41	1.20	5.81	12.56	2.16	7.36
11	Male	200 Breast	8	3.15	6.00	0.65	5.01	8.59	1.71	9.15
12	Male	200 Free	10	2.95	4.61	1.28	1.93	5.31	2.75	7.55
13	Male	200 IM	4	2.92	5.54	0.74	5.74	10.35	1.80	8.47
14	Male	100 Breast	16	3.04	5.94	0.62	5.24			8.98
		200 Breast	5	3.07	5.96	0.68	5.52	9.39	1.70	9.03
15	Male	400 IM	8	3.24	5.85	0.97	4.38	7.80	1.78	9.09
16	Male	200 Free	12	3.09	4.71	1.42	2.61	6.22	2.39	7.80
17	Male	400 IM	10	3.27	5.67	1.11	5.28	9.36	1.77	8.94

Worse than gold medallist (pink) — On par with gold medallist (yellow) — Better than gold medallist (green)

The green shaded numbers indicate that the British swimmer was better than the gold medallist in that event while the red shading is where they were worse. The yellow shading indicates that they had approximately the same result in the turn phase being monitored as the winner of the event.

The variables measured for the turn included the 5m "in" time, the 10m "out" time, total 15m turn time and the rotation time as described earlier. The breakout distance was calculated using known locations on the competition lane ropes and the time at which this occurred. Underwater velocity was calculated using the information on the underwater distance and time obtained from video recording at the competition.

When inspecting the red shaded areas, the identified British swimmers were not as good as the winners in 42% of the cases for the 5m "in" time, 63% for the 10m out time and 79% of the races for the total turn time. The strength of the British team during that competition was the rotation time with only 17% of the cases not as fast as the gold medallist in that event. Results showed that the breakout time had 50%, breakout distance 67% and underwater velocity 58% of the swims with red shading. Having noted this, there are also cases where the British swimmer was better than the winner of the event as shown by swimmer 8. In the 200m backstroke finals she was as good as, or better than the winner in all measured variables other than the underwater velocity. There was a similar trend in the 100m backstroke although she was slower than the winner for the 10m out time in that event.

From these data it is possible to determine that the turn phase that was the weakest when comparing British swimmers to the winners in the 2011 World Championships tended to be the "out" phase of the turn including the breakout time and distance, as well as the underwater velocity. These are all affected by the positioning of the legs and feet on the wall for maximum drive when leaving the wall (Barbini, 2012). Therefore the second part of the research outlined in this thesis is focused on the turning performance of swimmers with particular emphasis on the wall phase of the turn for performance improvement by British swimmers at International competitions. The final research question was: **Does the foot position during the wall contact phase effect the overall turning performance?**

As presented in the introduction this thesis reviews the literature (chapter 3) and examines competition analysis within swimming and its progression over time (chapter 4). The focus of chapter 5 is the enhancement of starting performance through the use of a new design in the starting block while the following chapter (6) examines the swimming turns with a focus on the wall contact phase. Chapter 7 concludes the work throughout the thesis with suggestions for future work.

Chapter 3 - Literature review

A review of the literature within swimming research has highlighted three main areas of investigation as shown in Figure 9. These include research within the competition environment, the use of technology in swimming research, and specific skills conducted in the training environment for enhanced competition performances.

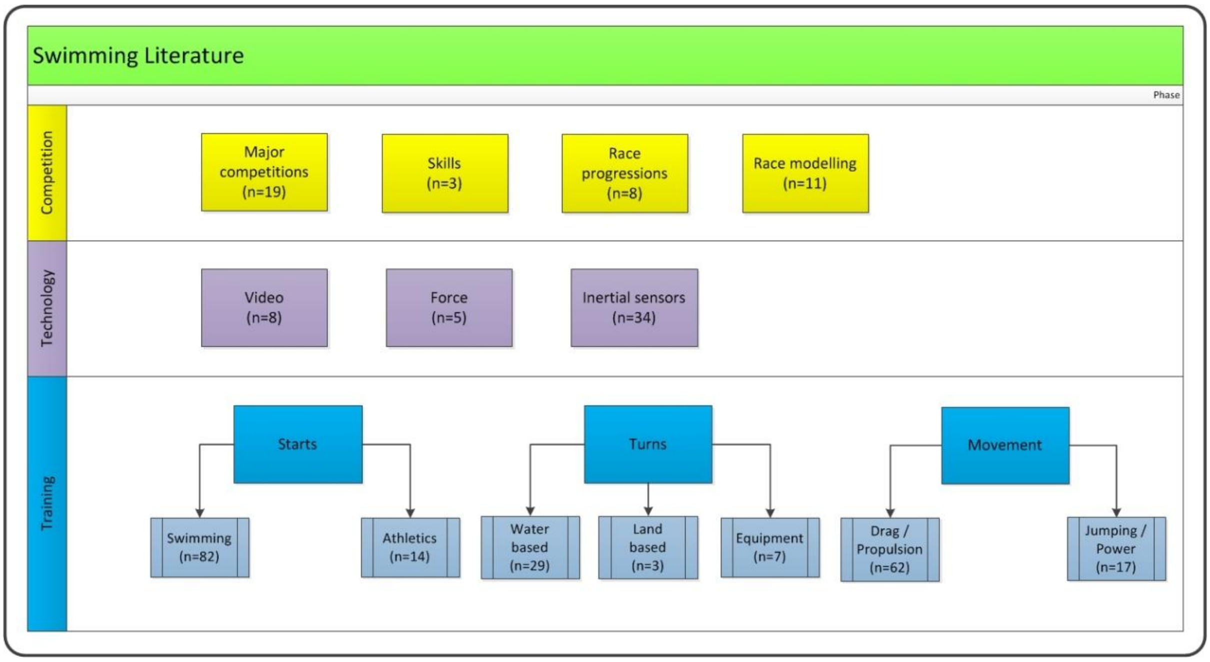

Figure 9: Summary of topics within swimming research literature

Research within the competition environment has been divided into four areas including: **major competitions**, analysis looking specifically at the **start and turn skills** within a race, the **progression** of performance within one year and over a period of years, as well as **modelling** of performance.

The technology to monitor swimming performance both above and below the surface of the water includes the use of **video** systems, **force** platforms and wearable **sensors** including accelerometers. These forms of technology have been used to monitor both competition and training situations.

Research within the training setting can be divided into three main categories: starts, turns and movement. For the purpose of this research, **starts** were investigated both in the swimming and athletics domains due to similarities in the explosive action of the movement. **Turns** are used to change direction and as such research examines both the approach and out phases of the skill along with the wall contact. Drag and propulsion are two factors that greatly influence the **movement** of the swimmer through water. In addition “dry land” training contributes significantly to a swimmer’s movement since explosive leg capability and strength play a role in the pool performance. Land-based activities are also monitored regularly since swimmers spend between 15 and 20% of their overall training time out of the pool. This is calculated on an average training commitment of 25 hours in the pool spread over 10 training sessions and 5 hours of dry land training in 5 sessions per week.

3.1 Competition analysis

Competitions have been used to monitor the performances of swimmers, when they are at their peak level of fitness, for more than thirty years, and sports science has become an integrated component within the athletic preparation (Davison and Williams, 2009). Some of the key research contributions relating to swimming competition analysis have been listed in **Error! Reference source not found.**Figure 10.

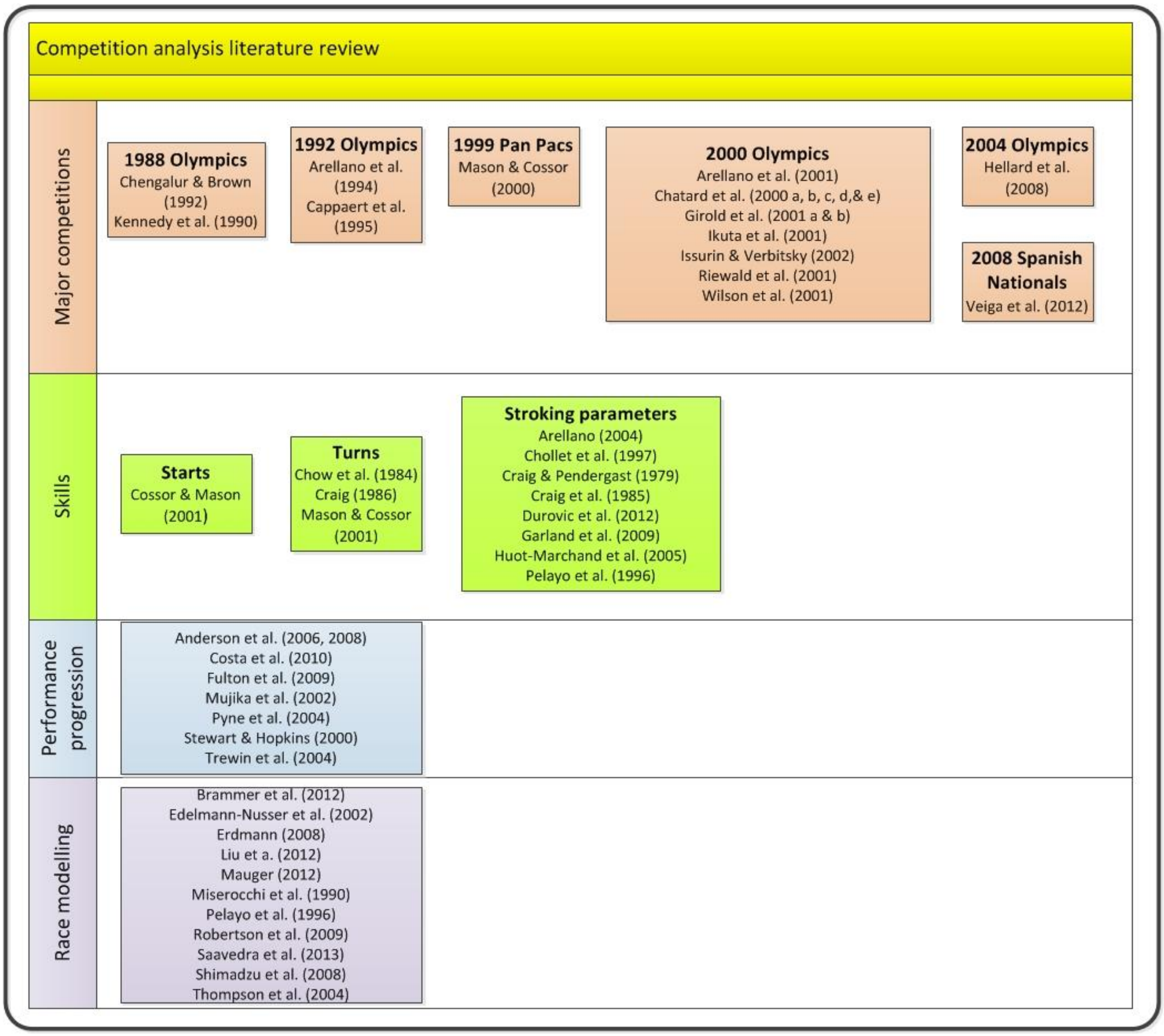

Figure 10: Competition analysis literature review summary

Portable race analysis systems have been developed in Australia, Great Britain, Japan, the Netherlands and Switzerland and are used by many other countries for their ease of use. The systems tend to include a small video camera mounted to a tripod that is then connected to a laptop computer in order to capture the footage directly. Feedback to coaches is both visual through the use of computers or iPods and numerical through reports and is provided to the coaches and athletes both at the pool and at team accommodation depending on the competition and rest schedules.

Research was conducted by Tor et al. (2012) to examine the reliability of data collected from a multi camera system and compared with a single camera swimming analysis system. Data suggested that there were errors in both types of analysis but no significant differences between the two systems were found so the authors noted that nations should look to develop single camera systems for use in competition environments.

3.1.1 Major competitions

Analysis of the 1988 Olympic Games was conducted by Chengalur and Brown (1992) and Kennedy et al. (1990) where both the 100m and 200m events were examined. The researchers concluded that the stroke length (SL) was the most important predictor of success and there was also a strong relationship between the height of the swimmer and final race time. In all events the males were faster and taller than the females with longer strokes and higher stroke rates.

1992 Olympic Games

Further research was conducted at the 1992 Olympic Games in Barcelona by a number of groups. Arellano et al. (1994) measured the SR, SL, start time, turn times, end times and average velocity of 335 male and female swimmers in the 50m, 100m and 200m freestyle events. The results obtained from this analysis showed that the males were older (22.0 years), taller (185.0cm) and faster (52.97s) than the females (19.9 years, 172.2cm and 58.23s respectively) in the 100m freestyle. The age of the swimmers was younger in the 200m events compared with the 50m events (22.6-21.2 years for males and 20.1-19.4 years for females). As the race distance increased, the stroke length increased (1.98-2.20m for males and 1.86-2.03m for females) while the average velocity (2.01-1.70m/s and 1.82-1.58m/s for males and females respectively), and stroke rate decreased (1.02-0.78 strokes per minute (SPM) and 0.98-0.79 SPM for males and females respectively). These findings for the age of the swimmers were anticipated due to the increased aerobic potential[4] of younger swimmers, based on their ability to recover, compared with older competitors so they are more easily able to cope with the longer distances. As the swimmers become older, they tend to focus on shorter races due to their increase in strength and power capabilities. From personal observations, it appears that this is in contrast to athletics where the middle and distance runners perform better with age and the trend is to move from shorter to longer race distances as observed from competition results.

In the same competition, three dimensional analysis of the stroke for elite and sub-elite male 100m freestyle swimmers was performed by Cappaert et al. (1995) revealing differences in the hand path and body position through the stroke. Elite swimmers showed

[4] Aerobic training refers to endurance type exercise where the heart rate is in the region of 50-70 beats per minute below the maximum heart rate.

more symmetry between the left and right arm strokes and also achieved a higher propelling efficiency[5] (54.2%) with lower hand forces (40.6N) when compared to the non-elite swimmers (45.2% propelling efficiency and 48.6N of force). Cappaert et al. (1995) found that the elite swimmers (those in the cyclically seeded heats and finals) had a lower hip roll angle compared to the shoulder roll angle but that they both occurred in the same direction. The sub elite swimmers (those in the unseeded heats) had greater lateral hip movement and less body symmetry compared with the elite group. The group suggested that the elite athletes were more streamlined and this aided in their superior performance compared to the sub elite group.

1999 Pan Pacific Championships

Competition analysis was conducted on the finalists competing at the 1999 Pan Pacific Championships where research findings showed that the free swimming segment had the greatest correlations (0.81 to 0.99) with better race results in the freestyle events (Mason and Cossor, 2000). Turn times were also shown to be significantly correlated with the swimming time in 92% of the events suggesting that faster turn times were achieved by the faster swimmers in the majority of the races. The female 800m freestyle was the only event where the stroke frequency (SF) was significantly correlated with the race result (-0.83, p=0.01). The authors showed that stroke length (SL) was not the most important contributing factor to successful performance within the elite level of swimmers as suggested by (Costill et al., 1992; Wilson et al., 2001). The second half of the race (-0.98) was more important than the first half (-0.93) in the distance freestyle events with significant negative correlations at the 0.01 level of confidence.

2000 Olympic Games

A team led by Dr. Bruce Mason of the Australian Institute of Sport was responsible for analysing the swimming races at the Sydney 2000 Olympic Games. Fixed cameras were placed in the overhead gantry that was then cabled back to the central analysis room. An International research team examined various parameters within the swimming performances at the Sydney 2000 Olympic Games (Arellano et al., 2001; Chatard et al., 2001a, 2001b, 2001c, 2001d; Cossor and Mason, 2001; Girold et al., 2001; Ikuta et al., 2001; Issurin and Verbitsky, 2003; Mason and Cossor, 2001; Riewald, 2001; and Wilson et al., 2001). The specific strategies of swimmers in the various 200m events were highlighted in the papers presented by Chatard et al. (2001) and Girold et al. (2001) as displayed in Figure 11. An increase in stroke rate and decrease in stroke length were seen in the medallists when compared to the non-medallists in the backstroke events.

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[5] Propelling efficiency was described by Toussaint et al. (1988) to explain the energy used by the hands to move the water. A higher propelling efficiency value refers to a more efficient swimming technique.

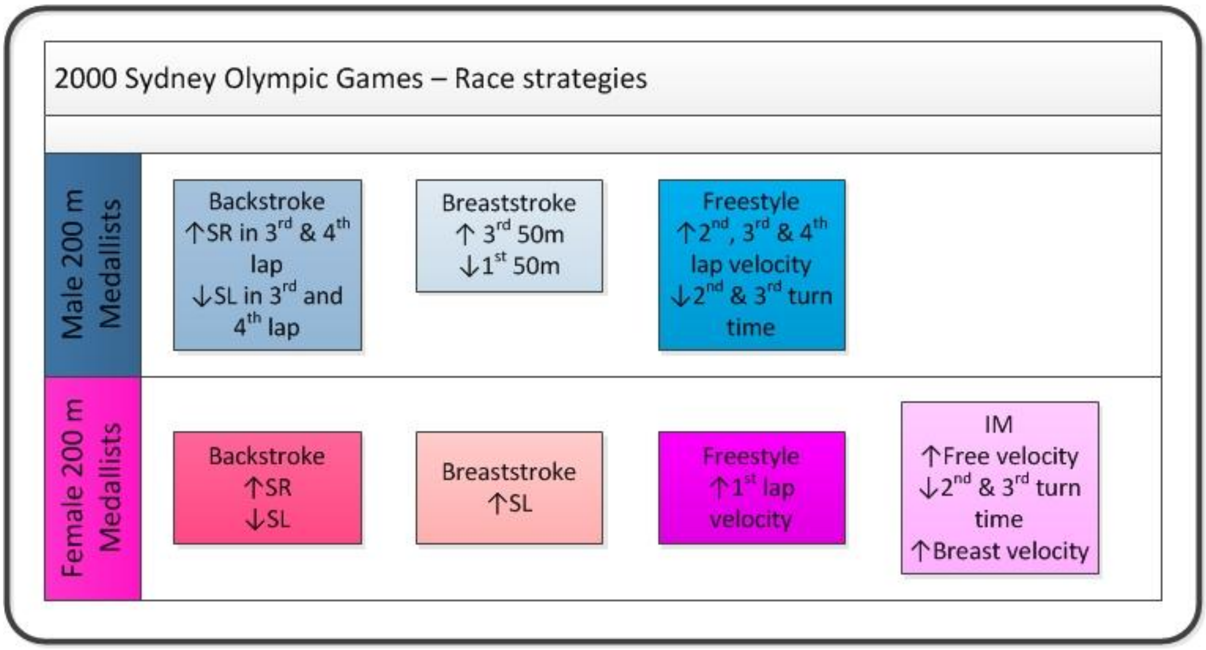


Figure 11: Significant ($p \leq 0.05$) strategic differences between the medallists and non-medallists in 200m finals at the Sydney Olympic Games (from Chatard et al. (2001) and Girold et al. (2001)

Those male swimmers on the podium in the 200m breaststroke had a slower first 50m but faster 3rd 50m than the other competitors in the finals whereas a longer stroke length was used by the medallists in the female equivalent event. Faster velocities for the medallists were seen in the 200m freestyle events while the men also performed the second and third turns faster than the others in the race. In the women's 200m IM the medallists had higher velocities in the breaststroke and freestyle laps as well as faster 2nd and 3rd turns when compared with the non-medallists.

Data from each of the phases of the female 50m, 100m and 200m finals and semi-finals at the 2000 Olympic Games were analysed using fixed video cameras. Results showed no correlation between the race time and the stroking parameters of stroke rate, stroke length and efficiency index (Arellano et al., 2001). The variables that did show a correlation with race time were exported to bespoke software to compute linear regressions. Equations used the formula:

Race component = (A * Race Time) + B

where A was the slope of the line and B was the y-intercept. Results of the regression analysis enabled predictions to be made on race component times required for specific race times and this information could be used within the daily training environment. For a swimmer to complete 100m freestyle in 55s they would need to have a start time of 6.80s, turn time of 7.84s, finish time of 2.87s, average velocity of 1.74m/s and a stroking time of 37.01s. This prediction was based on the swimmers competing in the Sydney Olympic Games but could vary with a larger subject population or with data from a different competition so should be used as a guide only.

Key findings from the analysis of the skill components during the 2000 Olympic Games were that the underwater distance and time had the greatest impact on start success with correlations ranging from -0.60 in the men's 100m butterfly to -0.94 in the women's 200m butterfly (Cossor and Mason, 2001). Turning performance had correlations ranging from -0.50 in the women's 200m backstroke to -0.79 in the women's 100m backstroke with underwater distance and ranges from -0.48 (men's 200m breaststroke) to -0.87 (men's 100m butterfly) with underwater time (Mason and Cossor, 2001). Those swimmers who travelled further and for longer during the underwater phase produced faster turn times and these could be maximised with effective underwater kicking after a good streamlined position. Similar results were observed in the butterfly, backstroke and freestyle starting performances (Cossor and Mason, 2001). All correlations were significant at the $p=0.05$ level.

Differences between grab and track starts were measured during the 2000 Olympic Games (Issurin and Verbitsky, 2003). The fastest average reaction time was observed in the men's 50m freestyle (0.71 ± 0.04s) when the swimmers used a track start while the fastest average reaction time using a grab start in the men's events was 0.79 ± 0.04s in the 100m breaststroke. Similar results were observed in the women's events with the fastest reaction time observed in the 100m freestyle (0.73 ± 0.05s) using a track start and 0.82 ± 0.03s in the 50m and 100m freestyle as well as the 200m IM when using a grab start.

The differences between the Japanese swimmers and other finalists was also discussed (Ikuta et al., 2001) with results indicating that the Japanese swimmers were faster in the free swimming phase but were approximately 0.30s slower in the starts and 0.15s slower in the turns than the other finalists in those events. In the men's 100m butterfly the medallists were 0.08-0.48s faster in the start and 0.08-0.36s faster in the turn compared with the Japanese swimmer. The Japanese swimmer won the silver medal in the women's 100m backstroke and was 0.72s slower in the free swimming phase which was greater than the 0.34s difference between the first and second positions.

An attempt was made to normalise the stroke length parameters within swimming performances at the Sydney Olympic Games when compared with the height of the swimmer (Riewald, 2001). Analysis of the data found that the normalised stroke length (NSL) was not a better predictor of performance than the absolute values within the elite group of swimmers racing at this competition. Whilst the concept of normalising the stroke length data on the anthropometric measures of the swimmers is logical, the lack of significant results in this study may be due to the fact that the data was normalised for the height of the swimmer (that was reported by individuals rather than measured by the researcher) and did not take in to consideration the length of the arms.

Wilson et al. (2001) investigated the stroke efficiency (stroke length multiplied by velocity) measures in the freestyle events at the Sydney Olympics and their impact on performance. The mean data showed differing trends depending on the length of the race and assumed similar body shapes of the swimmers in each race. The efficiency index for the female freestyle events ranged from a mean of 3.50 ± 0.20 in the 50m event to 2.99 ± 0.19 in the 800m event. A similar trend was observed in the male events with higher indices in the shorter events (4.69 ± 0.33) through to lower indices in the longest event (3.82 ± 0.29) with the exception of the 200m event which was lower (3.91 ± 0.25) than the 400m (4.19 ± 0.33). Regression coefficients were then used to predict the effect of the efficiency index and stroke length on the velocity and race time in the freestyle events. The efficiency index was seen to be an indicator of swimming efficiency in the longer male races (6.4% in the 200m, 4.0% in the 400m and 3.4% in the 1500m) but did not show any relationship in the female races. As a result of the data from the Sydney Olympics, the authors noted that swimming efficiency was not found to be related to stroke length or velocity in the freestyle events.

2004 Olympic Games

Research of the competition data assessed the stroke rate variability of female semi-finalists in the 200m events at the 2004 Olympic Games and 2004 French National Championships (Hellard et al., 2008). Results from the analysis showed that stroke rates and stroke lengths were higher for the Olympic group of swimmers when compared to the French national level females. The change in stroke rates over the race were lower in the Olympic group in all events except for breaststroke where both groups of swimmers used a higher stroke rate in the second half of the race as presented in Table 2. 217 strokes were analysed in the backstroke and freestyle races and 73 strokes were analysed in the butterfly and breaststroke races. On average the National level swimmers had a stroke length that was 10cm shorter than the Olympic swimmers but they also had a smaller change in SL throughout the race in all events except for the butterfly.

Table 2 Changes in stroke rate (spm) and stroke length (m) between the first and second 100m of the female 200m events at the 2004 Olympics and French Nationals in all four strokes

		Butterfly	Backstroke	Breaststroke	Freestyle
Δ Stroke rate (spm)	Olympic	0.8 ± 1.3	0.3 ± 1.3	-1.3 ± 1.7	0.3 ± 1.0
	National	1.2 ± 1.5	1.3 ± 1.6	-1.0 ± 2.2	0.7 ± 1.4
Δ Stroke length (m)	Olympic	0.09 ± 0.04	0.07 ± 0.07	0.18 ± 0.07	0.08 ± 0.05
	National	0.11 ± 0.04	0.05 ± 0.08	0.17 ± 0.20	0.05 ± 0.06

A novel approach to competition analysis was proposed by Veiga et al. (2012) where individual distances were used to analyse swimming performances. Starts were measured from the gun until the swimmer's head broke the surface of the water after the underwater phase, turns were measured from the head position during the last hand entry until they surfaced after the underwater phase and the free swimming was the complete distance between these two variables in the 100m events. This method was in contrast to the more traditional fixed distances used by other analysis teams. Results found faster free swimming velocities using the individual distances method due to the shorter start and turn times. The differences observed between the types of analysis varied depending on the gender and the event with moderate to high correlations. Authors suggested using both methods of analysis for future competition analysis although this would mean that comparisons could not be made between swimmers at the same competition or for one swimmer racing at different competitions where they may have changed their underwater skills.

3.1.2 Skills

Starts

The starting performance of the finalists competing in the Sydney Olympic Games were examined from the starting signal through until the time where the swimmer's head reached the 15m distance from the wall (Cossor and Mason, 2001). The leave block times were positively correlated with the criterion measure (15m time) in the men's 100m butterfly (0.629) and 400m individual medley (IM) (0.928) as well as the women's 100m breaststroke events (0.711). The underwater phase of the start was significantly negatively correlated with all of the men's 100m events (ranging from -0.602 to -0.843), the 200m butterfly (-0.886) and 200m freestyle (-0.634) races. In the women's races the underwater phase was also significantly negatively correlated in the 100m backstroke (-0.894), 200m butterfly (-0.942), and breaststroke (-0.780) and freestyle (-0.653) events. Interpretation of the correlations show that the females who spent less time and travelled shorter distances in the flight phase of the 100m backstroke had slower start times to 15m. In contrast a greater flight distance in the 200m IM and 400m freestyle races resulted in faster starts.

Turns

Chow et al. (1984) monitored the performances of both male and female finalists in 19 individual events competing at the 1982 Commonwealth Games in Brisbane. Measures used to assess the turning performance were the time and distance in to the wall as well as the same parameters after the turning motion. Results indicated that the faster that the swimmers approached the turn then the further they were from the wall at the commencement of rotation. As the distance of the race increased the underwater distance off the wall decreased and males were faster than females in the majority of the turn parameters measured. Turning techniques employed in the breaststroke events were different to the other strokes with the more successful women spending more time and travelling further underwater than the less successful swimmers while the opposite trend was observed in the male breaststroke events.

The time that swimmers spent holding their breath during the turn in American competitions[6] was monitored by Craig (1986) and the results are displayed in Table 3. Values in the second data column represent the breath holding time as a percentage of the total race using the calculation:

[6] The majority of swimming competitions held in America are raced in yards rather than the traditional metres used during international competitions.

$$\frac{\text{Breath holding time}}{(\text{average time of the event/number of laps}) * 100}$$

Immediately after each swim gas samples were taken to determine the ability of the swimmer to spend more time under the water in the event. Results found no differences in the volume of oxygen uptake (VO_2) values where the swimmer had completed three or five turns, which authors interpreted the swimmers as having achieved steady state for O_2 utilisation and transportation. Conclusions indicated that there were no physiological stresses but there were biomechanical gains through faster rotation times and by spending more time under the water during the turning phase of the race.

Table 3 Time spent breath holding by males and females during Collegiate swimming competitions held in yard pools (Craig, 1986)

	Event	Average time (s)	% Lap/Lap time	Subjects
Males	500y Freestyle	4.39 ± 0.11	29	46
	200y Backstroke	3.03 ± 0.11	20	16
	200y Breaststroke	5.06 ± 0.15	29	21
	200y Butterfly	3.84 ± 0.19	22	13
Females	500y Freestyle	4.27 ± 0.09	24	60
	200y Backstroke	3.39 ± 0.16	16	18
	200y Breaststroke	5.25 ± 0.14	24	34
	200y Butterfly	3.65 ± 0.14	20	26

Analysis during the 2000 Olympic Games highlighted the fact that the fastest swimmers in the free swimming segments[7] were not necessarily the swimmers who had the fastest turn times (Mason and Cossor, 2001). The "out" turn time[8] was significantly correlated with the total turn time in the majority of events for both males (ranging from 0.76 in the 200m backstroke to 0.94 in the 200m breaststroke) and females (ranging from 0.77 in the 200m freestyle to 0.96 in the 100m butterfly). In the women's IM events, the time from the swimmer's head passing the 7.5m point into the wall until foot contact was significantly correlated with total turn time in the butterfly to backstroke turn (0.93) and freestyle turn (0.90). Those swimmers who travelled further and spent more time in the underwater phase of the turn showed faster total turn times in butterfly (-0.88 males and -0.74 females), backstroke (-0.83 males and -0.80 females) and the authors recommended utilising this phase within the FINA rules to improve swimming performance.

[7] Free swimming segments are those parts of the race that do not include a start, turn or finish.
[8] Out turn time refers to the period of time from wall contact (either hand or feet) to a fixed distance after the swimmer has left the wall and differs between research groups (e.g. 5m, 7.5m, 10m, 15m or head surfacing).

Stroking parameters

The link between competition analysis and its uses in the training environment were presented by Arellano, (2004), who also discussed ways in which the relevant race parameters could be monitored on a daily basis by coaches in training. Simple measures include: counting strokes during each lap as a measure of efficiency, using stopwatches to monitor stroke rate for comparisons with competition values and recording lap times as an indication of velocity. In competitions and elite performance pools different coloured markers are displayed on the lane ropes at regular intervals so that start and turn times could be easily measured by the coach in the key sets of the training session where the swimmer trains at speeds similar to competition values (1.8-2.2m/s).

The stroking characteristics in freestyle swimming were examined by Pelayo et al. (1996) who analysed the performances of 628 national and international level swimmers in competitions. Comparisons were made between the male and female events and were then normalised for height. The males were taller, faster and had longer stroke lengths than the females in all events. Anthropometric variables were the same for males irrespective of the event in which they competed while there was a tendency for the females to be taller (173.25 ± 6.10cm) in the shorter distance races compared with the longer races (168.80 ± 6.12cm).

Chollet et al. (1997) looked specifically at the stroking characteristics (SR, SL and velocity) in the 100m freestyle event for male swimmers both in a training and competitive situation. Results showed that the best predictor of swimming speed was the stroke length ($r=0.78$, $p<0.001$) and more successful swimmers were those who maintained stroking parameters and velocities throughout the race. These results were similar to those previously reported (Chengalur and Brown, 1992; Chollet et al., 1997; Craig et al., 1985; and Kennedy et al., 1990).

Competitive swimmers were examined by Craig and Pendergast (1979) and Craig et al. (1985) where the swimming velocity, stroke rate (SR), distance per stroke (DPS) and lap times were measured in freestyle events ranging from 100-500 yards. Many of the college competitions in the United States are raced in yards rather than metres, as were the early Olympic Games until 1924 where the standard 50m pool length was adopted with marked lanes. Results showed that fatigue, measured in increased lap times, affected the stroking parameter variables over the longer events and that females relied on higher stroke rates (10% in the freestyle events) for success, although they also tended to have shorter strokes (1.57 ± 0.04m) compared with the males (1.62 ± 0.03m).

When the performance of female French swimmers were examined in the 200m freestyle over a two year period it was noted that the improvements in race times (1.66 ± 0.92s) were as a result of increased stroke rate (42.98 ± 2.48 to 44.09 ± 1.84spm) without a corresponding significant change to stroke length (2.44 ± 0.12 to 2.41 ± 0.09m) (Huot-Marchand et al., 2005). Significant improvements ($p=0.05$) in velocity were seen in the first

¾ of the race (1.72 ± 0.06 to 1.74 ± 0.04m/s) and a higher stroke rate in the first half of the race (42.67 ± 2.73 to 44.45 ± 1.93spm) between the two major competitions. In their conclusion the authors noted that it was not possible to determine the effects of training on the performance over the two year period so future research should aim to include this information in the study.

Garland Fritzdorf et al. (2009) monitored the stroking parameters of an elite male breaststroke swimmer over seven competitions and introduced a parameter termed "effective work per stroke" (eWPS) that examined the relationship between stroke rate and velocity. The calculation for eWPS uses a ratio of the real values (Vi) and model values (Vm):

eWPS (%) = 100 (Vi – Vm/Vm)

The model assumed that throughout the range of stroke rates there was a constant eWPS. The effectiveness parameters declined with slower race times as well as fatigue at the end of each race, although this trend was not observed when analysing the performances of the top eight performers in the same event. It was concluded that this measure of effectiveness was an appropriate way to monitor performances of an individual as well as to be used when preparing future race strategies.

Comparisons of the kinematic variables (stroke length, stroke rate, stroke index, start time and turn time) within the men's 100m freestyle were made between elite Serbian, Russian and European swimmers at the 2012 European Championships (Durovic et al., 2012). One fixed video camera was positioned perpendicular to the pool so that all 8 lanes for the full 50m length could be viewed. The Swimwatch© software (www.swimwatch.nl) was used to determine the kinematic variables for every 25m segment of the race. Results indicated that the stroke length was the greatest contributing factor to race performance where a longer stroke length (1.145 ± 0.064) resulted in a faster race time (48.70 ± 0.323). These stroke length values represent the distance travelled for each arm rather than a complete stroke cycle as used in other research. Concurrently, the stroke index (stroke length x velocity) also showed significant differences between the groups (2.19 ± 0.15 European, 1.90 ± 0.16 National elite and 2.16 ± 0.20 Regional elite). The faster swimmers also travelled further (12.25 ± 0.96m European 11.26 ± 1.68m Regional) under the water and achieved a higher velocity (3.46 ± 0.33m/s European 3.03 0.39m/s Regional) during the start compared to the slower regional level swimmers.

3.1.3 Performance progressions

Studies have investigated performances of swimmers over a period of time in order to determine if there are trends in world leading performances (Anderson et al., 2008, 2006; Costa et al., 2010; Edelmann-Nusser et al., 2002; Fulton et al., 2009; Mujika et al., 2002; Pyne et al., 2004; Trewin et al., 2004). On average, it was noted that there is an approximate improvement of 1% in race performance both within a season and on an annual basis for the most successful swimmers as displayed in Table 4.

This trend was based on the entire group but personal experience has shown that there will be some swimmers who are able to achieve greater improvements than others on an annual basis if there is a significant change to their training regime. The within season competitions enabled performances from the trials event through until the major competition of the year such as the World Championships or Olympic Games to be examined. The period of time between these two competitions varied by nation and ranged from 4-20 weeks.

Table 4 Percentage difference in race times for Australian and USA swimmers competing in the 1999 Pan Pacific Championships, 2000 Olympic Trials and Olympic Games. Differences in performances within each competition from heats to semis and finals are also presented

	Pan Pacific to Trials	Trials to Olympics	Pan Pacific to Olympics	Heat to Semi	Semi to Final	Heat to Final
USA	0.8	0.2	1.0	0.5	0.6	1.1
Australia	0.2	0.6	0.8	0.8	0.6	1.3

Comparisons between the progression trends of 26 US and 25 Australian Olympic swimmers were monitored in a 12 month period leading into the Sydney Olympic Games (Pyne et al., 2004) where the mean improvement in performance (0.9%) was similar for both nations (1.0% for the Americans and 0.8% for the Australians). The authors concluded that more successful swimmers tended to enhance their performance by 1% within the competition and a further improvement of 0.4% would largely amplify their chance of winning a medal.

Stewart and Hopkins (2000) monitored the performances of swimmers both within two competitions and between the two competitions that were held 20 days apart. Results found that the swimmers were more likely to be successful in the same event with an average of 1.4% difference between the competitions (1.3-1.5% likely range of true value). When the distance of the stroke was examined there was a 1.7% variation (1.5-1.9% range) in the race times and the different strokes resulted in changes of 2.7% on average (2.3-3.1%). The authors noted that there was less variation in performance between competitions by the faster swimmers (1.1%, range 0.9-1.4%) compared to the slower swimmers (1.5%, range 1.3-1.9%) when comparing times in the same event.

In separate studies, 40 elite swimmers were monitored over a 3.6 year period using data from competition performances, anthropometric measures (age, height and weight for both genders) and incremental tests (step test[9]) within the training environment (Anderson et al., 2008, 2006). Results from the step test during the taper[10] period related to changes in performance at the competition with stroke rate at the blood lactate level of 4 $mmol.l^{-1}$

[9] Step tests are either 5x200m or 7x200m swims every 5 minutes with an increase in speed of approximately 3-5s for every repeat. Times, heart rate, stroke count, stroke rate and lactates are measured on each repeat.

[10] The taper period within training cycles is the time leading into a competition where the volume and intensity of work is decreased with the goal of enabling the body to recover and perform optimally. The length of the taper is individual and relates to the sex, age and experience of the athlete and tends to range between 4 and 28 days and varies throughout the career of an individual.

being the best predictor. Skinfolds[11] for females were shown to be the best single predictor (*r* = -0.53) on performance and it was the combination of a number of variables that enabled effective competition predictions to be made. Stroke rate at 4 mmol/L and peak lactate were the best combination in the taper phase for males ($r = 0.58 \pm 0.24$) while maximal 200m time and stroke rate at 4 mmol/L were the best combination for females ($r = 0.52 \pm 0.32$).

Recording of the annual progression in the performance of 477 swimmers were based on race times at the major competition for each year over a five year period have resulted in an average performance improvement of 4.48% in the 50m and 3.58% in the 100m freestyle events during this time (Costa et al., 2010). On average there were improvements of race time between 0.6-1% between seasons leading up to the Olympics and approximately 3-4% across all events in the five year period. Results for the year leading into the Olympic Games were also a good predictor of success for the Olympic medallists where 87% of the medallists were ranked in the top 10 in the world prior during the year leading to the Olympic Games (Trewin et al., 2004).

3.1.4 Race modelling

Many swimmers and coaches choose to examine the performances of their competitors in order to gain an advantage when they compete against them. Most people tend to follow the same race plan each time that they compete and race analysis allows strengths and weaknesses to be determined. Race models designed around the race plan contain information on the speed for each lap as well as the stroking parameters within each lap although Liu et al. (2012) did however warn against using previous data to predict future performances. The current models used to predict future performances included biomechanical and physiological factors but not how the body interacts with the environment and until these complex factors are considered it is not possible to accurately predict future performances.

Modelling of the performance of 19 competitions and training performances in the final 4 weeks prior to the events was used to predict the performance of a female swimmer competing at the 2000 Olympic Games (Edelmann-Nusser et al., 2002). The authors created a non-linear mathematical model using neural networks that included training within the aerobic threshold, aerobic endurance and anaerobic training zones in the pool as well as dryland strength and dryland conditioning sessions. The neural model created for the individual (2:12.59) was consistent with the final performance (2:12.64) with a difference of 0.05s with the predicted time. The authors suggested that linear regression analysis models have a tendency for greater error than the non-linear patterns matching supported by neural network models used in this research.

[11] Skinfolds are a measure of the subcutaneous fat at various sites around the body using skinfold callipers and a tape measure (Pyne et al., 2006).

Phillips (2010) used information presented by Doc Counsilman at an ASCA convention in order to determine the ideal splits for the swimmers in his squad. This appeared to work for all swimmers in all events but with the change to the swim suit rules in 2008, times became much faster than those noted previously. As a consequence, a number of races were analysed at the 2009 NCAA Championships where results showed that the previous formula (2nd 50m 2s slower than the first 50m with the 3rd and 4th 50's 3 s slower than the first) no longer applied. The algorithm was seen to be different for each stroke and distance but varied by ± 0.1s between the males and females. With the rules changing yet again for the start of 2010, Phillips noted that he would analyse the results from the 2010 NCAA Championships to see if the suits really did have an impact on swimmer splits. Arellano et al. (2001) also noted the lack of trends in race strategies of elite swimmers at the Sydney Olympic Games.

Robertson et al. (2009) conducted a large study on 3057 performances of swimmers who finished within the top 16 positions at various international competitions over a seven year period. The more successful performances were observed with a stronger middle segment (r = 0.85 in the second 100m and r = 0.91 in the third 100m) within the middle distance events. Successful performances in the sprint events tended to exhibit faster back end speeds[12] than the less successful swimmers (mean 0.64 in the 1st 50m and 0.81 in the 2nd 50m for the finalists and 0.49 in the 1st 50m and 0.65 in the 2nd 50m for the semi-finalists). The fastest 8 swimmers in each event exhibited improvements of 0.4-0.8% between the times in the heats and finals whereas the top 16 swimmers after the heats improved by 0.5-1.1% in the semi-finals depending on the event, stroke and gender of the athlete. The authors concluded that the more successful performances in future competitions would be based around improved times within the middle part of the race.

Mauger et al. (2012) examined the racing strategies of 264 swims by elite level swimmers competing in the 400m freestyle event at numerous competitions. Each of the 16 free swimming segments were compared as a percentage of the average race velocity and swims were then classified in to one of five pacing profiles: positive, fast-start-even, parabolic, negative and variable as described by Abbiss and Laursen (2008). Each of the pacing strategies relates to the velocity of the athlete throughout the race. When a swimmer gets faster throughout the event it is referred to as positive while the opposite strategy is referred to as negative. Fast-start-even strategy refers to high speeds at the commencement of the race and even speeds for the rest of the event. Where a swimmer starts fast then slows down in the middle of the race and picks up speed towards the end of the race it is known as a parabolic strategy and where there is no pattern it is known as a variable strategy. The time difference between the positive pacing and fast-start-even groups was 1.7s with the former group producing a performance that was on average 95.4 ± 2.19% of the world record while the latter group averaged 96.08 ± 2.12% of the world

[12] Back end speed refers to the time for the second half of the race, regardless of the distance.

record. There was a significant effect observed with respect to gender with the females able to swim closer to the world record on average when compared to the males. The most successful race strategy was achieved by starting the race quickly and then maintaining an even pacing for the rest of the race with the parabolic strategy more successful than the positive pacing technique.

Other researchers modelled the performances of the finalists competing in the Olympic Games from 1972-2008 in order to predict the performances in 2012 with highly accurate results when compared to the actual event times (Brammer et al., 2012). Means and standard deviations for the top 8 swims in each event were used to compute a best-fit power curve using the formula:

$\text{Time} = a \times \text{year}^{b}$

a and b were coefficients and the percentage difference between the actual and predicted times for each previous Olympic year was averaged for each event. The results of the modelling predicted improved race times within a 95% confidence interval in all events except the women's 100m breaststroke and the influence of the "high-tech" suits was noted by the authors.

Pacing strategies within the 200m and 400m Individual Medley (IM) of elite swimmers competing at 26 international competitions was assessed for the period 2000-2011 (Saavedra et al., 2012). Data presented in Tables 5 and 6 show that less time was spent in the butterfly leg of the event and the greatest percentage of race time is spent in the breaststroke leg for both males and females in both distances which were expected based on previous competition data. Differences in pacing were observed between the males and the females with the males utilising a positive strategy (faster butterfly and backstroke compared to breaststroke and freestyle) and the females employed a negative strategy (faster breaststroke and freestyle than the butterfly and backstroke segments). Further statistical analysis identified backstroke (r = 0.821 men and 0.777 women in the 200m IM and r = 0.806 men and 0.760 women in the 400m IM) as the stroke most highly correlated with final race time for the medallists.

Table 5 Average percentage of race time and standard deviation for each stroke in the 200m IM for finalists and medallists (Saavedra et al., 2012)

Stroke	Men 1-3	Men 4-8	Women 1-3	Women 4-8
Butterfly	21.72±0.35	21.53±0.35	21.78±0.40	21.64±0.40
Backstroke	25.30±0.56	25.36±0.48	25.47±0.44	25.50±0.55
Breaststroke	28.98±0.61	29.03±0.55	29.17±0.58	29.20±0.68
Freestyle	24.01±0.40	24.08±0.52	23.58±0.38	23.66±0.50

Table 6 Average percentage of race time and standard deviation for each stroke in the 400m IM for finalists and medallists (Saavedra et al., 2012)

Stroke	Men 1-3	Men 4-8	Women 1-3	Women 4-8
Butterfly	22.79±0.40	22.62±0.40	22.81±0.37	22.74±0.36
Backstroke	25.50±0.60	25.65±0.54	25.42±0.48	25.55±0.53
Breaststroke	28.45±0.50	28.55±0.62	29.86±0.63	28.90±0.66
Freestyle	23.26±0.42	23.17±0.47	22.90±0.32	22.81±0.41

Shimadzu et al. (2008) developed a stochastic model[13] to analyse the performance in the men's 200m freestyle at the 2004 Japanese National Championships with the results reported to be closely related to the actual race time. Each 50m lap was divided into three segments to examine the changes of individual swimmer's times as the swimmer passed each of the 21 points (0, 15, 20, 30, 45, 50, 57.5, 70, 80, 95, 100, 107.5, 120, 130, 145, 150, 157.5, 170, 180, 195 and 200m) within the race. The model resulted in a linear fit of the individual parameters as a function of the race time with the actual data for 31 of the 34 subjects within a 95% confidence limit. The authors suggested that the reason that the other three swimmers did not fit the model was due to the way that they swam the race and offered suggestions such as improved pacing and turn times to improve their performance. The model could be used by coaches to improve future performances of the swimmers by training them to fit the racing strategy created from the stochastic model.

The finalists in the 1500m freestyle at the 2008 US Olympic trials were analysed to determine the performances of elite male swimmers competing in distance events (Erdmann, 2008). Velocities were calculated for each lap except the first one where the influence of the start affected the lap time. The winner of the race showed an increase in velocity for each 500m segment of the race (1.682, 1.673 and 1.711 m/s) while the other competitors became progressively slower (1.661, 1.645 and 1.626m/s). Data was also presented comparing the world record (1.708, 1.704 and 1.708m/s) and the winner of the US Olympic trials (1.671, 1.691 and 1.706m/s). The authors suggested that swimmers intending to improve their performances in the 1500m freestyle event should practice suitable pacing strategies although with the data presented in the paper it appears that individuals have their own approach to pacing the event suggesting that the swimmers should work on their own strength and weaknesses.

Thompson et al. (2004) examined the impact of changing speeds on the stroking parameters and metabolism of swimmers in the 200m broken[14] breaststroke event. Nine male swimmers (23 ± 5 years, 1.80 ± 0.04m, 77.5 ± 6.9kg) were participants in the study that involved completing three 200m broken breaststroke swims at 98%, 100% and 102% of their

[13] Stochastic models use random variables within the mathematical calculations over a period of time.

[14] A swim can be divided into shorter segments so that the swimmer can practice the speeds required in a competition environment without tapering or wearing race suits. The rest between each of the repeats is also varied to enable the swimmer to achieve the target times.

best time (163.3 ± 14.0s) in a randomised order and 48 hours apart. The pacing was controlled using an audio device that bleeped as the swimmer was due to pass each 12.5m segment of the swim. Results showed that as the speed increased so did the stroke rate (31.3 ± 2.8 at 98% and 36.7 ± 4.0 spm at 102%) but it became ineffective during the latter stages of the 100% trial which resulted in changes to the pacing strategy.

3.2 Technology

A summary of research related to the technology used to monitor swimming performance both in competitions and training is presented in Figure 12.

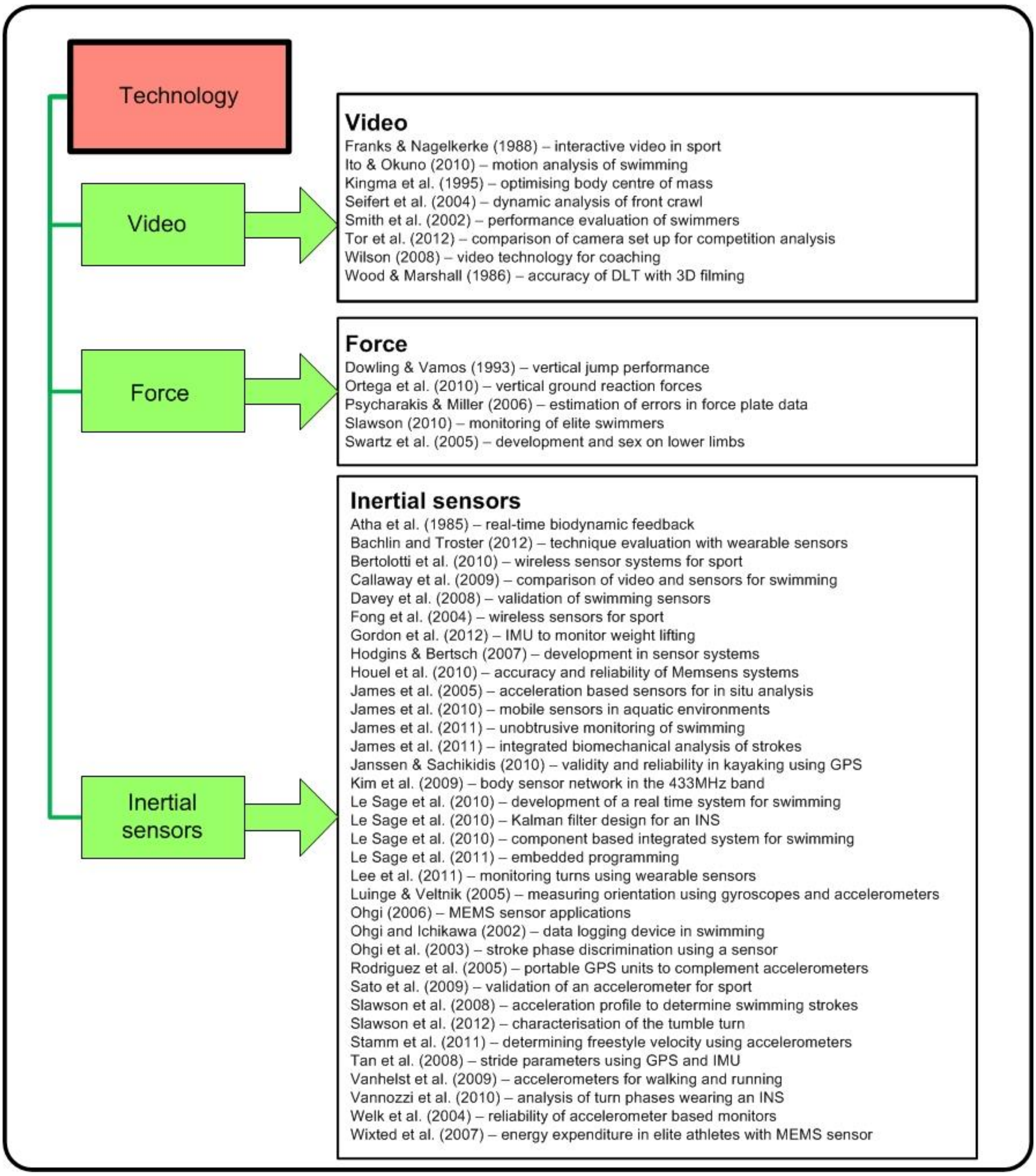


Figure 12: Technology used to monitor swimming performance

3.2.1 Video

The use of video systems is common in most research due to the availability, ease of use, immediate feedback mechanism and relatively low cost of approximately £500 (Wilson, 2008). Standard video cameras are typically operated at 25 frames per second (fps) in most countries except for the United States and parts of Japan, where they are operated at 30fps. Franks and Nagelkerke (1988), Kingma et al. (1995), Seifert et al. (2004) and Smith et al. (2002) have all used video technology to evaluate the performance of athletes. Within the sport of swimming Ito and Okuno (2010) combined video images from above the water and below the water to provide a more complete representation of the stroking characteristics throughout the free swimming phase.

Franks and Nagelkerke (1988) used a number of video cameras with synchronised images linked to specialised software and hardware in order to develop a system for analysing hockey. The use of 60Hz video cameras and pressure mats during lifting activities enabled researchers to estimate accurately the centre of mass of subjects when standing (Kingma et al., 1995). The greatest measurement errors when using the video cameras came from estimations in the masses and centre of masses of the segments rather than the digitisation of the video.

Wood and Marshall (1986) discussed the validity of extrapolating data from three dimensional filming to analyse performance and reported larger errors when analysing outside of the control point. Technology has developed rapidly so that the equipment used today is smaller, cheaper and easier to use (Wilson, 2008) than the equipment used in the previous studies.

The paper presented by Wilson (2008) was aimed at coaches and explained the improvements in camera technology such that they could be readily used for real time analysis in a training situation or as part of a computer software system for offline analysis. The author also noted that the frame rates required to capture the movement varied, depending on the sports and could be as low as 25Hz for swimming through to 200Hz for golf and cricket due to the speed of the movement within each of the sports.

Smith et al. (2002) discussed biomechanical (starting, turning, finishing and clean swimming speed), physiological (aerobic and anaerobic capacities, oxygen uptake and lactate levels) and psychological (anxiety, confidence, concentration and motivation) parameters that could be used to monitor swimmers and included the competition environment. Within the review it was noted that the initial phase of performance analysis should be the race parameters where video cameras are used to monitor the performance of the swimmers. It was suggested that this was now an indispensible tool for not only scientists but coaches, swimmers and even the media.

Competition analysis within swimming has been conducted by various groups around the world using different set ups and Tor et al. (2012) compared the accuracy of the analysis when using a single camera or a multi camera system. Whilst there were some differences noted in the measurement parameters (start time, average velocity, average stroke length, average stroke rate, turn time, in turn time and out turn time), the only meaningful statistical difference was noted for the first turn time. Using the single camera system the first turn time was 8.45s and it was 8.24s using the multi camera analysis system. Due to the low magnitude of differences between the swimming analysis systems, the authors concluded that the single camera analysis system was as accurate as the multiple camera system.

The timing of the phases within the freestyle stroke was measured using two underwater cameras operating at 50Hz from both a lateral and frontal view (Seifert et al., 2004). Information was collected on the swimming velocity, stroke length, stroke rate and the phases of the stroke that were described as: opposition (propulsive phase of one arm commences at the end of the propulsive phase of the opposite arm), catch-up (lag time between propulsive phases of the arms), or superposition. Results showed a change in the co-ordination patterns of the swimmer i.e. the relative timings of the stroke phases, when they reached the 1.8m/s velocity where there was a decrease in stroke length and increase in stroke rate. The proportion of the propulsive phases increased at the higher speeds due to a decrease in the entry and catch phases with the pull phase being the greatest phase.

3.2.2 Force

The inclusion of force platforms within swimming research allows for kinetic analysis but currently is limited to starts and turns and will be discussed further in the skill specific sections of the literature review. Early research used single axis force data to measure performance (Dowling and Vamos, 1993) but most of the current research employs tri-axial data (Slawson, 2010).

Dowling and Vamos (1993) measured 97 adults performing a maximal vertical jump to determine variables that resulted in good jumping performance. Vertical forces were measured at a sample rate of 100Hz and the centre of mass was used to calculate power by multiplying the vertical velocity of the centre of gravity by the vertical force. The top three independent variables that were significantly correlated with jump height, at the p level of 0.01, were maximum force (0.519), maximum positive power (0.928), and ratio of negative impulse to positive impulse (-0.514). Results of the study showed that there was too much variability between subjects from the force-time curves and velocity (14.7%) however peak power (Watts/BW) and vertical jumping ability were strongly correlated as presented in a scattergram but not correlation values were noted in the paper.

Psycharakis and Miller (2006) noted that a number of biomechanical research studies within the sporting domain use force platforms but do not report any potential errors in the equipment. The researchers designed a number of tests to measure the potential errors for cross-talk, hysteresis, linearity and frequency ratio[15] using one subject performing drop jumps in addition to the application of known weights onto the force platform. Results indicated a combined maximum potential error of 8.17% within the data even though each individual component was within the acceptable ranges (3.16% for nonlinearity and 5.01% for hysteresis) (Bartlett, 1997; Dainty and Norman, 1987).

Vertical forces were measured during landing techniques of athletic children and adults (Swartz et al., 2005). The group chose to report normalised data as Newton/joules (N/J) for peak ground reaction forces to allow for differences in body anthropometries.

$$\frac{N}{J} = \frac{VGRF}{\frac{1}{2} mv^2}$$

where N was Newtons of vertical force, v was the instantaneous velocity of the centre of mass measured in m/s and m was the mass of the subject measured in kg. The average peak vertical forces shown by the children in the group were 8.23 ± 2.58NJ and 4.93 ± 1.44NJ for adults when landing on their self selected dominant leg. Through the analysis of the single axis force data, the researchers found significant differences in landing techniques when measuring hip and knee angles, between children and adults, although gender was not a factor for the biomechanical measures within the study.

A study investigating the bilateral landings and jump heights of 30 adult male footballers (27.41 ± 3.99 years, 1.75 ± 0.07m and 76.62 ± 4.77kg) found peak forces of 2.58 body weights (BW) for the first peak force phase and 9.92BW for the second peak force phase in counter movement jumps (Ortega et al., 2010). These values were higher than the second peak values reported by Abián et al. (2008) with 7.51 ± 2.38BW but the authors suggested that this was due to the lower skill level of the subjects. The best of the five trials performed on a single axis force platform (500Hz sampling frequency) were analysed using the Quattro Jump© software (*Kistler Quattro jump software*, n.d.).

3.2.3 Inertial sensors

Sensors monitoring acceleration have been tested for reliability (Davey et al., 2008; Houel et al., 2010c; Sato et al., 2009; Welk et al., 2004; Vanhelst et al., 2009) as well as for use within sport (Bertolotti et al., 2010; Fong et al., 2004; Gordon et al., 2012; James et al., 2005; Ohgi, 2006; Tan et al., 2008; Vanhelst et al., 2009; Vannozzi et al., 2010; Wixted et al., 2007). Micro sensor technology has also been used within the health and medical sectors (Hodgins and Bertsch, 2007; Kim et al., 2009; Luinge and Veltink, 2005; Rodríguez et al., 2005). An initial attempt to use external devices to monitor swimming was discussed by Atha et al. (1985) where the flow of water was measured and auditory feedback was provided real time to the swimmer via an ear plug, and the development of inertial sensors for use within

[15] The ratio between the natural frequency of the platform and the maximum frequency of interest in the signal and was measured by striking an iron pipe on the platform 10 times.

aquatic environments was discussed by James et al. (2010) and Janssen and Sachlikidis (2010).

Swimming specific research using inertial sensors has discriminated between the various phases within a stroke (Callaway et al., 2009; Le Sage et al., 2011b, 2010a; Ohgi et al., 2003) as well as monitoring of the skill phases (Le Sage et al., 2010b, 2010c; Lee et al., 2011; Slawson et al., 2012). It was possible to differentiate between the strokes of butterfly, backstroke, breaststroke and freestyle through the patterns of the acceleration traces (Davey et al., 2008; Le Sage et al., 2010a; Slawson et al., 2008).

Ohgi et al. (2003) attached an inertial sensor containing a tri-axial accelerometer on the wrist of a male and female swimmer to examine the various phases of the stroke within breaststroke. These included the: outsweep[16], insweep[17] and recovery[18] phases as described by Maglischo (2003). The discrimination of the various phases of breaststroke was more successful than earlier studies (Ohgi and Ichikawa, 2002) due to the smaller packaging that allowed the weight of the sensor to be reduced from 78 to 50g.

The majority of the inertial sensor systems within swimming are able to store the information but the system developed by Le Sage et al. (2010a) also allowed for real time wireless transmission of the data to a laptop located on poolside. This information could then be fed back to the coaches so that changes may be recommended on the stroke or skill mechanics within a training session. Early indications by Le Sage et al. (2010c) suggested that the use of these sensors, located on the small of the back, enabled real-time accurate information on the number of strokes, stroke rates, number of kicks and kick rates as well as the change in position of the body through the skills of starts and turns to be derived.

James et al. (2011a & b) described the development of monitoring systems specific to the swimming environment that were based around tri-axial inertial sensors mounted on the wrist and ankle. Initial monitoring examined lap times, starts and turn segments through the use of a single sensor but it was noted that it was possible to monitor the phases of the stroke through the use of multiple sensors. The authors noted that the ability to monitor multiple body segments for longer periods of time would identify levels of fatigue through changes to the co-ordination of the stroke. Future work targeted enhancing the radio communication of the sensors for real time analysis along with the development of infrastructure to enable synchronisation and processing of all sensors simultaneously.

Another portable sensor incorporating tri-axial accelerometers was developed to monitor the movement of the swimmers and provide the coach with training information (Stamm et al., 2011). The equipment used to monitor the swimming performance included the small

[16] Outsweep is the period of time from full arm extension in the breaststroke through the catch and until they reach the widest point of the arm stroke

[17] The insweep in breaststroke is defined as the hands and arms squeezing together underneath the body

[18] The recovery is the period of time after the insweep as the hands and arms extend forward back to the fully extended position

tri-axial inertial sensor, a cable based velocity meter attached to the swimmer's suit and a video camera. Data showed that it was possible to monitor the velocity of a swimmer from the acceleration profiles of the inertial sensor but that there was a large difference in these values (± 15.6% for the forward direction integration and ± 12.6% for the total acceleration velocity integration) when compared to the velocity meter (± 8.9%) data due to the difficulty of analysing acceleration data to integrate for velocity and positive profiles. Any offsets in acceleration data will lead to linear (velocity) and quadratic (position) errors.

An entire swimming monitoring system is being developed by Bachlin and Tröster (2012) that consists of both a recording and monitoring device. The *SwimMaster©* system (*SwimMaster*, n.d.) includes inertial sensors, weighing 34g, attached to the left and right wrists as well as the upper and lower back. Feedback will be provided to the swimmers through both an acoustic and visual sensors when the system is further developed. The algorithms have been developed and validated to evaluate the velocity, body rotation and balance as well as the stroking parameters of the swimmer. The only reported errors were 20% between the visual and sensor data for body roll. Authors of the paper envisioned swimsuits with integrated sensors for real time feedback to the swimmers on their technique.

3.3 Training

Swimming research within the daily training environment has focused on three main areas: starts, turns and techniques (Figure 13). Research within the area of technique has been divided into: drag/propulsion, jumping/power, specific strokes, body position and kick/pull.

Many of the research groups work with younger athletes so that there are greater subject numbers available for statistical analysis (Blanksby et al., 2004; Blanksby et al., 1998; Blitvich et al., 2000; Cossor et al., 1999; Elias et al., 1998; Galbraith et al., 2008; Hardt et al., 2009; Prins and Patz, 2006) but the current research was targeted at the elite level of swimmers within Great Britain. An overview of the swimming literature was conducted by Barbosa et al. (2010) who presented the current interaction between biomechanics, physiology and performance in competitive swimming.

3.3.1 Starts

The analysis of the start within swimming has been comprehensive with research conducted on the different types of starts including the grab, track and swing techniques (Agnesina et al., 2006; Arellano et al., 2005; Blanksby et al., 2002; Burkett et al., 2010; Elipot et al., 2009; Galbraith et al., 2008; Guimaraes and Hay, 1985; Houel et al., 2006; Jorgic et al., 2010; Kruger et al., 2003; Miller et al., 2003; Taiar et al., 2006; Takeda and Nomura, 2006). Other researchers have investigated swimming starts for each of the different strokes (Seifert et al., 2007b; Vantorre et al., 2010) as well as techniques to minimise potential injuries (Blitvich et al., 2000, 1999; Cornett et al., 2011; Hardt et al., 2010). Figure 14 illustrates the range of research and analyses that have been conducted on the starting technique within swimming.

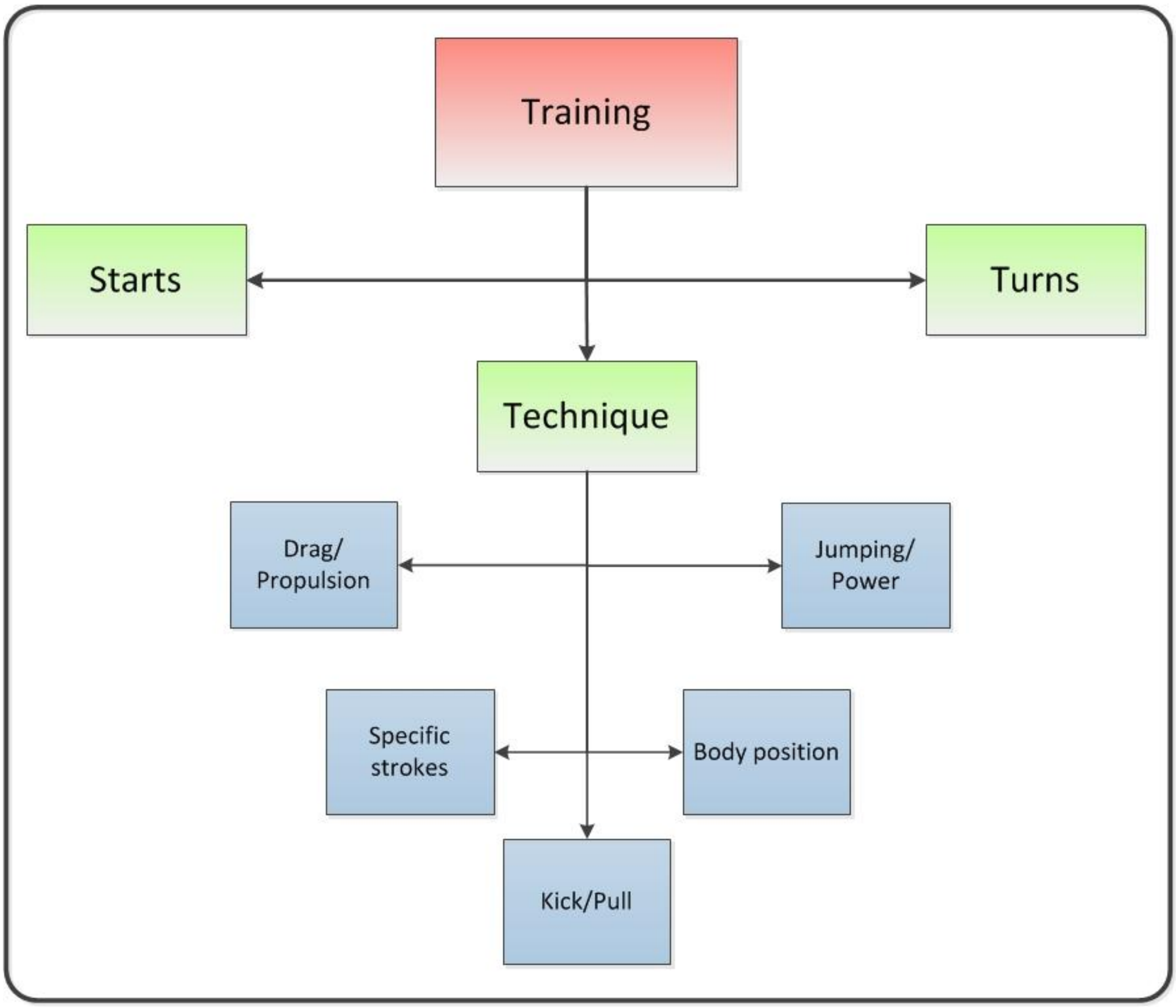


Figure 13: Summary of literature review in the area of training

A number of people have reviewed the changes in starting technique as the block design and technology has evolved (Kibele et al., 2005; Lyttle and Benjanuvatra, n.d.; Mason, 1997; Ruschel et al., 2007; Sanders and Bonnar, n.d.; Schnabel and Kuchler, 1998). Arellano et al. (2000), Cossor et al. (2010) and Slawson et al. (2010) all used a multi components approach to their analysis of the starting technique via integrated force, video, wireless sensors and light emitting diodes (LEDs) video markers within the systems.

Kinetic analysis

Starts within swimming comprise of a number of different phases including the block, flight and underwater phases. Researchers have elected to monitor these phases specifically to determine the impact on starting performance through to the 15m distance from the block.

Hinrichs (2006) reviewed the forces on the block in both grab and track starts and the effect of symmetry. The idea of bilateral deficit (difference between the two legs pushing together compared to the sum of two unilateral pushes) was discussed where the sum of two unilateral forces was greater than a simultaneous effort and was the hypothetical basis for the theory that track starts produced greater forces than the grab starts.

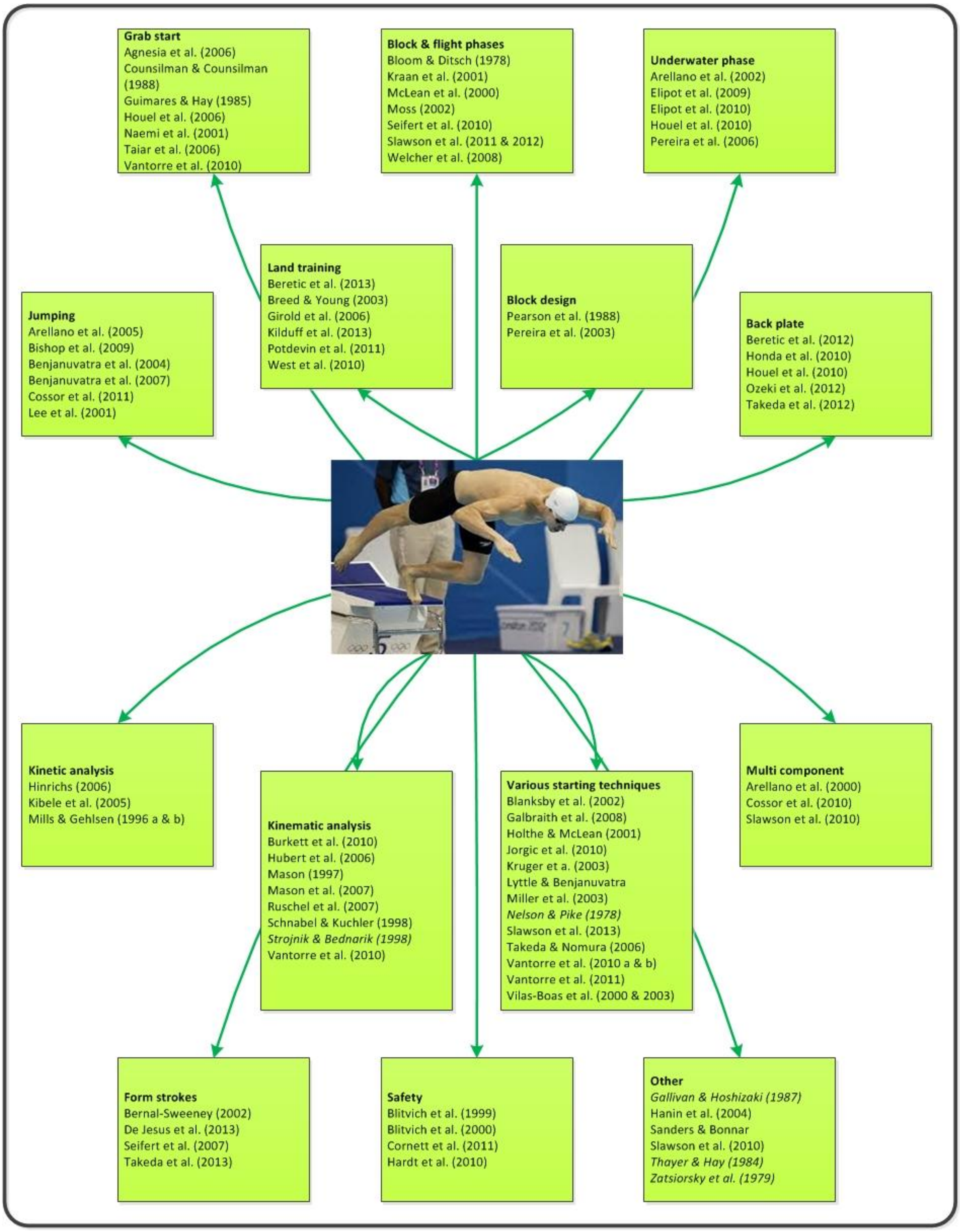


Figure 14: Various forms of research conducted on swimming starts

Block and flight phase

The technique during the block phase was discussed by Kraan et al. (2001) who found that a backwards step prior to the traditional starting motion resulted in higher push-off forces (537.4 ± 104.1 compared to 264.7 ± 55.1N) that occurred sooner (0.268 ± 0.052 and 0.776 ± 0.201s) than the start with no backwards step. Despite the potential advantage when using this technique, this type of start has not been used within a competition environment. Moss (2002) recommended pulling on the front of the block for a more effective start in order to maximise the propulsive ability of the arms prior to the leg movement.

Seifert et al. (2010) looked at the flight phase of the start of 11 elite male sprinters using their preferred starting technique (grab). Block, flight and entry times were measured as well as the takeoff and entry angles before the group was divided into groups based on the use of a piked or flat style of start. No differences were observed for the time to reach 15m after the starting signal and the authors noted that it is important to minimise the decrease in velocity after entering the water.

A summary of the results measured in the start research is noted in Table 7 including the information on the type of style used, takeoff angle, entry distance and angle, block time, flight time and level of swimmer.

Block design

Pereira et al. (2003) looked at the influence of the height and angle of the starting block which was highly relevant to the changes seen in the current starting block design. Their study only used three subjects but the average data for all swimmers showed that the fastest start to 15m was 0.75m above the surface of the water with a slope of 10° when compared to 0.50m heights and no slope on the block.

Underwater phase

Pereira et al. (2006) measured the underwater phase and Takeda et al. (2009) investigated the velocity during the transition between the underwater and stroking phases of the start.

Back plate (wedge)

Researchers have been investigating the mechanics of the swimming start using the OSB11 block in order to determine the differences in technique to the more traditional track start (Cossor et al., 2010; Honda et al., 2010; Houel et al., 2010a; Slawson, 2010).

Land based starts

With the introduction of the rear wedge on the starting block, there was no information within swimming to use so research into other sporting starts was investigated (Figure 15). Hunter et al. (2004) and Estevan et al. (2013) examined the influence of the stance limb specifically whilst Ben Mansour et al. (2007), Ito et al. (1992) and Kugler & Janshen (2010) took a more holistic approach to the body components and their influence on starting performance. Greene (1986) used regression equations to predict start performance in athletics using stride parameters with timing information within a sprint event.

Table 7 Summary of data on swimming start research

Study	Level	Start style	Takeoff angle (°)	Takeoff position	Entry dist. (m)	Entry angle (°)	Block time (s)	Flight time (s)
Arellano et al (2000)	Elite	Preferred	.-3.26 ± 8.55	CoM off block			0.85 ± 0.11	0.39 ± 0.15
Blanksby et al (2002)	National	Grab			3.23 ± 0.30		0.86 ± 0.07	0.32 ± 0.07
		Track			2.73 ± 1.25		0.88 ± 0.08	0.30 ± 0.04
		Handle			3.01 ± 0.31		0.85 ± 0.04	0.24 ± 0.07
Burkett et al (2010)	Olympic	Preferred			3.17 ± 0.48		0.77 ± 0.05	0.6 ± 0.05
Galbraith et al (2008)	National	Track	4.0 ± 2.3	Hip to horizontal			0.67 ± 0.07	0.30 ± 0.08
		One-handed	2.7 ± 2.2	Hip to horizontal			0.69 ± 0.08	0.34 ± 0.06
Guimaraes and Hay (1985)	High school	Grab	75.8 ± 9.20	CoM takeoff to entry				
Houel et al (2006)	National	Track	-5.26	CoM to horizontal				
Jorgic et al (2010)	Cadets	Grab	33.67 ± 5.69	CoM to horizontal	3.21 ± 0.17	33.33 ± 5.13		0.33 ± 0.10
		Track	23.33 ± 1.53	CoM to horizontal	2.98 ± 0.13	29.33 ± 5.51		0.23 ± 0.03
Kruger et al (2003)	National	Grab	31.5	Undefined			0.91 ± 0.14	0.33 ± 0.05
		Track	32.5	Undefined			0.91 ± 0.10	0.34 ± 0.08
Lyttle and Benjanuvatra (n.d.)	Varied		-0.5 to 45	CoM off block		30-40		
Maglischo (2003)	Varied		30-40	Suggested	3 to 4			0.3-0.4
Miller et al (2003)	University	Grab	6.23 ± 1.55	Body to horizontal	3.31 ± 0.12	.-39.54 ± 2.64	0.95 ± 0.04	0.25 ± 0.04
		Track	7.04 ± 1.03	Body to horizontal	3.17 ± 0.15	.-41.47 ± 1.87	0.94 ± 0.04	0.25 ± 0.04
Ruschel et al (2007)	National/State	Preferred			2.97 ± 0.12	32.51 ± 6.24	0.85 ± 0.06	0.34 ± 0.03
Seifert et al (2010)	Elite	Grab	24 ± 5.5	Hip to horizontal	3.79 ± 0.34	37.1 ± 3.8	0.84 ± 0.06	0.31 ± 0.06
Takeda and Nomura (2006)	University	Grab	24.7 ± 3.7	CG to horizontal	3.25 ± 0.2			
		Track	33.4 ± 1.4	CG to horizontal	3.15 ± 0.10			
Welcher et al (2008)	University females	Grab					0.87 ± 0.05	0.34 ± 0.04
		Track front					0.80 ± 0.06	0.31 ± 0.06
		Track rear					0.87 ± 0.08	0.33 ± 0.08

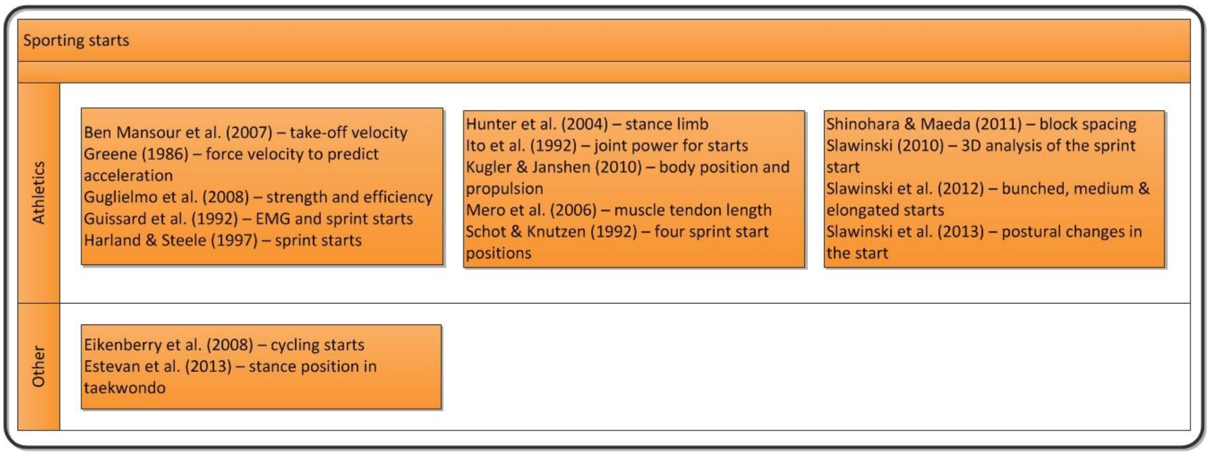


Figure 15: Start analysis in athletics, cycling and taekwondo

Starting techniques were also discussed for cycling (Eikenberry et al., 2008) where 10 experienced and 10 inexperienced cyclists were tested for pedal asymmetries by completing track and field starts. 18 of the 20 subjects showed significant asymmetries between the legs while there was no correlation between footedness and stance preference. Results also showed faster reaction times when the left leg was at the rear of the block while faster movement and overall response times were faster with the right leg placed in the rear.

Guissard et al. (1992) monitored the lower limb muscle activity using electromyography (EMG) when the angle of the foot plate surface and the horizontal was changed between 30, 50 and 70° and noted that decreasing the angle of the plate resulted in faster starting velocities without any increase in the time of the pushing phase or EMG activity. Mero et al. (2006) also adapted the block angle and found greater horizontal vertical velocity of the centre of mass as the subject left the block when the angle was set to 40° (3.39 ± 0.23m/s) compared with a block angle of 65° (3.30 ± 0.21m/s).

Block spacing was monitored (Harland and Steele, 1997; Schot and Knutzen, 1992; Shinohara and Maeda, 2011; Slawinski et al., 2012) with a preference towards the medium stance position reported by Harland and Steele (1997). Schot and Knutzen (1992) tested 12 experienced collegiate sprinters and found better horizontal displacement, propelling impulse and average velocity when the starts were performed in the elongated position. The forward lean stance on the block increased the vertical velocity when leaving the blocks. The elongated stance position for 9 well trained sprinters produced higher velocities of the centre of mass when leaving the blocks (Slawinski et al., 2012). The kinetic energy was also greatest in the elongated position (324.3 ± 48.0J) compared with the bunched (317.4 ± 57.2J) and medium (302.1 ± 53.2J) positions with the suggestion that this was attributed to faster head and trunk movements.

Shinohara and Maeda (2011) tested 18 different block positions for track and field starts and found no differences in the impulses or forces applied to the ground on the first step. As the distance between the two plates increased the magnitude of impulse applied to the front block decreased and an increase was observed in the rear plate. Slawinski et al. (2013) also examined the relationship between spacing and angular velocity of joints for both upper and lower limbs with higher velocities observed with smaller distances between the blocks. Having noted this, the authors suggested that a medium stance resulted in a faster pushing time and optimal joint velocities.

The kinetic energy of eight elite sprinters was calculated for both upper and lower limbs when completing four maximal 10m athletic sprint starts (Slawinski et al., 2010). Authors suggested that improved starting performances could be achieved by greater synchronisation between the arms and legs during the push phase of the start.

3.3.2 Turns

A review of the current literature highlights that there are fewer studies investigating the swimming turn compared to those examining the starting technique. This is despite suggestions that improvements to turning technique can reduce lap times by as much as 0.20s per lap (Maglischo, 2003). The percentage of race time spent turning varies depending on the stroke, length of the race and the length of the pool but can account for as much as 33% (Thayer and Hay, 1984) to 38% (Maglischo, 1993) of the race time in short course (25m) events.

Figure 16 identifies the areas of swimming turn research that have been investigated to date. As was observed in the start literature review, turns have been investigated for each of the strokes including butterfly (Kishimoto et al., 2010; Lyttle and Mason, 1997; Tourny-Chollet et al., 2001), backstroke (Blanksby et al., 2004), breaststroke (Blanksby et al., 1998; Kishimoto et al., 2010; Mills, 2006) and freestyle (Cossor et al., 1999; Lyttle et al., 1999; Lyttle and Mason, 1997; Mills, 2007; Pipes-Neilsen, 2007; Prins & Patz, 2006; Slawson et al., 2010; Slawson et al., 2010). These studies used different levels of swimmers who showed different techniques throughout the turn and it is these styles that need to be investigated further.

Lyttle and Benjanuvatra (2007) reviewed the literature on swimming turns and described each of the phases including the approach, rotation, and wall contact, glide and stroke preparation phases. In summary, they noted that swimmers should maintain their velocity during the approach phase, not rotate too close to the wall, contact with the feet 30-40cm below the surface of the water and that the body should remain streamlined at approximately 50cm underwater to reduce the impact of wave drag.

Performances of freestyle turns by age group and collegiate swimmers were monitored using both video cameras and a single axis force platform (Blanksby et al., 1996, 1995; Cossor et al., 1999; Nicol and Kruger, 1979; Takahashi et al., 1983). The benefits of including a force platform to measure turning performances were noted by Pereira et al. (2006). Variables reported include the peak force, impulse and wall contact time.

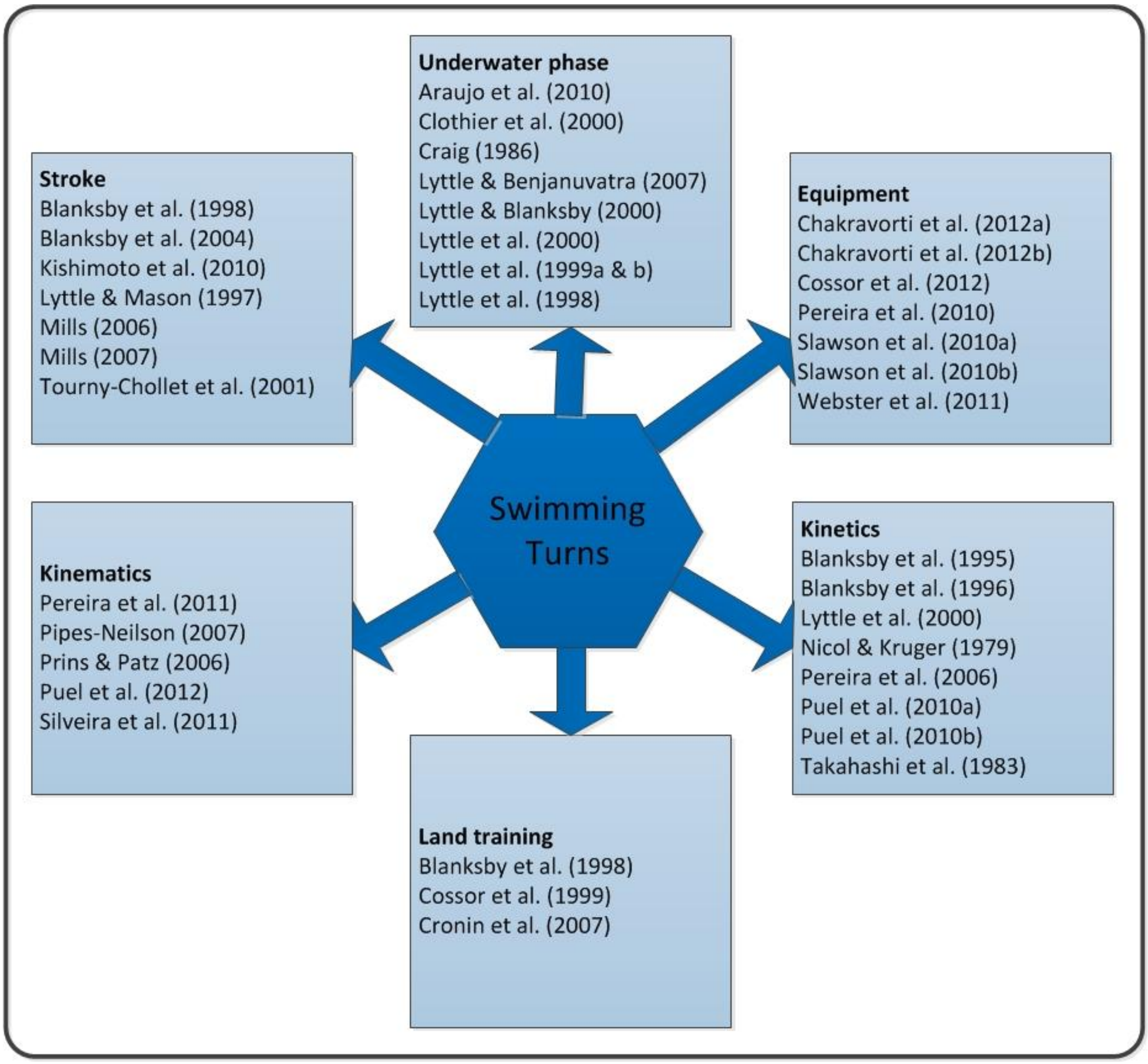


Figure 16: Research literature into swimming turns

Kinematic analysis

The mechanics used during swimming turns has been discussed by numerous researchers (Pereira et al., 2011; Pipes-Neilsen, 2007; Prins and Patz, 2006; Puel et al., 2012; Silveira et al., 2011) with the kinematic variables summarised in Table 8. Seventeen swimmers performed three trials in each of four different turning techniques where the rolling, wall contact, push, glide and total turn times were monitored (Pereira et al., 2011). Results showed no differences between the turning techniques. Two major techniques used when contacting the wall include a rotation of the feet to the side or to contact with the toes pointing towards the surface of the water (Pipes-Neilsen, 2007).

Puel et al., (2010a, 2010b, 2012) performed 3D analysis of swimmers performing one freestyle turn for each of the 8 females with the inclusion of a force platform. The head was used to measure distance and velocity variables. No correlations were observed between the criterion measure and the maximum speeds or impulse. This group of swimmers had a high velocity approaching the wall and had an average glide time of 0.28 ± 0.08s after leaving the wall.

Table 8 Kinematic variables measured in swimming turn research

Authors	Subjects	Level	Age (years)	Weight (kg)	Height (m)	Turn distance (m)	Wall contact (s)
Pereira et al. (2011)	9 males 8 females	National	17.9 ± 3.2	64.5 ± 11.9	1.73 ± 0.09		
Prins & Patz (2006)	12 males 11 females	Collegiate	19 - 25				0.28
Puel et al. (2010a & b, 2012)	8 females	National	22.3 ± 4.1	62.2 ± 6.2	1.75 ± 0.06	3m RTT	0.34 ± 0.04
Silveira et al. (2011)	6 males 5 females	Sprinters	16 ± 3	63.4 ± 8.9	1.82 ± 0.08	5m RTT 7.5m RTT	0.32 ± 0.08

Twenty-three University swimmers were the subjects used to monitor the wall contact phase during turns in a short course pool (Prins and Patz, 2006). The push off velocity was measured during the first 60cm after the swimmer left the wall with an average 2.47m/s within the group. Foot plant index[19] average within the group was 0.45 although there was no significant relationship between this and the push-off velocity. Tuck index was the only variable to be significantly related to push off velocity with swimmers rotating closer to the wall having higher push off velocities. The wall contact time averaged 0.28s and was also divided into active and non-active phases but neither was related to push-off velocities within the research group. Prins and Patz (2006) suggested turning closer to the wall for more successful performances when measuring turns 5m in to the wall and back to the same point.

Underwater phase

With a large percentage of race time spent in the underwater phase of the turn in short course races, Craig (1986) measured the times that swimmers held their breath during a turn in competition and then compared this to the simulated experiments within training where the expired air of eight collegiate swimmers was examined. During competition it was found that the average breath holding times for men ranged from 3.03s (200 yard backstroke) to 5.08s (200 yard breaststroke). Values were slightly lower than those measured in the women's events with a range of 3.39s (200 yard backstroke) to 5.25s (200 yard breaststroke). This research was performed prior to the introduction of UUS and the change to the FINA rules of maximum distances prior to surfacing in swimming events. The

[19] Foot plant index measures the depth of the feet during the wall contact phase in relation to the height of the swimmer. For example, the foot plant index of 0.45 means that the depth of the feet on the wall was 45% of the swimmer's height beneath the surface of the water.

results showed no differences after the 3 turn and 5 turn testing conditions which the authors explained as the swimmers having achieved a steady state of oxygen utilisation and transport. It was also suggested that there would be no detriment to maximising the underwater phase of the turn from a physiological perspective if turns lasted less than 6.50s.

Araujo et al. (2010) investigated the wall contact phase of 34 swimmers performing freestyle turns. Their ability ranged from state to international level competitors and the variables measured included the knee angle on the wall, 15m total turn time (7.5m in and out) as well as the peak force, impulse and contact time. An underwater force platform capturing at 800Hz protruded 20cm from the wall so markings along the bottom of the pool were adjusted for the swimmers. Each swimmer performed eight turns with 12 minutes rest between each to enable complete recovery. The fastest and slowest trials were excluded from the analysis although the authors did note that freestyle was not the preferred stroke for all subjects used in the research. Due to the age, stroke and skill level within the group, values in each of the parameters ranged greatly. Wall contact times ranged from 0.11-0.70s with an average of 0.41s while peak vertical forces varied between 0.61-2.78 and average of 1.42 body weights. Regression analysis suggested that peak vertical force (perpendicular to the force platform) normalised for body weight, as well as impulse, had the greatest contributing factors towards improved turning performance. The authors suggested that a knee angle between 100-120° was optimal for peak forces and fast RTTs. Correlations showed that the higher peak forces were registered when the wall contact time was decreased and that a knee angle of 100-120° was optimal for peak forces. Peak forces ranged from 0.61BW to 2.78BW with a mean of 1.42BW. The average wall contact time for the group was 0.41 ± 0.11s and the average knee flexion was 78.9 ± 23.5°.

The drive off the wall is the phase in which power can be developed to enable the swimmer to travel through the water more quickly. Various studies have investigated the underwater phase after the wall contact phase to ensure that this velocity was maintained for as long as possible (Lyttle and Benjanuvatra, 2007; Lyttle and Blanksby, 2000; Lyttle et al., 1999a; Lyttle et al., 1999b; Lyttle et al., 2000, 1998). Correlations between peak velocities during the drive phase and the head depth indicated that the swimmers should be 0.40 ± 0.06m beneath the surface of the water (Puel et al., 2010b).

Hydrodynamic drag was included in the research on swimming turns by Lyttle et al. (1999) due to the fact that drag increases exponentially with the increase in swimming velocity (Rushall et al., 1994). Thirty adult male experienced swimmers were used in the study with similar anthropometric values to ensure that measurements in drag were not influenced by body shape. Only the time spent pushing off the wall was monitored in the wall contact phase and commenced when the hip moved forward. The fastest 5m RTT of the three trials conducted by each swimmer was used in the analysis of the freestyle turn and glide action. Centre of gravity (CG) was calculated through two dimensional analysis and used with the mass, acceleration and propulsive force measured on the force platform to determine the drag profile at 0.17s intervals. Only the propulsive phase of the wall contact was used as part of the analysis which represented 67.5 ± 15.2% of the total wall contact time. In contrast to the research by Araujo et al. (2010) impulse was not significant in the final regression model using a linear fit while the wall push off time was. Within the group of elite male swimmers tested peak drag force, peak propulsive force and the push off time were the three variables associated with an improved push-off velocity. A gradual development of force such that the peak force is close to the time when the feet leave the wall, with the body in a streamlined position, was proposed as a more effective swimming turn.

The optimal glide path during the turn was determined after towing 40 swimmers of similar anthropometric parameters (Lyttle et al., 1999). The passive tows were completed at speeds ranging from 1.6-3.1m/s and at depths of 0.2, 0.4 and 0.6m below the surface of the water. Multiple linear regressions were used to determine glide velocity-depth relationships from the passive drag values and this information was then used to calculate the drag force for glide depth and velocity. Results of these data suggested that swimmers should leave the wall 0.4m from the surface of the water for 0.5m and then use a gradual ascent for a further 0.5m before commencing stroking. This research did not examine the effects of kicking during the underwater phase and should be used in future work.

In the study by Lyttle et al. (2000), sixteen male swimmers with similar anthropometry were towed at speeds similar to those observed at various stages within competitions (1.6, 1.9, 2.2, 2.5 and 3.1m/s). At each speed, swimmers performed either kick (freestyle and dolphin) or streamlined glide positions (prone and lateral) to monitor differences in the underwater phase of the turn. Results indicated that the streamlined position is important for minimising the impact of drag on the body as it moves through the water and that the optimal velocity for the timing of the first kick is between 1.9m/s and 2.2m/s. The transition from the underwater to free swimming phases was discussed by Clothier et al., (2000) after both dolphin and flutter kicking techniques.

Strokes

With the technique varying significantly between each of the strokes, researchers have investigated them independently. Butterfly turns were examined by Tourny-Chollet et al. (2001) to determine if the swimming speed was related to the wall contact time and if there were any differences in technique between the European champion and other swimmers in the same event. Analysis during a French national level competition in the 200m butterfly found significant differences between the fast and slow swimmers, particularly during the final turn where the velocity after the turn was 1.72m/s for the faster swimmers and 1.58m/s for the slower swimmers. When comparisons were made for the various phases between the European champion and the other competitors it was found that the champion was not the best in any one particular phase although the wall contact time for the hands was an area in which he was the second best competitor. The average of seven trials for four butterfly and three freestyle elite swimmers were analysed by Lyttle and Mason (1997). With small subject numbers, descriptive statistics were used to report differences between the kinetics of the turns by stroke. Butterfly swimmers produced greater peak forces (1406.7 ± 117.2N) than the freestyle group (1345.3 ± 236.5N). This may have been due to the increased contact time (0.40 ± 0.03s) compared to 0.29 ± 0.05s for the freestyle swimmers.

Backstroke turns were measured by Blanksby et al. (2004) where the fastest 5m RTT of three trials was analysed. Twenty-four variables were measured and were grouped due to the large number of variables compared to the subject numbers. No significant differences were found between the genders so the groups were combined for the statistical analysis. Results of the best of the three performances by each of the 36 swimmers found that the trochanterian height[20] had the strongest relationship with the 5m RTT followed by the take off velocity from the wall and the peak force. Of the grouped relationships, anthropometry and force contributed 34% towards the success of the criterion measure. Swimmers within this group who produced the highest vertical forces and take-off velocities were those with the shortest wall contact times, lower tuck indexes[21] and 2.5m RTT. The majority of swimmers also tended to resume their stroking too early when compared to their swimming velocity during the approach to the turn. The authors noted the problems with wave measures on the force platform affecting the peak values but are confident of the repeatability of the system so that comparisons could be made between swimmers and trials.

A similar protocol was used by Blanksby et al. (1998) to monitor 23 age group swimmers performing breaststroke turns on a 2D force platform. The best of the three trials for each swimmer was used in the analysis and found that the surface (breakout) distance was the greatest predictor of 5m RTT followed by the height of the swimmer and the horizontal velocity at breakout. Blanksby et al. (1998) found that while the distance (5m in and 5m out) comprised 20% of the event that the time was only 18.26% so there was a gain in performance throughout the turning period. Results showed that those swimmers travelling further in the underwater phase of the turn had a faster 5m RTT (criterion measure for the study) while height was the second most important variable to improved turn times. The velocity during swimming resumption and rotation times during the turn were the final two factors reported as important to breaststroke turns in age group swimmers.

More research has been performed on freestyle turns compared with the other strokes and this may be due to the greater number of races performed in this stroke during competitions. Analysis on three elite male swimmers performing seven freestyle turns showed wall contact times of 0.29 ± 0.05s and peak forces of 1345.3 ± 236.5N (Lyttle and

[20] The height of the leg from the greater trochanter to the ground is referred to as the trochanterian height
[21] Tuck index is a measure to determine how far the swimmer is from the wall during the contact and is the distance of the greater trochanter divided by the trochanteric height.

Mason, 1997). Rotation times were reported for the period of time after head flexion until the feet came into contact with the wall and were 0.72s on average for the group. The authors suggested that the two most important variables within freestyle turns from this pilot study were the approach speed and the maintenance of a streamlined position after the wall contact phase.

Land training

The effect of plyometric training on freestyle turns of age group swimmers found no significant differences between the control and study groups (Blanksby et al., 1998; Cossor et al., 1999) where the 2.5m RTT was used as the criterion measure. The 20 week study period was deemed to be an appropriate length but it was suggested that future research should work with older swimmers who could perform higher intensity plyometric exercises.

The relationship between dry land power tests and turns was measured by Cronin et al. (2007) with vertical jump heights (58.4 ± 8.6cm) and squat jumps with 20kg (242.9 ± 29.4W) and 30kg (334.5 ± 52.6W) masses reported. Tests conducted in the pool measured the velocity of the swimmer every 2m to see where changes occurred. The group of 67 swimmers was divided into a fast and slow sub group for further analysis and this found that there were little differences between the groups after 6 m. The velocities reported for the fast group between 2-4m of 5.8 ± 0.2m/s are much higher than those reported in other studies. 19% of the variance associated with turn velocity was seen in the initial velocity from the wall after the contact phase. There was a significant correlation between the velocity 2-4m after the turn and the power and height variables measured.

Equipment

Inertial sensors have been used to monitor turn performances of elite swimmers (Lee et al., 2011; Le Sage et al., 2012, 2011a, 2010a; Slawson et al., 2010). The focus of the research by Lee et al. (2011) was the wall contact and push off phase. Comparisons were made between an elite swimmer and triathletes and the angle at which the feet contacted the wall as well as the angle when they left the wall. Results found greater rotation around the longitudinal axis by the triathletes in both phases and the authors felt that this would negatively impact the turn performance. The sensors also showed differences in the acceleration profiles between the two swimmers as they left the wall and this was due to the streamline position and kicking action during the underwater phase. In contrast, Slawson et al. (2010) examined the turns of a triathlete performing a 400m short course freestyle swim to determine the repeatable traits within the acceleration traces. Results showed that on average 46% of the time was spent in the approach phase, 32% during rotation and 22% for the glide when the acceleration data was combined with vision systems information.

The development of a waterproofed pressure mat enabled data to be extracted for each leg independently (Cossor et al., 2012; Webster et al., 2011) during the wall contact phase of the turn through the use of bespoke software (Chakravorti et al., 2012a; Chakravorti et al., 2012b).

Pereira et al. (2010) used a force platform and two video cameras to monitor the turning performance of a national level swimmer. The swimmer performed trials where there was contact with the wall and others where there was no contact in order to determine the effect of the wave on the force measures. Software was developed to graphically remove the effects of the wave from the impulse and force measures recorded during swimming turns.

With researchers using different distances to measure turn performances, Silveira et al., (2011) suggested using a distance of 10m (5m round trip) when measuring turns where the underwater phase had less of an impact than the 15m (7.5m round trip) distance.

3.3.3 Movement

The ability to drive off the blocks during the start and the walls during the turn relies on power from the lower limbs. Hay (1993) reviewed the previous literature on jumping in athletics and noted that there was a dearth of information on the takeoff phase for long jump and triple jump. He noted that the mechanisms used to perform a long jump were similar to those in other sports including baseball, volleyball, basketball, football and gymnastics. A summary of the subjects used within the research on jumping and power in the lower limbs is presented in Table 9.

Jumping

The effectiveness of jumping (Benjanuvatra et al., 2007; Cossor et al., 2011) and resistance training (Breed and Young, 2003) on starting performance has been investigated. 23 female swimmers practiced the grab, rear-weighted track and swing starts over an 8 week period and were randomly assigned to the resistance training or control group. Land training sessions were completed three times each week for 9 weeks after which time there were significant changes ($P < 0.05$) in the track start take off angle (31.7%), velocity (1.7%) and horizontal impulse (10.3%). Welcher et al. (2008) analysed the differences in front and rear weighted starts. Results showed higher horizontal velocities at take-off for rear weighted starts (3.99m/s) compared to front weighted starts (3.90m/s).

Equipment

Linthorne (2001) noted that the use of a force platform when monitoring jumping performance enables scientists to calculate the height of the jump, acceleration, impulse, displacement, and ground reaction forces upon landing. The author also suggested that skilled jumpers tended to have a greater jump height when using a counter movement jump technique when compared with a squat jump.

A summary of the anthropometric data within the research investigating jumping and leg power are noted in Table 9.

Table 9 Summary of subjects analysed in research monitoring jumping and power of the lower limbs

Authors	Subjects	Sport/level	Age (years)	Height (m)	Weight (kg)
Arai et al. 2013	7 males	Hurdlers	20.2 ± 1.4	1.75 ± 0.07	67.3 ± 5.9
Blache & Monteil (2013)	8 males	Exercise twice per week	25.0 ± 4.2	1.78 ± 0.03	68.5 ± 4.9
Carlson et al. (2009)	15 males 22 females	Collegiate	20.2 ± 1.3 19.8 ± 1.0		69.5 ± 7.2
De la Fuente et al. (2003)	44 males 21 females	PE students	24.6 ± 1.8 24.14 ± 1.4	1.78 ± 0.06 1.64 ± 0.04	73.9 ± 6.6 58.8 ± 7.1
Garrido et al. (2010)	16 males 12 females	National age	12.01 ± 0.6		
Guex et al. (2013)	11 males		31.8 ± 5.3	1.80 ± 0.05	76.4 ± 8.4
Hara et al. (2008)	5 males		27.6 ± 3.8	1.72 ± 0.09	69.9 ± 5.8
Hardt et al. (2009)	11 males 11 females	Competitive age	14.2 ± 1.0 13.6 ± 1.3	1.76 ± 0.08 1.63 ± 0.07	65.8 ± 9.0 54.2 ± 9.0
Jidovtseff et al. (2010)	10 males		26.4 ± 4.0	1.80 ± 0.05	77.0 ± 9.0
Kariyama et al. (2011)	12 males	Athletes	22.0 ± 2.2	1.75 ± 0.06	65.8 ± 4.0
Maulder & Cronin (2005)	18 males	Athletic	25.1 ± 4.3	1.77 ± 0.05	78.8 ± 9.3
Moir (2008)	50 males 50 females	Recreational	21.7 ± 2.2 20.8 ± 1.9	1.78 ± 0.07 1.66 ± 0.06	82.6 ± 13.2 66.2 ± 12.0
Ortega et al. (2010)	30 males	Footballers	27.4 ± 4.0	1.75 ± 0.07	76.6 ± 4.8
Papaiakovou (2013)	15 flexible 15 inflexible	Males	21.3 ± 2.7 22.9 ± 1.9	1.78 ± 0.08 1.81 ± 0.07	73.8 ± 7.6 75.5 ± 6.5
Pearson & Hussain (2013)	8 males	Recreational	21.0 ± 1.0	1.78 ± 0.04	73.0 ± 12.8
Sharp et al. (1982)	18 males 22 females	Competitive	15.8 ± 0.4 14.7 ± 0.3	1.75 ± 0.01 1.64 ± 0.01	64.6 ± 1.3 54.0 ± 1.2
Willson et al. (2006)	24 males 22 females	Basketball, volleyball	19.9 ± 2.3 19.4 ± 0.7	1.83 ± 0.10 1.72 ± 0.07	79.8 ± 10.4 66.0 ± 6.4

Arm swing

A study was designed by Hara et al. (2008) to determine the importance of the arm swing to jump height. The five subjects performed squat jumps and CMJ both with and without the use of arms with the highest jumps measured with the use of arms in a CMJ technique. Analysis of the joint torques also showed that the effect of countermovement and arm swing were independent but had cumulative effects on jumping performance.

Horizontal jumping

Maulder and Cronin, (2005) aimed to determine the reliability of a new horizontal jump performance (unilateral concentric) and to compare this to other jumping styles. The new jumping technique was found to be an appropriate measure of leg power when compared to the more traditional tests. Results also found that the horizontal jumping test was a better predictor of sprint performances compared to the vertical jumps. The improvements in the stretch shorten capabilities (SSC) capabilities enhanced vertical jumps. The symmetry index scores also found very little difference between the dominant and non-dominant legs.

More recent research examined 10 elite jumpers (six males and four females) to determine the horizontal to vertical velocity within the triple jump (Yu, 2001). Results found a direct relationship between the loss in horizontal velocity and the increase in vertical velocity although optimal technique for the sport was not discussed.

Single leg movement

Single and double leg jumps (Kariyama et al. 2011; Maulder & Cronin, 2005; Willson et al., 2006) and asymmetries in jumping (Hardt et al., 2009) were examined. Kariyama et al. (2011) monitored single and double leg jumping performances of 12 male athletes in both the eccentric and concentric phases with the contact time seen to be shorter using the double leg technique. Results also found greater power output around the hip joint in single leg jumps and around the ankle joint for double leg jumps.

Squat jumps

Willson et al. (2006) examined the lower limb mechanics during a single leg squat to assess any differences between males and females. Analysis of 24 males and 22 females found differences in technique between the sexes with greater frontal projection angles observed in the females. The torque values for males were greater than the females in everything except trunk extension.

Electromyography (EMG) was used to record the muscles within the erector spinae when 8 male athletes performed maximal squat jumps (Blache and Monteil, 2013). Results found lower jump heights (8.4cm) when no back extension was used during the jump and the erector spinae should be considered as a trunk extensor when monitoring jump performances.

Drop jumps

Arai et al. (2013) assessed 7 male hurdlers performing drop jumps from 0.2 and 0.4m at three different efforts (no rebound, 50% maximum rebound height and maximal height). Measures included knee and ankle joint angles, maximum vertical force and EMG of the lower limbs. Results found that the co-activation of the agonist and antagonist muscles during the 30ms after landing impacted on the jump height and not the height of the drop jump.

Vertical jumps

The variables from 8 different vertical jump exercises by ten males were compared in order to determine the common mechanical properties (Jidovtseff et al., 2010). Results indicated that the jumps with a greater lowering of centre of mass produced greater vertical heights but the mechanical parameters were predisposed to the type of jump.

Carlson et al. (2009) looked at different land training methods and its impact on vertical jump heights. Subjects completed 6 weeks of training in one of 4 groups: strength, strength-plyometric, strength-Vertimax®, or strength-Vertimax® with arms. Results found no significant differences between the training modalities although there were significant within group performance improvements over the testing period for the group incorporating plyometric training and the group training with the Vertimax machine without the use of arms.

Moir (2008) used three methods to calculate the vertical jump height of 50 men and 50 women. These included: the vertical velocity of the COM at take-off, time in the air, and adding the vertical displacement prior to take off to the height calculated using the COM at take-off. Results showed differences between the jump height of males and females and not the method used to calculate the jump height.

When landing from a vertical jump there are generally two peak forces and these were monitored by Ortega et al. (2010). Significant correlations were observed between flight height and the first force, force one and the duration of the second peak as well as a negative correlation between the second peak force and the length of time at which it occurred. The authors concluded that increasing the time when the second peak force occurs during landing should decrease the risk of injury in the lower limbs.

Papaiakovou (2013) examined the vertical jump for subjects with good and poor ankle dorsiflexion when performing counter movement jumps (CMJ) and drop jumps from a height of 60cm. Results showed differences in performances for both types of jumps highlighting the importance of ankle movement for vertical jump performance. Subjects with limited ankle joint flexibility required a greater trunk lean or the raising of the heels in order to perform the jumping techniques.

Post activation potentiation

Pearson and Hussain (2013) noted the lack of research relating to post activation potentiation (PAP) and jumping performance and therefore monitored CMJ performances before and 4 minutes after various voluntary muscle contractions. The results of tests performed on 8 males indicated no significant improvements in performance after using PAP techniques prior to the jumps.

Gouvêa et al. (2013) reviewed the research of 14 studies on the PAP rest interval and the impact on jumping performance. The results indicated small effects where the rest interval was 4-7 minutes or more than 16 minutes and medium effects with rest intervals of 0-3 or 8-12 minutes between the PAP exercise and jump performance. The small period of 0-3 minutes rest resulted in a decrease in performance and the review of literature highlighted the importance of timing to jump performance when using PAP.

Power

The relationship between the hamstrings and quadriceps was measured for 11 track athletes, 11 squash players and 11 tennis players (Read and Bellamy, 1990). No differences were observed between the sports although at the higher test speeds results indicated a prominence for the hamstring when compared to the quadriceps, particularly with the non-preferred leg. There were also no notable differences in the power output between the preferred and non-preferred leg. Guex et al. (2013) used 11 male subjects to assess the optimal knee angle to maximise the hamstring length with two different hip positions. While changes in the muscle length were observed after 30 concentric contractions between hip angles of 0° (3°) and 80° (15°) the authors also noted that fatigue had an impact on the performance.

Swimming power

It has been suggested that there is a comparison between vertical jumping and the initial phase on the block in swimming starts. These relationships have been examined by Girold et al. (2006), Potdevin et al. (2011), Sharp et al., (1982), and West et al. (2010). The relationship between arm power on land and swimming performance was measured by Sharp et al. (1982). The authors suggested an optimal velocity of 2.40m/s for peak power and that the effect of fatigue appeared to have no impact on the swimming performance. In addition, it was concluded that the use of a swim bench was beneficial to improve arm power for swimmers.

In a study performed on a group of physical education students performing swimming starts and vertical jumps, no differences in timings were observed for the males and females although the males had a higher horizontal take off velocity (4.07m/s) compared to the females (3.63m/s)(de la Fuente et al., 2003). When peak forces were normalised for body weight there were no significant differences between the groups and although the males entered the water with their hands 0.44m further than the females this may have been due to the height difference between the groups. The results of the study also showed no correlations between vertical CMJ performances and the forces produced on the start block.

Swimmers have tended to choose their front leg on the starting block without any scientific backing and this was investigated further by Hardt et al. (2009). The start performances of 11 male and 11 female swimmers were monitored to determine if there were any asymmetries between the legs and if this related to the dominance or footedness of the subject. Results showed that there were no correlations between footedness, dominance for the one-legged jump or hop and the stance preference for the swimming start. The fastest starting times were those where the swimmer used their preferred leg in the forward position rather than the dominant leg as proposed by a footedness questionnaire. It was suggested that this was due to the fact that they had more practice with this technique and further investigation would be required.

Garrido et al. (2010) aimed to identify the land training tests that were related to sprint swimming performance. Analysis of the data found moderate relationships between the sprint swimming (25m and 50m) tests with the bench press and leg extension tests. There was a small association with the throwing of a medicine ball and the swimming tests. The authors concluded that there were some land tests that were suitable measures of sprinting performance for age group swimmers.

3.3.4 Free swimming technique

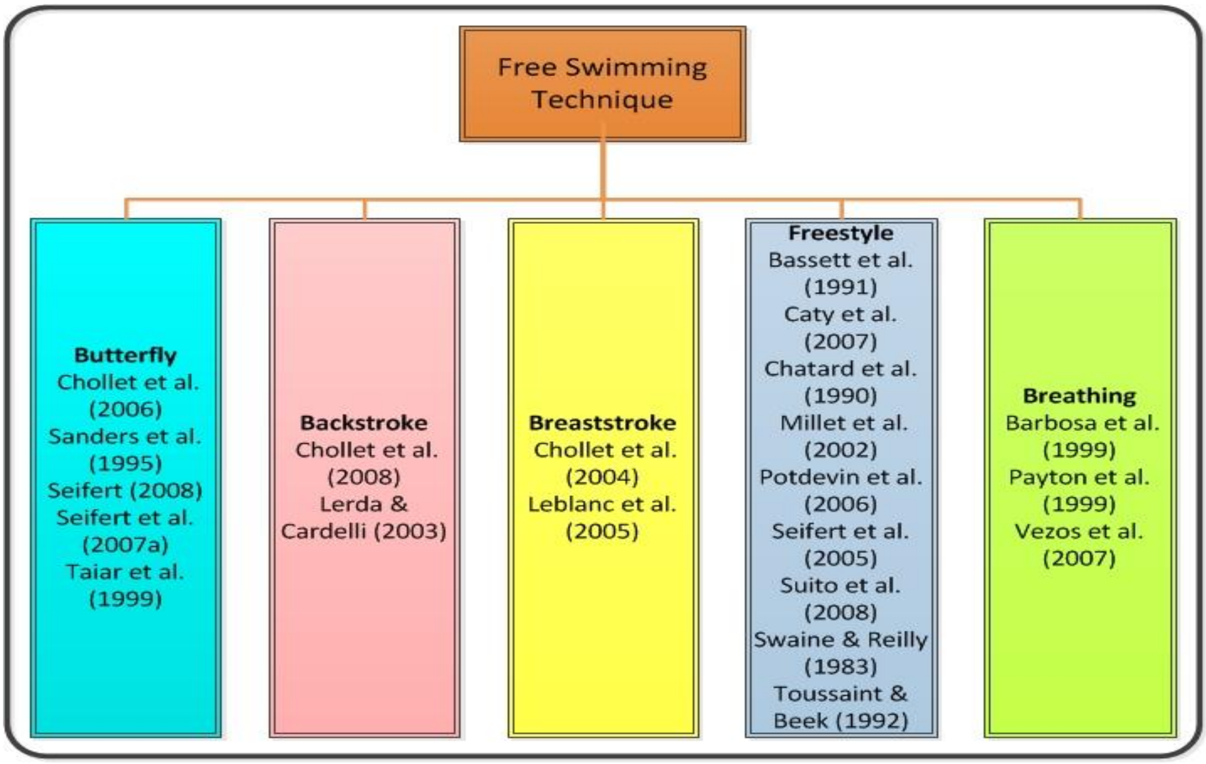


Figure 17: Research into the mechanics of the various strokes within the free swimming component of a race

The skill component of a swimming race varies in importance depending on the distance of the event as discussed earlier. Shorter races require swimmers to be skilled in both starts and turns to be successful in total race performances but as the distance of the race increases, the free swimming component becomes more important. As such, researchers have investigated the stroke mechanics with particular reference to the timing of each of the phases as outlined in Figures 17 and 18.

Butterfly was researched by Chollet et al. (2006), Sanders et al. (1995), Seifert (2008), Seifert et al, (2007a) and Taiar et al. (1999) while the timing in backstroke was discussed by Chollet et al. (2008) and Lerda & Cardelli (2003). Breaststroke mechanics were monitored by Chollet et al. (2004) and (Leblanc et al. (2005) and freestyle timing was researched by Bassett et al. (1991), Caty et al. (2007), Chatard et al. (1990), Millet et al. (2002), Potdevin et al. (2006), Seifert et al. (2005), Suito et al. (2008), Swaine and Reilly (1983) and Toussaint and Beek (1992).

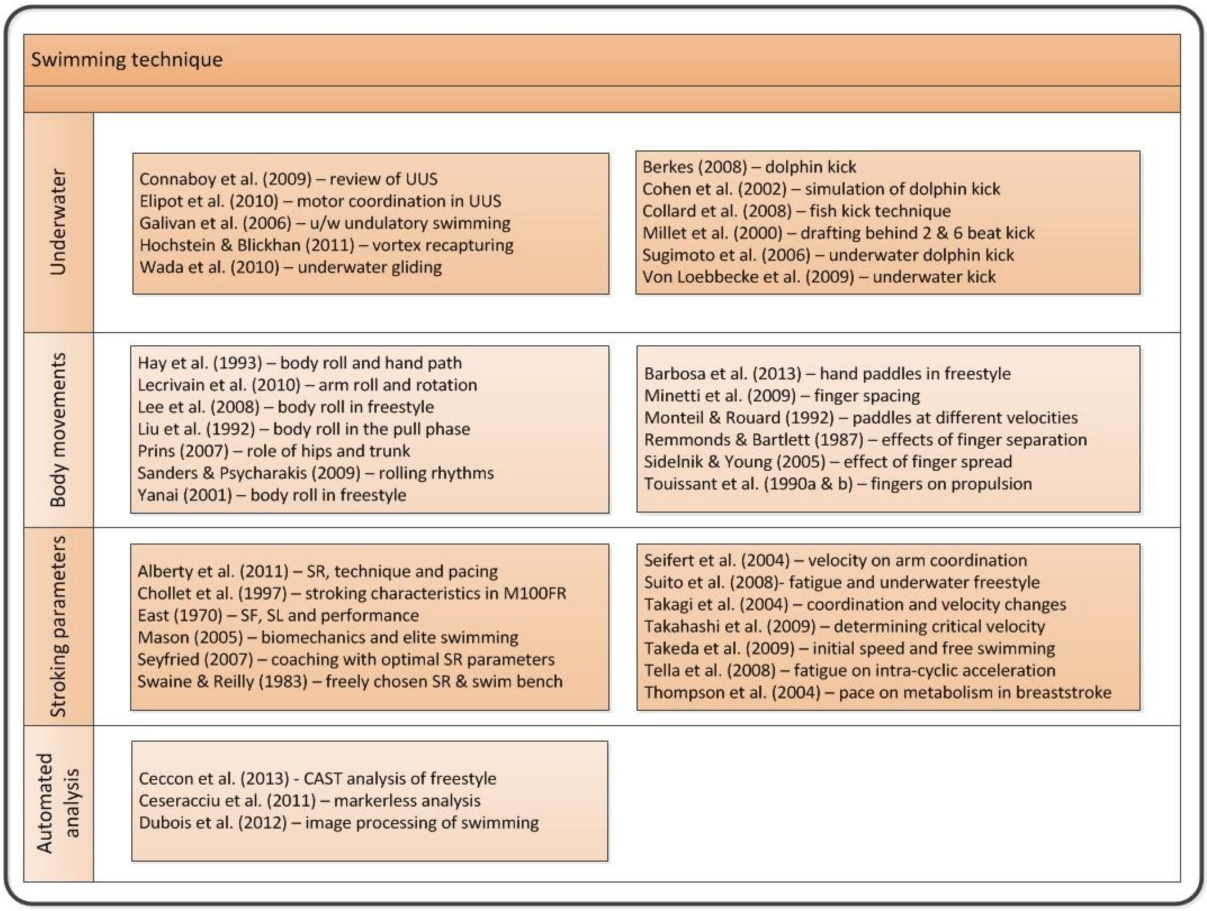


Figure 18: Review of swimming technique literature including underwater segments, body movements, stroking parameters and automated analysis systems

The effect of breathing on the stroke mechanics was analysed by Barbosa et al. (1999), Payton et al. (1999) and Vezos et al. (2007). The analysis of six male swimmers tested at their 200m pace showed no significant differences in stroke length between the breathing (2.24 ± 0.27m) and non-breathing (2.15 ± 0.22m) trials. The swimmers did need to roll further (66 ± 5° breathing, 57 ± 4° non-breathing) but this did not impact on the width of the stroke (0.28 ± 0.07 breathing, 0.27 ± 0.07 non-breathing). These results were in contrast to the study on ten female swimmers where there were significant differences in stroke duration, displacement and velocity of the hand through the various phases of the freestyle stroke (Vezos et al., 2007).

3.3.5 Drag and propulsion

A number of systems have been developed to measure drag and propulsion within swimming. The three forms of drag within swimming include *form drag* resulting from the shape of the object, *skin* or *friction drag* (interaction between the surface of the object and the water), and *wave drag* (formation of waves near the surface of the water).

Research relating to the areas of drag and propulsion are noted in Figure 19.

Counsilman (2005) summarised the papers on lift and drag within swimming and noted that the majority were theoretical and that the debate relating to the lift propulsion theory will continue. Successful swimmers tend to work on the feel within the water rather than concentrating on the lift or drag components throughout the phases of the stroke. It was noted that faster swimmers had a lower coefficient of drag (Havriluk, 2005).

Lauder (2009) attempted to answer ten of the most common questions relating to the hydrodynamics within swimming. These were based around the propulsion of the body throughout the water and computational methods that have been developed to measure these.

Polidori et al. (2006) identified a potential decrease in skin drag of 5.3% as the water temperature increased from 20-30° C if the laminar flow around the swimmer remained constant, but due to the turbulent nature of the movement a 1.5% decrease in friction drag was found for swimmers travelling over 1m/s. When studying the wave drag on a swimmer, Vennell et al. (2006) noted that while this type of drag can comprise 50-60% of the total drag acting on a swimmer travelling at 1.7m/s that it can be completely eliminated if they travel 1.8 chest depths below the surface of the water. The influence of body hair removal in swimming was assessed by Sharp and Costill (1989). Of the thirteen male swimmers, nine shaved the hair on the trunk, arms and legs. Whilst drag was not measured in the study, the results indicated a decrease in the physiological requirement by the swimmers and the authors intimated that there was a reduction in active drag.

Passive drag

Measurements of passive drag are done using various towing systems attached to a force measuring device (Havriluk, 2005; Kolmogorov and Duplishcheva, 1992; Lyttle et al., 1998a; Marinho et al., 2009; Webb et al., 2011; Zamparo et al., 2009). When measuring active drag, the swimmer is towed in a prone position along the surface of the water at speeds similar to their maximum swimming velocities (1.8-2.1m/s).

Drag and propulsion

Active drag
Formosa et al. (2012) – comparison of MAD and assisted towing methods
Hollander et al. (1986) – MAD during crawl arm stroke
Huijing et al. (1988) – active drag and body dimensions
Kolmogorov & Duplishcheva (1992) – active drag at maximal velocity
Kolmogorov et al. (2000) – technology for decreasing active drag
Kugovnik et al. (1988) – assessing active drag
Mason et al. (2010) – method to analyse active drag
Niklas et al. (1993) – active drag in a flume
Toussaint et al. (1988) – active drag related to velocity

Passive drag
Benjanuvatra et al. (2002) – drag forces with Fastskin™ & standard suits
Chatard et al. (1990) – passive drag to determine swim performance
Costa et al. (2011) – passive drag during gliding
Counsilman (2005) – lift versus drag
Gatta et al. (2013) – effect of caps on passive drag
Havriluk (2005) – performance differences in swimming
Pease & Vennell (2010) – angle and depth on passive drag

Gliding
Lyttle et al. (1998) – role of drag in the streamlined glide
Marinho et al. (2009) – hydrodynamic drag in the glide
Marinho et al. (2010) – water depth and glide phase
Naemi et al. (2008) – development of Glide Coach
Naemi et al. (2010) – hydrodynamic glide efficiency
Naemi & Sanders (2008) – hydrokinematic measurement of glide efficiency
Roig (2010) – gliding capacity
Thow et al. (2012) – feedback mechanisms on gliding

Kicking
Cappaert & Gordon (1998) – frontal surface area
Fulton et al. (2011) – kick rate of Paralympic swimmers
Gatta et al. (2012) – power in flutter kick
Hollander et al. (1988) – legs and propulsion

Power
Brandt & Pichowsky (1995) – energy conservation
D'Acquisto et al. (2007) – performance characteristics of male swimmers
Zamparo et al. (1996) – effect of torque on drag

Propulsion
Berger et al. (1999) – propulsive forces in front crawl
Johansson & Norberg (2003) – webbed feet and swimming propulsion in birds
Nicolas et al. (2010) – swim fin propulsion
Payton & Bartlett (1995) – estimating propulsive forces
Takagi & Sanders (2002) – hand propulsion in swimming
Toussaint et al. (1988) – propelling efficiency
Toussaint et al. (2002) – pumped up propulsion
Valiant et al. (1982) – effect of lift and drag on the forearm
Vorontsov & Rumyantsev (2008) – resistive forces
Vorontsov & Rumyantsev (2008) – propulsive forces

CFD/Models
Bixler et al. (2007) – accuracy of CFD for passive drag
Kudo et al. (2008) – fluid forces on the hand
Marinho et al. (2013) – CFD during the glide
Novais et al. (2012) – effect of depth on drag
Pendergast et al. (2006) – CFD and swimsuit drag reduction
Tan et al. (2007) – flow visualisation of a robotic fish
Von Loebbecke et al. (2009) – computational model for underwater kicking

Strokes
Chatard et al. (1991) – energy cost in freestyle for women
Clarys & Jiskoot (1975) – total resistance in freestyle
Formosa et al. (2011) – force time profile in freestyle
Formosa et al. (2013) – backstroke coordination
Formosa et al. (2013) – freestyle coordination
Shahbazi-Moghaddam & Sabbaghian (2005) – drag force in butterfly
Toussaint et al. (2004) – determination of drag in free
Van der vaart et al. (1987) – estimation of drag in free
Vilas-Boas et al. (2010) – drag coefficients in breaststroke underwater stroke

EMG
Clarys (1985) – hydrodynamics and EMG
Clarys (1988) – Brussels EMG project
Clarys et al. (1988) – surface EMG in MAD & free swimming

Drafting
Chollet et al. (2000) – drafting in triathletes
Janssen et al. (2009) – effects of drafting in front crawl

Figure 19: Research into the areas of drag and propulsion within the aquatic environment

The effects of passive drag within swimming has been measured by a number of researchers (Benjanuvatra et al., 2002; Chatard et al., 1990; Costa et al., 2011; Counsilman, 2005; Gatta et al., 2013; Havriluk, 2005; Pease and Vennell, 2010; Webb et al., 2011). In the study by Benjanuvatra et al. (2002) swimmers were towed in a prone streamlined position on the surface of the water and 0.4m below the surface at speeds of 1.6, 2.2 and 2.8m/s. When the subjects were tested wearing the Fastskin™ suit their passive drag values were significantly lower than with a standard swimsuit in all instances except at 2.2m/s along the surface of the water. Similar results were observed in the active drag tests for the five male and four female subjects and the authors suggested that this was due to lower frictional drag when wearing the Fastskin™ suit.

218 swimmers were towed in a prone position along the surface of the water at 1.4m/s in the study by Chatard et al., (1990a). An increase in passive drag of 22 ± 3% was observed after a maximal expiration by the swimmer and was related to the surface area and vital capacity of the individual. These values were lower than the 34% reported when towing 7 male swimmers passively (Chatard et al., 1990b). Costa et al. (2011) used Computational Fluid Dynamics (CFD) and inverse dynamics to assess the passive drag of swimmers with their arms in a streamlined position above their head and while the arms were by the side of the body to replicate two positions used within breaststroke. The calculated drag values were similar for both methods with the arms above the head but the values calculated using CFD were higher than the inverse dynamics method when the arms were by the side of the body.

Pease and Vennell (2010) used a mannequin within a flume to determine the impact of the angle of attack (-4 to +4°) on the drag produced. Depths ranged from 0.20-0.80m and velocities of 0-2.55m/s were used as part of the study. Wave drag was lower for the negative angles of attack when the body was 0.20m below the surface of the water with no other differences observed.

Webb et al. (2011) then used two different methods to predict passive resistance of the body in the water at speeds of 0-2m/s using theoretical analysis and found similar results to experimental testing. Average values of 59%, 33% and 8% were observed for measures of wave drag, pressure and skin friction respectively. Values of 131.4N were calculated using the VPM and 133.9N using the Naval architecture approach (Molland et al., 2011) at a constant velocity of 1.53m/s.

In the study by Gatta et al. (2013) 16 swimmers were towed in a streamlined prone position at 1.5, 1.7 and 1.9m/s when wearing two types of swimming caps. Similar drag values were noted when the swimmers used the lycra and silicone caps but there was a decrease in force of 5-6.5% when wearing the helmet cap compared to the silicone caps. The authors concluded that the type of cap worn by the swimmer would affect their fluid dynamics at the speeds used within this study.

Active drag

Whilst passive drag is an indicator of the hydrodynamic effects generated whilst swimmers are being towed through the water at various speeds and depths it is not a true representation of what occurs for the majority of swimming events. Researchers have therefore attempted to gain a further understanding of the drag forces generated whilst swimming (Formosa et al., 2012; Hollander et al., 1986; Huijing et al., 1988; Kolmogorov et al., 2000; Kolmogorov and Duplishcheva, 1992; Kugovnik et al., 1988; Niklas et al., 1993; Toussaint et al., 1988b; Toussaint et al., 2004).

Formosa et al. (2012) noted that there was a 55% difference in the calculated active drag for nine swimmers at the maximum towed speed of 1.68m/s using the assisted towing method (ATM) and MAD system. It was noted that the MAD system was unable to assess the early catch phase and the contribution of the legs to the propulsion of the swimmer and may account for the smaller force values. The mean propulsive forces were calculated during arms only swimming at speeds ranging from 1.0-2.0m/s (Hollander et al., 1986). Observed forces were similar to those measured in passive drag trials.

Five research projects carried out between 1991 and 1999 to monitor the active drag of swimmers from both age group and elite categories at both sea level and altitude conditions (Kolmogorov et al., 2000). The authors concluded that training and technique were contributors to reducing active drag. Toussaint et al. (2004) used two methods of determining active drag within swimming: Velocity Perturbation Method (VPM) and the Measurement of Active Drag (MAD) system on six elite swimmers. Velocities were significantly higher when using the MAD system (66.9N) compared to the VPM (53.2N). It was suggested that the legs used within the VPM were the reason for the differences observed.

In a study of 32 males and 9 females aiming to monitor propulsive arm forces, swimmers travelled at velocities ranging from 1.0 to 1.8m/s (Toussaint et al., 1988b). On average the drag force was related to velocity by the power of 2.28 ± 0.35 for females and 2.12 ± 0.20 for the males with the largest variations within the group observed at the slowest speed. Niklas et al. (1993) used two methods to calculate active drag: the added drag and MAD system. The values that were observed were 31.1N within the flume and 33.3N for the MAD system. Mason et al. (2010) developed a mathematical model to calculate active drag measures from passive and active trials when tethered to a force transducer.

Gliding

Gliding techniques are utilised when pushing off the wall and has been researched extensively (Lyttle et al., 1998; Marinho et al., 2010, 2009; Naemi and Sanders, 2008; Naemi et al., 2010, 2008; Roig, 2010; Thow et al., 2012; Vilas-Boas et al., 2010). Skin drag refers to the forces acting along the body and the water deformation along the surface of the water generates the wave drag. Pressure drag is the differential between the upper and lower surfaces of the body as it moves through the water and is proportional to the square of the velocity, the cross-sectional area of the swimmer as well as the density of the water (Marinho et al., 2009).

Marinho et al. (2009) created a model using computational fluid dynamics to determine the level of drag created by a swimmer in a streamlined position. Simulations ranged from 1.6-

2.0m/s in order to represent typical velocities of elite swimmers during the glide phase in a start and turn. The model was designed with boundary layers representative of competitive situations with a width of 2.5m and a depth of 1.8m with the swimmer's midline 0.9m from the surface of the pool. Drag coefficients were reported with the arms placed by the side as well as with them extended in front of the body. The total drag was reported on a combination of the skin (friction), pressure (form) and wave drag components which are characteristic within swimming. Results showed a total drag coefficient ranging from 0.824 at 1.6m/s through to 0.736 at 2m/s with the arms by the side. When the swimmer was in a more streamlined position these values were reduced to 0.480 at 1.6m/s and 0.428 at the fastest speed of 2m/s. It was noted that as the speed used within the model was increased, the total drag coefficient was reduced in both swimmer positions although the drag was lower with the arms stretched above the head of the swimmer.

CFD simulations were used by Marinho et al. (2010) on a 3D model of a male swimmer being towed in a prone streamlined position at a speed of 2.5m/s. The depths measured were 0.20, 0.50, 1.00, 1.50, 2.00, 2.50 and 2.80m beneath the surface of the water. Drag forces measured increased as the depth of the model increased although the authors indicated that a maximum depth of 2.00m would be beneficial when performing starts and turns. Similar trends were observed by Pease and Vennell (2010) when measuring total drag at depths of 0.2-0.8m at velocities of 0.34-2.55m/s.

Roig (2010) included three fixed cameras and a velocity meter to determine the gliding velocity of Spanish swimmers in both a prone (or dorsal position for backstrokers) and lateral positions. Better gliders had a lower glide coefficient and either pushed off the wall with a higher initial velocity or had a smaller rate of change to the velocity throughout the glide.

Software was developed that enabled the glide efficiency of a swimmer to be quantified as they pushed off the wall (Naemi et al., 2008). Naemi and Sanders (2008) defined this glide efficiency through the use of the initial and final velocity of the swimmer and this time with an average value of 4.19m using 5 elite swimmers. It was noted by Naemi et al. (2010) that this new method of measuring glide efficiency may be more representative than previous models due to the natural posture that the swimmer holds when being measured. Nineteen elite swimmers were divided into three different groups to monitor the impact of different types of feedback on gliding performance after a start (Thow et al., 2012). Whilst all groups improved over the 4 week period, the group with the greatest improvement was the one that used the GlideCoach© software and verbal feedback.

Kicking

Measures of drag and propulsion while kicking have been discussed by a few authors (Cappaert and Gordon, 1998; Fulton et al., 2011; Gatta et al., 2012; Hollander et al., 1988). Twelve Paralympics swimmers were towed in a prone streamlined position followed by kicking at different speeds and amplitudes (Fulton et al., 2011). When the kick rate was approximately 150 kicks per minute there was an increase in force of 24.2 ± 5.3% as the speed of the trial increased by 5%. When the swimmers used greater kicking amplitudes it resulted in a decreased kick rate of 13.6 ± 5.1% and increased the force by 25.1 ± 10.6%. Gatta et al. (2012) tested 18 competitive male swimmers that were towed at speeds ranging from 1.0–2.0m/s in order to assess the power produced from flutter kick. Results indicated that the drag equalled the propulsive power from the kick at 1.26m/s and after this point the power was reduced as the velocity increased.

Power

Power and energy use was discussed by a few researchers (Brandt and Pichowsky, 1995; D'Acquisto et al., 2007; Zamparo et al., 1996). Brandt and Pichowsky (1995) assessed the mechanical power to propel the swimmer in the horizontal plane. D'Acquisto et al. (2007) monitored 14 male swimmers performing sub maximal and maximal freestyle swims where air expired, velocity and blood lactate were measured. Faster swimmers were able to use more mechanical power to overcome drag and less wasted to the water.

Eight elite male swimmers were used as subjects to investigate the underwater torque acting on the body by attaching air, water or a 2kg weight to the waist when travelling at speeds of 1.00 and 1.23m/s (Zamparo et al., 1996). The torque within the water is the force that is acting on the body in order to move it to a vertical position. Results found an increase in underwater torque (force that the feet tend to sink multiplied by the distance of the feet from the centre of volume of the lungs) of 73% between the air and weight trials. There was a significant correlation between the energy cost and torque of the swimmer at 1.2m/s at which point the authors suggested that the extra drag acting on the body at the faster speeds resulted in less of an effect of torque.

Propulsion

Propulsive forces in swimming were investigated by Berger et al., 1999; Johansson and Norberg, 2003; Nicolas et al., 2010; Payton and Bartlett, 1995; Takagi and Sanders, 2002; Toussaint et al., 2002, 1988a; Valiant et al., 1982; Vorontsov and Rumyantsev, 2008a, 2008b. In early research, Valiant et al. (1982) used an accelerometer to monitor the lift and drag forces of the hand during freestyle swimming for four swimmers. It was noted that the early phases of the stroke were unable to generate enough propulsive force to accelerate the swimmer forward.

The propelling efficiency of four swimmers was measured on the MAD system with ranges of 46-77% (Toussaint et al., 1988b). The total efficiency (product of propelling and mechanical efficiency) ranged from 5-8% within the group. Toussaint et al. (2002) reported that previous theories suggested that lift and drag of the hand were responsible for the propulsion within swimming. Theoretical models suggest that the pressure gradient along the forearm could also influence the propelling efficiency of the body.

Payton and Bartlett (1995) had 10 operators digitise the right arm action during breaststroke to determine the hydrodynamic forces acting on the hand. The errors in measurement of the hand speed led to errors of 27% for lift and 20% for drag measures leading the authors to suggest that research should report the measurement errors when performing hydrodynamic analysis in swimming.

Berger et al. (1999) calculated the propulsive force using a 3D kinematical analysis and compared with data gathered from the MAD system. Similar results were observed between both methods with a small difference (5%) observed and this may be due to the point of hand entry. Examination of birds moving through the water showed that webbed feet increased the propulsive forces of kicking through the use of both drag and lift (Johansson and Norberg, 2003).

Nicolas et al. (2010) noted that the world records for fin swimming are approximately 10% faster when competing underwater rather than along the surface. After analysing fin swimmers moving along the surface of the water and below the authors found that the amplitude of the monofin was greater during underwater swimming (0.55m) than surface swimming (0.46m).

Strokes

Swimmers move through the water using different methods in each of the four strokes and these have been investigated (Chatard et al., 1991; Clarys and Jiskoot, 1975; Formosa et al., 2013a, 2013b, 2011; Shahbazi-Moghaddam and Sabbaghian, 2005; van der Vaart et al., 1987).

Results on 12 elite male swimmers using the MAD system showed a mean propulsive force of 53.2 ± 5.8N when the velocity was 1.48m/s (van der Vaart et al., 1987). Chatard et al. (1991) towed 84 swimmers in a prone position at 1.4m/s and VO_2 max was measured in relation to 400m swimming performances. Increases in passive drag values by 34% were observed when comparing maximal expiration compared with inspiration prior to the trial. Authors found correlations between passive drag with height, weight and surface area values for both males and females and suggested that passive drag could be a predictor of swimming performance.

Toussaint et al. (2004, 1988) developed a system that enabled the swimmer to place their hand on fixed pads set along the bottom of the pool. These pads incorporated force transducers with the information hard wired from these pads to a computer located by the side of the pool. The distance that these pads were set apart was dependant on the individual swimmer and their specific SL as measured in competitions. In these studies swimmers used their arms only so that the leg kick did not influence the results that showed mean drag forces of 28.9N for males and 20.14N for females.

Shahbazi-Moghaddam and Sabbaghian (2005) used an indirect method of determining active drag (IMAD) on 20 female swimmers who performed 3 maximal effort 10m swims and then glided for as long as possible. The values of 26 to 36N of drag force for the better swimmers within the group are similar to values reported in earlier studies. Results also showed strong correlations between anthropometry and active drag values.

Vilas-Boas et al. (2010) monitored two gliding positions within breaststroke for 12 national level swimmers (6 males and 6 females). In the first position the arms were extended above the head and produced drag forces of 31.67 ± 6.44N which was lower than the second position where the arms were by the side of the body (46.25 ± 7.22N). Results of the female sub-group ranged from 28.68 ± 2.82N in the first position to 49.58 ± 7.47N in the second position which was a greater range than observed in the males (34.66 ± 7.87N for position one and 42.92 ± 5.66N in position two). The authors concluded that the first gliding position was more hydrodynamic than the second so swimmers should spend more time in that position when pushing off the wall in breaststroke.

In the first study into freestyle technique Formosa et al. (2011) used 8 elite male swimmers towed passively and actively to examine the force time profile in freestyle. The minimum force was observed at 45% within the stroke (insweep) and the maximum force was at 75% of the stroke (upsweep). Results also showed that only half of the group had a symmetrical stroke and the symmetry within the stroke was affected by breathing for the other half of the group. Further research used 20 subjects to perform trials that included breathing and others that used no breathing within the test (Formosa et al., 2013b). When breathing, 7 of the males and all 10 females had a symmetrical stroke as identified by time but when examining the drag force profiles only 4 females and 2 males were considered symmetrical in their stroke patterns.

Formosa et al. (2013b) analysed ten males and nine females completing maximum backstroke repeats in both assisted and free swimming repeats. Whilst the gender of the swimmer did not impact on the coordination of the stroke the timing of the maximum drag force was different for the males and females.

CFD/Modelling

Other researchers have used computational fluid dynamics (CFD) or mathematical modelling to determine the drag acting upon a swimmer (Bixler et al., 2007; Kudo et al., 2008; Marinho et al., 2013; Mason et al., 2010; Novais et al., 2012; Pendergast et al., 2006; Tan et al., 2007; von Loebbecke et al., 2009). Bixler et al. (2007) created a CFD model of the swimmer that was designed to calculate the total drag acting on the swimmer when travelling at 1.5 and 2.25m/s and results were within 4% of data from a real swimmer.

Kudo et al. (2008) generated a model of the hand to monitor the fluid forces acting at various flow speeds. 12 pressure transducers were attached to the hand and sampled at a rate of 200Hz. CFD simulations were performed on a 3D model of a male swimmer that was towed in four different positions: prone, rotated to 45°, rotated to 90°, and a supine position (Marinho et al., 2013). Results indicated that towing in a prone position produced the lowest coefficient of drag and should be used during the underwater phase of starts and turns.

Novais et al. (2012) generated a CFD model of a swimmer in a prone streamline position with drag force calculated for velocities between 1.5 and 2.5m/s. The authors noted that these were approximate speeds achieved by swimmers when pushing off the wall after a turn. The centre line of the body was also moved between depths of 0 and 1.0m below the surface of the water. Results indicated that the drag decreased through to a depth of 0.75m. In a separate study, Pendergast et al. (2006) used 7 males and 7 females who were towed in a prone position at speeds of 0.4 to 2.2m/s in order to monitor the laminar flow of water around the chest, back and buttocks. The authors concluded that the use of different swimsuits affected the pressure drag at the higher swimming speeds.

In a slightly different approach Tan et al. (2007) used a robotic fish to monitor the flow of water around the tail and to measure the hydrodynamic forces throughout the movement. Von Loebbecke et al. (2009) – used a multi component technique to analyse the underwater dolphin kick of one male and one female model travelling at 1.7m below the surface of the water. The downwards portion of the kick was found to produce the greatest percentage of thrust when travelling at speeds of 0.95 and 1.31m/s.

Drafting

The final area researched within drag and propulsion is drafting which is used both within triathlon and open water swimming events (Chollet et al., 2000; Janssen et al., 2009). Chollet et al. (2000) had 6 male subjects perform a 400m swim in both a drafting and non-drafting situation. Swimmers maintaining a higher velocity and with lower body mass benefited more from drafting than others within the group. Janssen et al. (2009) noted that there was a decrease of 9% drag when towed behind an active swimmer and 20% behind a passive swimmer. Results indicated that the best position to draft within swimming was to be placed 0.50m behind the toes of the lead swimmer.

EMG

A number of studies were conducted within a Dutch Marine ship model testing station to monitor the movement of the swimmer through the water (Clarys, 1985; 1988; Clarys and Jiskoot, 1975; Clarys et al., 1988). The passive drag calculated when towing a swimmer in a prone position at the surface of the water was lower than when the swimmer was below the water. The active drag values were double those achieved in a passive drag situation, which suggested that the shape of the body may have little effect on the propulsion of the swimmer.

3.4 Summary

The literature presented within this chapter was comprehensive within the areas of swimming technique and competition analysis. Various methods have been used to analyse the performances of swimmers both in the training and competition environments using both kinetic and kinematic methods.

Competition analysis originally required large teams of people to analyse the data with results taking approximately 6 months to generate. With the improvements in technology it is now possible to provide the race statistics and video footage to the coaches and athletes within minutes of the completion of a race. The information provided is similar for the majority of software systems used globally with some programmes now including more comprehensive details on the start and turn phases of the race.

The aim of this research was to continue with the analysis of international competitions to monitor the trends within swimming as well as to develop software that was appropriate within the British environment.

Whilst swimming starts have been researched in depth previously there was no information relating to the performance of the swimmers using the new OSB11 designed starting block. Earlier analysis used force platforms to monitor the block phase of the start as well as towing devices for the underwater phase. A multi component approach was used within the current research to monitor the starting performance utilising the new block with the focus on the block and flight phases.

Research relating to swimming turns was more limited than swimming starts with all studies using single and tri-axial force platforms to monitor the wall contact phase. Limitations with this type of equipment included the cost, weight, wave pressure, and position on the wall. The largest short coming was the inability to differentiate the forces generated by the left and right feet. As such there was nothing reported in the literature on the relationship between foot placement on the wall and turn performance which became the focus for the final phase of this research.

Chapter 4 - Competition Analysis

Objective 1

To monitor the performances of swimmers during the major international competition each year and to determine the relative strengths and weaknesses of the British swimmers within these competitions. This would include comprehensive information on the skill phases (starts and turns) of the race which accounts for 30% of the 100m long course events. The ultimate purpose was to improve the swimming times and rankings of the British teams throughout the research period.

4.1 Introduction

As the science of swimming has developed, the desire to analyse performances during competitions has evolved. Smith et al. (2002) intimated that the initial evaluation of a swimmer is through the assessment of their performance within a competition environment. By measuring what actually happens within the race, coaches and athletes are able to adapt their race models to maximise their potential and take advantage of their competitor's weaknesses. These small changes can be made during a competition but the greatest advantage of race analysis is to strengthen weaknesses over the following training cycle.

A typical race analysis aims to provide detailed information to coaches in order for them to find small areas of improvement at the competition. Information on the lap times for the race tends to be obtained from the official timing system at the competition and the pool is then divided into further sections for further analysis depending on the needs of the coach.

Early race analysis systems required scientists to trawl through various video images and then manually draw lines to indicate the various pool distances. Times were recorded for set distances and again manually entered into a spreadsheet for further calculations on the race parameters. Stroke rates were measured using stop watches from one hand entry through a pre-determined number of strokes to the same position. The time taken between these two points was then used to calculate the stroke rate in either SPM or SPS.

As technology has improved, the analysis process has become more automated and accurate so that results can be provided within minutes of the end of the race rather than months (Smith et al., 2002). Slawson et al. (2010) discussed the methods in which the body or part of the body could be automatically detected within an image using histograms to generate boundary thresholds that may be used for automated tracking of the swimmer within a competition.

Coaches are able to use the information in order to enhance the skill components of the race which have been shown to be important to the end result of many races (Arellano et al., 2000; Blanksby et al., 2002; Burkett et al., 2010; Mason, 1997). In shorter events, start times can comprise more than 20% of the overall race time (Mason, 2001) but is less important to the outcome of longer races.

Each swimmer has an optimal stroke rate but it is possible to alter both stroke rate and stroke length during different phases of the training cycle in order to maximise the velocity throughout the race. The efficiency index generated by some analysis methods also highlights the importance of maintaining the stroke length throughout the entire race in order to optimise performance.

By training athletes to both maximise the distance off the wall in the underwater phase as well as the free swimming speed through the stroke rate and stroke length relationships will result in improved performances during future competitions.

The objectives of this chapter include the evolution of swimming performance at international competitions as well as the contribution of starts and turns to overall performances for British swimmers.

The chapter on competition is divided into the following sections:

1. Olympic performance progressions
2. British performances at the 2011 World Championships
3. British performances at the 2012 Olympic Games
4. Event progressions from 2011-2013

4.2 Methods

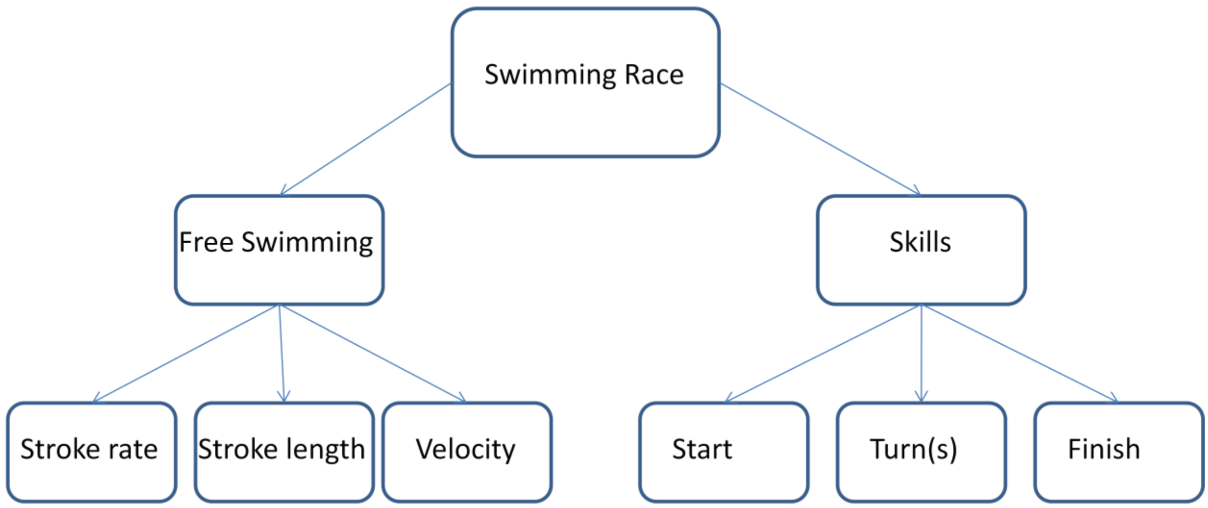


Figure 20: Components of a swimming race

The swimming race can be divided into a number of components as noted in Figure 20 and includes information on the free swimming and skill components used within the race. The skills within swimming race are the start, turn and finish while the free swimming segments make up the rest of the event.

The start time is the period of time from the starting signal (gun) until the swimmer's head passes through a set distance (usually 15m). Turn times tend to have the greatest variation in measurements when comparing systems from different countries. Researchers have measured turns from the time that the head passed the 7.5m in to the wall and back out to the same distance as well as the 5m in to the wall and out again as this is easy to measure both in competitions and training while some analysis systems use the 5m distance in to the wall and either 10m or 15m away from the wall. As the swimmer finishes a race their time is measured from the point at which the head passes the 5m distance in to the wall.

Within each lap the free swimming component of the race is divided into a number of segments. The most traditional division is at the 25m (for long course competitions) so that there are two segments per lap but some analysis systems divide the lap into three or five segments. Additional segments allow for a more accurate representation of what is occurring at each stage of the race but can also been seen as too informative, particularly in longer events.

Utilising the time and distance information from the free swimming components of the race analysis, velocity is calculated using the formula:

$$V = \frac{d}{t}$$

where velocity is measured in metres per second (m/s), distance is measured in metres (m) and time in seconds (s).

The swimmer's velocity is influenced by their stroke rate and stroke length as shown in the formula:

$$V = SR \times SL$$

where velocity is measured in m/s, stroke rate in SPS and stroke length in m.

Stroke rates are not always used by coaches but help to understand how efficient a swimmer is throughout the various free swimming segments of the race. Values are reported as strokes per minute (SPM) and is the number of strokes that a swimmer would take if they continued to use the same stroke rate for an entire minute. An alternative value is seconds per stroke (SPS) where the time is measured for a swimmer to complete one complete stroke cycle.

Stroke length is the distance that the swimmer travels for each stroke cycle and is another measure of stroke efficiency. Generally an increase in stroke rate corresponds with a decrease in the stroke length resulting in a similar velocity. In many races, swimmers tend to increase their stroke rate in the final 15m without an increase in stroke length resulting in a decrease in the velocity with an increase in energy utilisation.

Details of previous competition analyses provided by Rein Haljand are available from the website www.swim.ee where the analysis has been adapted over the years in order to work with the latest technology as well as to provide information as quickly as possible. This information can be invaluable both during the competition as well as afterwards as it allows for detailed analysis of all swimmers in the semi-finals and finals whereas other systems may focus on individual athletes.

Initial analysis of the swimming competitions was generated using the GreenEye© race analysis system that was developed by Swimming Australia. Sheffield Hallam University then designed Nemo© that included each of the variables noted above but also divided the start and turn components into various phases so that more information could be provided to the coaches and swimmers.

Both race analysis systems were portable and could be battery operated if required. The set up included a digital camera attached to a tripod with the video signal linked to a laptop through a Firewire cable. The operator was located around the centre of the competition pool as high as possible for the best possible view of the pool. During some competitions the video image was wirelessly transferred to a central feedback station as well as iPods/iPads of the coaches and swimmers.

Prior to the commencement of each session the lane rope positions were measured for accurate assessment of the location of the swimmer in the event. This information was used for both breakout distances as well as the 5m, 10m, 15m, 25m, 35m and 45m positions on each lap to calculate velocities and stroke rates.

Individual reports for the race were generated within the software and were available to the coaches and swimmers. These data were then used to assess performances at each of the competitions as well as the progression of individual athletes.

4.3 Results

An analysis from the 2010 European Championships in the men's 100m backstroke is presented in Table 10 and was generated from information on www.swim.ee and www.omegatiming.com. Results showed that the winner (Lacourt) did not have the fastest start time to 15m (Donets did at 6.18s) but that his total turn time was 0.18s faster than

Donets. The out turn time (time from feet touching the wall until his head passed the 35m mark) was similar for the two swimmers so the advantage was gained during the approach phase of the turn (the time from the head passing the 45m mark until the feet touched the wall).

Table 10 Skill information in the men's 100m backstroke final at the 2010 European Championships

	Donets	Driebergen	Borisov	Lacourt	Stravius	Grigoriadis	Wildeboer	Tancock
Turn in (s)	2.88	2.97	2.82	2.73	2.82	3.00	2.85	2.78
Turn out (s)	6.84	7.33	7.22	6.81	6.90	7.50	7.41	7.30
Turn total (s)	9.72	10.30	10.04	9.54	9.72	10.50	10.26	10.08
Start (s)	6.18	6.54	6.48	6.34	6.20	6.62	6.38	6.26

This example shows how comparisons may be made between individual athletes within an event so that improvements may be made prior to the next competition.

4.3.1 Olympic Performance Progressions

Times from the performances at the Olympic Games from 1984 through to 2012 were monitored for the first, second, third and eighth places in each of the finals. Over the 28 year period the times in each of the races progressed with new world records set at every Olympic Games in at least one event. For comparisons to be made between the competitions, the time difference between the different places was converted to a percentage with the results displayed in Tables 11-16. These percentage differences were divided into three categories: less than 1% (highlighted green), between 1 and 3% (highlighted orange), and greater than 3% (highlighted in red).

When examining the data for the difference between the 1st and 8th place in each male event (Table 11) there was only one instance where the difference was less than 1%; the 100m freestyle at the 2004 Olympics. At the 1984 Olympic Games only 33% of the male events had a range of 1-3% while this increased to 69% of the events in 1988 and 62% in 1992. 85% of the male events at the 1996 Olympics had a difference of 1-3% between the winner and the last position while this value decreased to 62% in Sydney and 50% in Athens. The value increased to 77% in the 2008 Olympic Games while the results from the London Olympics showed the greatest number of male races where there was a difference of more than 3% for the swimmers competing in the finals.

Results for the female events were similar to the males where there was only one event (the 200m freestyle at the 2004 Olympic Games) where there was less than 1% difference between the 1st and 8th position in the final as highlighted in Table 12. The percentage of races that had a range of 1-3% difference in the final tended to be lower for the females when compared to the males and was approximately half for the 1984, 1988 and 1992 Olympic Games. The percentage of races that resulted in a range of 1-3% between the finalists was 67% in 2004 but decreased to 31% in 2008 with an increase to 46% of the races in the 2012 Olympic Games.

Data was then compared between the 1st and 3rd placed swimmers in each final from the 1984-2012 Olympic Games and presented in Tables 13 and 14. The highlighted cells show that there were no male events where the range was greater than 3% and there were only 5 female races that had a difference of more than 3% in the performance of the medallists. These events were the 100m and 200m butterfly as well as the 400m IM at the 1984 Olympics, the 200m backstroke in Atlanta and the 100m breaststroke in Beijing.

When comparing the male events for the medallists, 75% of the races that were in the middle range of performance differences for the medallists in the 1984 Olympic Games and this decreased to 46% in 1988 and 31% in 1992. All competitions were less than 50% except for the London Olympics where the difference between the gold and bronze medallists was 1-3% in 62% of the male finals.

Table 14 presents the data for the female events at the Olympics from 1984-2012 where there were fewer finals where the difference was less than 1% when compared to the male data. 33% of the female finals at the 1984 Olympics had a range of 1-3% difference between the winner and third place and this increased to 62% in the 1988 and 1992 Olympics. Once again the results in the female events at the London Olympic Games showed a greater percentage of races (62%) where there was a difference in time of 1-3% for the medallists.

The final phase of the competition analysis from the Olympic Games was to examine the performance difference between the first and second placed swimmers as presented in Tables 15 and 16. The only two events where the difference was greater than 3% was the 400m IM at the 1984 Olympics and the 200m backstroke at the 1996 Olympics for the female finals.

In the male events there were 33% of events at the 1984 Olympic Games where the difference between the first and second place was between 1-3%. The results from the 1996 Olympics had the fewest events (8%) where the difference was within the range of 1-3% with an increase to 15% in 2000 and 31% in 2004. The data within Table 15 highlights the small differences in performances between the first two places in each of the male events between 1984 and 2012.

The trend for the female events at the Olympic Games was different to the male events as presented in Table 16. 55% of the races at the 1984 Olympic Games had a difference of 1-3% between the first two competitors. As was seen in the male events, 23% of the races at the 2008 Olympics had performances that were 1-3% different in times between the top two swimmers and this value increased to 31% at the 2012 Olympic Games.

Table 11 Percentage difference between the 1st and 8th place for males at the 1984-2012 Olympic Games

		2012 London	2008 Beijing	2004 Athens	2000 Sydney	1996 Atlanta	1992 Barcelona	1988 Seoul	1984 LA
1st-8th	50 Freestyle	2.91%	1.93%	1.97%	2.35%	2.43%	3.57%	3.91%	
	100 Freestyle	1.90%	2.32%	0.27%	2.31%	2.11%	2.12%	3.61%	2.60%
	200 Freestyle	4.28%	4.20%	3.40%	3.75%	1.30%	1.79%	1.86%	3.79%
	400 Freestyle	3.97%	2.82%	2.56%	3.47%	2.00%	2.87%	1.68%	1.63%
	1500 Freestyle	3.33%	2.68%	3.31%	3.43%	2.72%	4.12%	1.81%	2.38%
	100 Backstroke	2.99%	2.69%	2.19%	3.62%	3.08%	3.66%	2.48%	3.41%
	200 Backstroke	3.91%	2.62%	4.26%	2.19%	2.19%	1.68%	2.36%	3.40%
	100 Breaststroke	3.91%	2.21%	3.75%	2.29%	2.59%	1.20%	1.65%	3.81%
	200 Breaststroke	1.67%	2.92%	1.90%	2.34%	2.56%	3.36%	2.65%	4.60%
	100 Butterfly	1.61%	2.47%	2.49%	2.13%	2.37%	1.73%	2.65%	3.88%
	200 Butterfly	1.93%	2.70%	2.93%	2.57%	2.07%	3.08%	2.69%	2.69%
	200 Individual Medley	4.06%	5.41%	4.11%	2.87%	4.21%	1.62%	3.33%	3.96%
	400 Individual Medley	3.81%	4.53%	4.54%	3.51%	2.05%	2.49%	3.27%	3.00%

Less than 1% difference

1-3% difference

More than 3% difference

Table 12 Percentage difference between the 1st and 8th place for females at the 1984-2012 Olympic Games

		2012 London	2008 Beijing	2004 Athens	2000 Sydney	1996 Atlanta	1992 Barcelona	1988 Seoul	1984 LA
1st-8th	50 Freestyle	2.59%	2.87%	2.46%	5.19%	3.75%	4.25%	2.41%	
	100 Freestyle	1.89%	2.16%	2.53%	3.15%	2.80%	2.39%	2.78%	2.41%
	200 Freestyle	3.46%	2.55%	0.98%	1.10%	2.26%	2.53%	3.25%	3.18%
	400 Freestyle	1.95%	3.20%	2.39%	2.89%	2.43%	2.63%	3.31%	4.20%
	1500 Freestyle	2.88%	3.56%	2.41%	3.42%	2.30%	3.19%	2.95%	4.11%
	100 Backstroke	3.59%	2.06%	2.25%	2.92%	2.72%	3.44%	3.76%	3.13%
	200 Backstroke	4.47%	3.75%	2.79%	4.76%	4.42%	5.04%	5.50%	3.22%
	100 Breaststroke	3.08%	4.76%	2.27%	4.02%	3.01%	3.66%	4.00%	2.93%
	200 Breaststroke	4.39%	3.45%	2.06%	2.02%	3.25%	2.74%	2.58%	3.30%
	100 Butterfly	3.08%	3.09%	3.53%	4.75%	2.92%	3.96%	4.03%	4.97%
	200 Butterfly	2.20%	3.16%	3.47%	3.70%	3.18%	3.39%	2.66%	5.11%
	200 Individual Medley	4.93%	3.68%	3.15%	3.66%	1.79%	4.09%	3.54%	5.64%
	400 Individual Medley	2.61%	4.49%	5.51%	4.34%	2.23%	3.95%	3.85%	5.06%

Green	Less than 1% difference
Yellow	1-3% difference
Pink	More than 3% difference

Table 13 Percentage difference between the 1st and 3rd place for males at the 1984-2012 Olympic Games

		2012 London	2008 Beijing	2004 Athens	2000 Sydney	1996 Atlanta	1992 Barcelona	1988 Seoul	1984 LA
1st-3rd	50 Freestyle	1.16%	0.88%	0.41%	0.23%	0.72%	1.75%	2.51%	
	100 Freestyle	0.59%	0.96%	0.80%	0.88%	0.57%	0.97%	2.00%	1.01%
	200 Freestyle	1.71%	2.07%	0.58%	1.22%	0.57%	0.86%	0.69%	2.05%
	400 Freestyle	2.03%	0.41%	0.45%	2.82%	0.66%	0.78%	0.17%	0.24%
	1500 Freestyle	1.06%	0.21%	0.29%	0.95%	0.67%	2.08%	0.63%	0.76%
	100 Backstroke	1.53%	1.20%	0.55%	2.01%	1.67%	1.46%	0.27%	1.24%
	200 Backstroke	0.47%	0.86%	2.22%	0.71%	0.54%	0.78%	0.92%	1.75%
	100 Breaststroke	1.73%	0.77%	1.31%	0.74%	1.11%	0.42%	0.26%	2.10%
	200 Breaststroke	0.79%	1.01%	1.09%	1.40%	0.45%	0.86%	1.25%	2.96%
	100 Butterfly	0.45%	1.06%	0.21%	0.42%	1.62%	0.17%	0.56%	1.43%
	200 Butterfly	0.22%	0.83%	1.28%	0.71%	0.83%	1.90%	1.13%	0.40%
	200 Individual Medley	1.68%	1.97%	1.40%	1.56%	1.01%	0.20%	1.82%	2.38%
	400 Individual Medley	1.51%	1.71%	1.54%	1.40%	0.54%	0.82%	1.26%	1.19%

(green)	Less than 1% difference
(yellow)	1-3% difference
(pink)	More than 3% difference

Table 14 Percentage difference between the 1st and 3rd place for females at the 1984-2012 Olympic Games

		2012 London	2008 Beijing	2004 Athens	2000 Sydney	1996 Atlanta	1992 Barcelona	1988 Seoul	1984 LA
	50 Freestyle	1.39%	0.46%	1.32%	1.26%	1.07%	1.74%	0.86%	
	100 Freestyle	0.82%	0.51%	1.03%	1.10%	0.78%	0.55%	1.01%	0.29%
	200 Freestyle	1.90%	0.20%	0.35%	0.48%	1.17%	1.48%	1.14%	0.38%
	400 Freestyle	0.64%	0.12%	0.35%	0.82%	0.58%	1.61%	1.12%	1.75%
	1500 Freestyle	1.14%	1.78%	0.41%	0.92%	0.58%	1.07%	0.54%	1.49%
	100 Backstroke	0.85%	0.67%	0.84%	1.12%	1.50%	1.22%	1.10%	0.57%
	200 Backstroke	1.97%	1.49%	0.53%	2.21%	3.20%	2.41%	2.34%	0.68%
1st-3rd	100 Breaststroke	1.49%	3.22%	0.77%	0.74%	2.10%	1.81%	1.28%	1.41%
	200 Breaststroke	0.94%	1.96%	1.68%	0.69%	0.79%	0.16%	1.10%	0.67%
	100 Butterfly	1.69%	0.91%	0.47%	2.73%	0.17%	0.66%	0.87%	3.42%
	200 Butterfly	0.41%	1.65%	1.55%	0.98%	1.65%	0.28%	0.99%	3.80%
	200 Individual Medley	1.07%	1.45%	1.19%	1.98%	0.60%	1.70%	1.68%	2.41%
	400 Individual Medley	1.64%	0.83%	0.97%	1.30%	1.19%	0.37%	0.71%	3.14%

Less than 1% difference

1-3% difference

More than 3% difference

Table 15 Percentage difference between the 1st and 2nd place for the males at the 1984-2012 Olympic Games

		2012 London	2008 Beijing	2004 Athens	2000 Sydney	1996 Atlanta	1992 Barcelona	1988 Seoul	1984 LA
1st-2nd	50 Freestyle	0.93%	0.70%	0.05%	0.00%	0.58%	1.75%	0.98%	
	100 Freestyle	0.02%	0.23%	0.12%	0.80%	0.14%	0.83%	0.92%	0.88%
	200 Freestyle	1.71%	1.80%	0.49%	0.45%	0.42%	0.15%	0.59%	1.52%
	400 Freestyle	0.86%	0.26%	0.12%	1.26%	0.45%	0.07%	0.09%	0.11%
	1500 Freestyle	0.98%	0.08%	0.21%	0.59%	0.67%	1.32%	0.25%	0.59%
	100 Backstroke	1.44%	1.07%	0.53%	0.65%	1.60%	0.11%	0.24%	0.99%
	200 Backstroke	0.33%	0.34%	2.05%	0.50%	0.38%	0.34%	0.19%	1.25%
	100 Breaststroke	0.80%	0.49%	0.28%	0.44%	0.20%	0.29%	0.02%	0.55%
	200 Breaststroke	0.12%	0.96%	1.04%	1.23%	0.35%	0.82%	0.45%	1.80%
	100 Butterfly	0.45%	0.02%	0.08%	0.34%	0.49%	0.06%	0.02%	0.28%
	200 Butterfly	0.04%	0.59%	0.45%	0.35%	0.79%	1.42%	1.10%	0.31%
	200 Individual Medley	0.55%	1.97%	1.38%	0.66%	0.18%	0.17%	1.18%	1.32%
	400 Individual Medley	1.48%	0.94%	1.41%	0.97%	0.14%	0.52%	1.01%	0.40%

(green)	Less than 1% difference
(yellow)	1-3% difference
(pink)	More than 3% difference

Table 16 Percentage difference between the 1st and 2nd place for the females at the 1984-2012 Olympic Games

		2012 London	2008 Beijing	2004 Athens	2000 Sydney	1996 Atlanta	1992 Barcelona	1988 Seoul	1984 LA
	50 Freestyle	0.95%	0.04%	1.25%	0.78%	0.12%	1.16%	0.59%	
	100 Freestyle	0.71%	0.08%	0.59%	0.92%	0.69%	0.36%	0.97%	0.00%
	200 Freestyle	1.70%	0.13%	0.16%	0.07%	0.35%	0.08%	0.86%	0.23%
	400 Freestyle	0.13%	0.03%	0.20%	0.51%	0.42%	0.08%	0.85%	1.27%
	1500 Freestyle	0.83%	1.23%	0.08%	0.59%	0.40%	0.94%	0.38%	1.13%
	100 Backstroke	0.60%	0.42%	0.21%	0.56%	0.46%	0.75%	1.09%	0.13%
	200 Backstroke	1.48%	0.78%	0.41%	1.60%	3.14%	1.85%	1.01%	0.50%
1st-2nd	100 Breaststroke	0.12%	2.34%	0.76%	0.65%	0.53%	0.25%	1.15%	1.15%
	200 Breaststroke	0.80%	1.29%	0.16%	0.15%	0.23%	0.14%	0.53%	0.51%
	100 Butterfly	1.56%	0.65%	0.21%	2.35%	0.02%	0.20%	0.76%	1.55%
	200 Butterfly	0.23%	0.43%	0.25%	0.55%	1.59%	0.26%	0.31%	2.80%
	200 Individual Medley	0.45%	0.11%	0.43%	1.43%	0.31%	0.20%	0.54%	1.87%
	400 Individual Medley	1.05%	0.16%	0.04%	0.86%	1.01%	0.07%	0.61%	3.14%

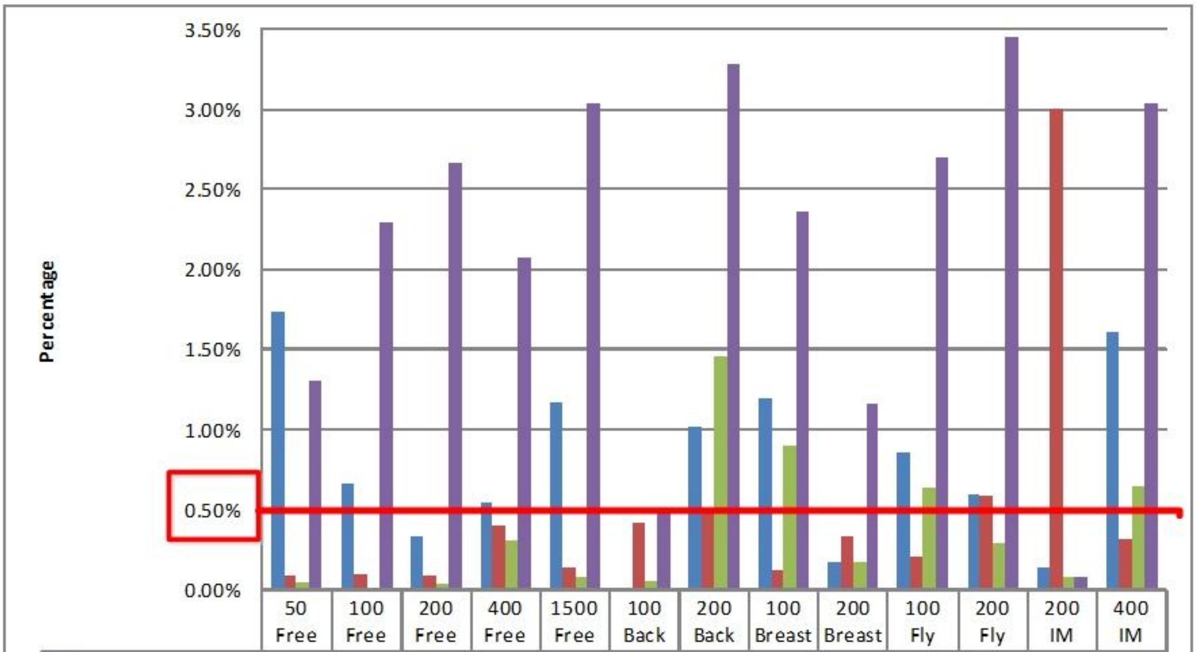
(green)	Less than 1% difference
(yellow)	1-3% difference
(red)	More than 3% difference

4.3.2 British performances at the 2011 World Championships

The final race times of swimmers was analysed at the World Championships in 2011 for both male and female events in order to see the percentage difference between the medallists and British swimmers in each event. As it has been previously noted, a 1% improvement in time is achievable at the elite level on an annual basis and this mark has been highlighted in Tables 17 and 18.

Data from these tables indicate that there were two male and eight female events where the British swimmers were within the 1% difference in time to potentially medal in the 2012 London Olympic Games. These events included the 100m backstroke and 200m IM for the males and the 50m, 100m, 400m and 800m freestyle as well as the 200m backstroke, 100m and 200m butterfly and the 400m IM for the females. The negative percentages seen in the women’s 800m freestyle and 200m butterfly events were due to the fact that British swimmers medalled in these races at the 2011 World championships.

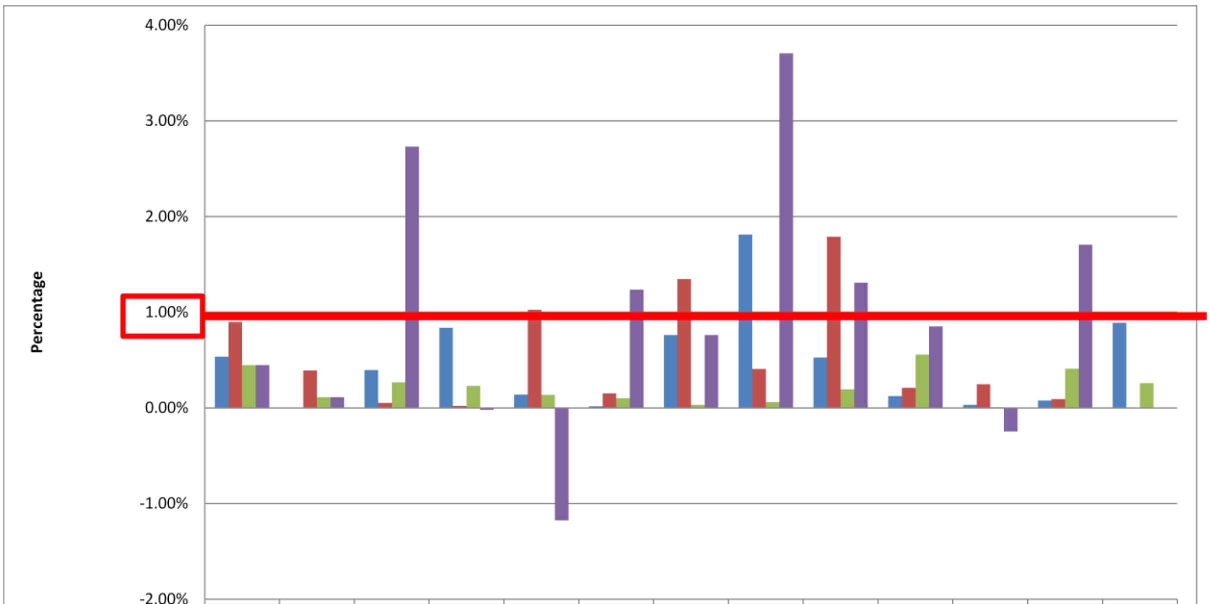
Table 17 Percentage difference between the medallists and British swimmers in the male events at the 2011 World championships



	50 Free	100 Free	200 Free	400 Free	1500 Free	100 Back	200 Back	100 Breast	200 Breast	100 Fly	200 Fly	200 IM	400 IM
% Diff Gold-Silver	1.74%	0.67%	0.33%	0.54%	1.17%	0.00%	1.01%	1.19%	0.17%	0.86%	0.59%	0.14%	1.61%
% Diff Silver-Bronze	0.09%	0.10%	0.09%	0.40%	0.14%	0.42%	0.51%	0.12%	0.33%	0.21%	0.58%	3.00%	0.32%
% Diff Bronze-4th	0.05%	0.02%	0.04%	0.31%	0.08%	0.06%	1.46%	0.90%	0.17%	0.64%	0.29%	0.08%	0.65%
% Diff British-Bronze	1.31%	2.30%	2.67%	2.08%	3.04%	0.51%	3.29%	2.36%	1.16%	2.70%	3.46%	0.08%	3.03%

In each of the other male events is appeared that the chances of medalling in the 2012 Olympics was limited so the focus of the support should be around the swimmers in the 100m backstroke and 200m IM events.

Table 18 Percentage difference between the medallists and British swimmers in the female events at the 2011 World championships



	50 FREE	100 FREE	200 FREE	400 FREE	800 FREE	100 BACK	200 BACK	100 BREAST	200 BREAST	100 FLY	200 FLY	200 IM	400 IM
% Diff Gold-Silver	0.54%	0.00%	0.40%	0.84%	0.14%	0.02%	0.76%	1.81%	0.53%	0.12%	0.03%	0.08%	0.89%
% Diff Silver-Bronze	0.90%	0.39%	0.05%	0.02%	1.03%	0.15%	1.35%	0.41%	1.79%	0.21%	0.25%	0.09%	0.00%
% Diff Bronze-4th	0.45%	0.11%	0.27%	0.23%	0.14%	0.10%	0.03%	0.06%	0.19%	0.56%	0.01%	0.41%	0.26%
% Diff British-Bronze	0.45%	0.11%	2.73%	-0.02%	-1.18%	1.24%	0.76%	3.71%	1.31%	0.85%	-0.25%	1.71%	0.00%

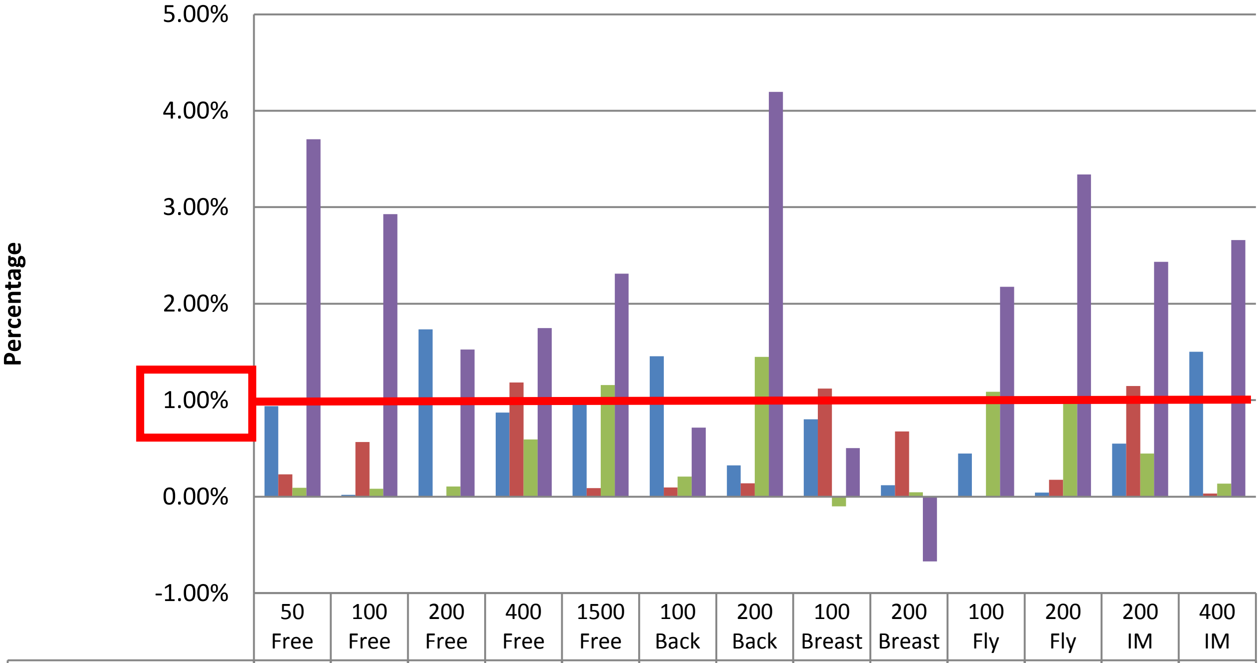
The data presented on the female swimmers indicated that there were many more events where there was a chance of a medal at the London Olympics.

4.3.3 British performances at the 2012 Olympic Games

Similar analysis was conducted on the British swimmers competing at the London 2012 Olympic Games with the data presented in Tables 19 and 20.

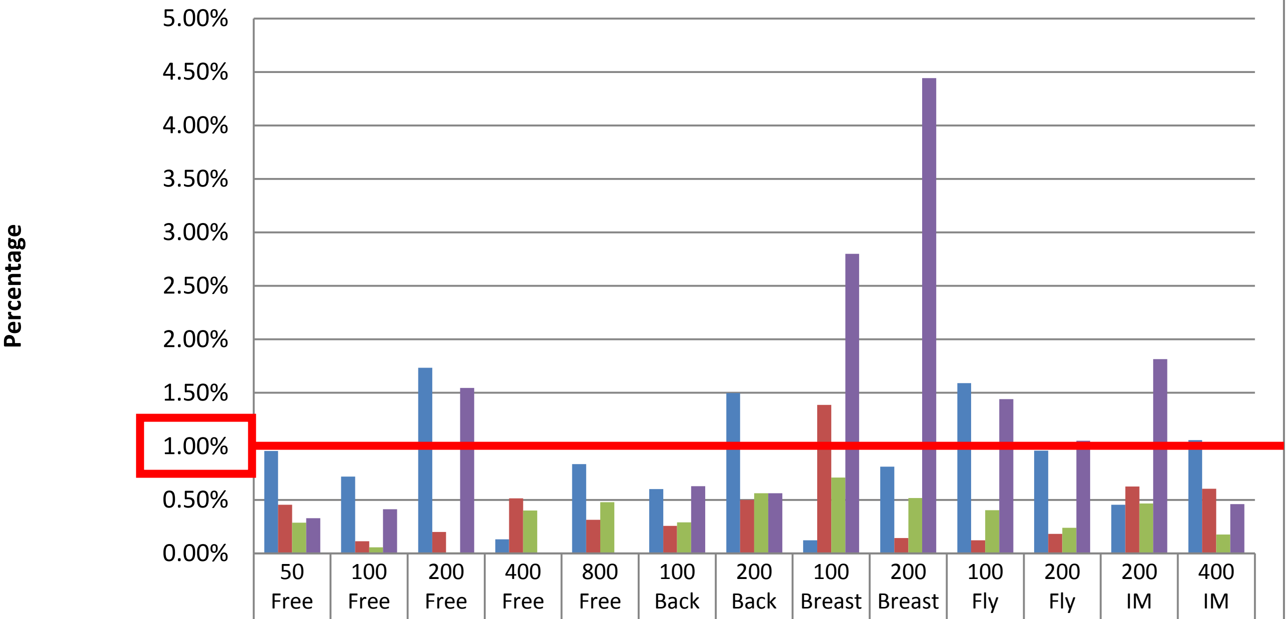
When examining the performances of the British males there was only one medallist in the 200m breaststroke event. The swimmer in the 100m backstroke was 0.72% away from the bronze medal while the swimmer in the 100m breaststroke performed a time that was 0.50% away from a medal. Results suggested that the swimmer in the 100m backstroke did not improve at the same rate as his competitors between the 2011 World Championships and the 2012 Olympic Games while the breaststroke swimmer made large improvements as they were not within the suggested 1% range after the performances in 2011. The swimmer in the 200m IM event was the closest to a potential medal at the end of 2011 (0.08%) but regressed in London to be 2.44% away from the podium.

Table 19 Percentage difference between the medallists and British swimmers in the male events at the 2012 Olympic Games



	50 Free	100 Free	200 Free	400 Free	1500 Free	100 Back	200 Back	100 Breast	200 Breast	100 Fly	200 Fly	200 IM	400 IM
% Diff Gold-Silver	0.94%	0.02%	1.74%	0.87%	0.99%	1.46%	0.33%	0.80%	0.12%	0.45%	0.04%	0.55%	1.50%
% Diff Silver-Bronze	0.23%	0.57%	0.00%	1.18%	0.09%	0.09%	0.14%	1.12%	0.67%	0.00%	0.18%	1.15%	0.03%
% Diff Bronze - 4th	0.09%	0.08%	0.10%	0.59%	1.16%	0.21%	1.45%	-0.10%	0.05%	1.09%	1.01%	0.45%	0.14%
% Diff British - Bronze	3.71%	2.93%	1.52%	1.75%	2.31%	0.72%	4.20%	0.50%	-0.67%	2.18%	3.34%	2.44%	2.66%

Table 20 Percentage difference between the medallists and the British swimmers in the female events at the 2012 Olympic Games



	50 Free	100 Free	200 Free	400 Free	800 Free	100 Back	200 Back	100 Breast	200 Breast	100 Fly	200 Fly	200 IM	400 IM
% Diff Gold-Silver	0.96%	0.72%	1.73%	0.13%	0.83%	0.60%	1.50%	0.12%	0.81%	1.59%	0.96%	0.45%	1.06%
% Diff Silver-Bronze	0.45%	0.11%	0.20%	0.51%	0.31%	0.26%	0.50%	1.39%	0.14%	0.12%	0.18%	0.62%	0.60%
% Diff Bronze - 4th	0.29%	0.06%	0.01%	0.40%	0.48%	0.29%	0.56%	0.71%	0.52%	0.40%	0.24%	0.47%	0.18%
% Diff British - Bronze	0.33%	0.41%	1.55%	0.00%	0.00%	0.63%	0.56%	2.80%	4.44%	1.44%	1.05%	1.81%	0.46%

Whilst the results from the 2011 World Championships indicated that there were potential medals in 8 events, Great Britain ended with 2 bronze medals at the London Olympics. These were obtained in the 400m and 800m freestyle events. In the 50m freestyle the swimmer decreased the gap from the podium from 0.45% in 2011 to 0.33% in 2012 but the 100m freestyle performance changed from 0.11% down to 0.41% over the same time period. Performances in the 100m backstroke improved from 1.24% away from a medal in 2011 to 0.63% in 2012 with a similar trend in the 200m backstroke (0.76-0.56%). The only other female event within the 1% range of a medal was the 400m IM that was 0.46% away in 2012 but did result in a bronze medal in 2012. The noticeable decrease in performance by British females was in the butterfly events with a medal in the 200m butterfly in 2011 and 1.05% away in 2012. The weakest stroke for British swimmers was breaststsroke where they were 2.80% away from the podium in the 100m event and 4.44% in the 200m event.

As a result of the decrease in medals between the 2011 World Championships and 2012 Olympic Games times were compared between the Trials and major competition for the year (approximately 15 weeks apart) as well as the performances at the major events between the two years (Table 21).

Cells that are highlighted in green in the first two columns show that the time during the major event was faster than the time during the Trials for that year. Yellow cells indicate performances that were between 0 and 1% slower while the red cells show swims that were more than 1% slower during the major competition compared with the Trials. Similar formatting was used in the final column were performances were compared between the 2011 World Championships and the 2012 Olympic Games.

Results showed that there were some swimmers who were able to improve their performances both between the Trials and major meet each year as well as improvements in time on an annual basis (e.g. in the men's 200m and 400m freestyle, 100m breaststroke and women's 200m backstroke and freestyle). Likewise there were swimmers who did not improve their times between the Trials and major event but did improve each year (e.g. women's 400m freestyle and men's 1500m freestyle). In both the women's 200m IM and men's 400m IM the swimmers did not improve their time within the year but did between the years and this may have been due to the fact that they did not reach the finals in the major events.

During 2011 68% of the performances were faster during the World Championships compared to the Trials which was better than the 41% achieved in 2012. There was a 60% improvement in times for the British swimmers when examining the data at the major championships in 2011 and 2012.

Table 21 Performance progressions of British swimmers between the Trials and major meets in 2011 and 2012

		2011 Trials - Event	2012 Trials - Event	2011-2012
Female	400 FR	0.48%	0.27%	-0.41%
	800 FR	-0.55%	0.36%	0.56%
Female	200 IM	1.24%	2.23%	-0.82%
Male	50 FR	-0.95%	-0.13%	1.38%
	100 FR	-0.57%	-0.65%	0.14%
Male	400 FR	-0.23%	-0.49%	-0.72%
Male	1500 FR	0.57%	0.09%	-1.93%
Female	100 BF	-0.23%	0.71%	0.19%
	200 BF	-0.43%	3.01%	3.33%
Male	200 IM	-2.89%	0.06%	0.59%
Female	50 FR	-1.95%	1.39%	-0.53%
	100 FR	-2.86%	0.17%	0.34%
Male	100 BR	-0.86%	-1.02%	-1.50%
	200 BR	0.09%	-1.81%	-2.36%
Male	200 BK		-0.40%	
Female	200 BF	-0.51%	0.34%	0.39%
Female	200 FR	-1.70%	-0.10%	-1.05%
Female	400 IM	-1.79%	0.55%	-0.02%
Female	100 BR		-1.21%	
Male	400 IM	1.29%	1.22%	-0.44%
Male	200 FR	-0.59%	-0.68%	-1.27%
Male	100 BF	0.94%	1.03%	-1.22%
Male	200 BF	1.29%	0.90%	-1.03%
Female	200 BK	-2.26%	-1.11%	-1.18%
Female	100 BK	2.21%	-1.67%	-4.54%
Female	200 BR	-1.54%	0.37%	0.31%
Male	100 BK	-0.36%	0.17%	0.00%

4.3.4 Race analysis from the 2012 Olympic Games

With the performances of the British swimmers not to the level of expectations in London further analysis was conducted on the results of each of the swimmers in the races. The Nemo© software was used to measure the start times (15m), turn times (5m in and 10m out) and finish times. Stroke counts were the total for the race while stroke rate values were averaged for each of the free swimming segments. Velocity was used with the stroke rate values to determine the stroke length within the race. Values for the height and weight of the swimmers were taken from the official website and were self reported by the athletes.

Data within Tables 22 and 23 indicate that for both the males and females, as the event distance increased, the time for the starts and turns decreased. The finish time was similar in the 100m, 200m, and 400m events for the females, was fastest in the 50m events and slowest in the 800m events.

Table 22 Mean competition analysis data for the male freestyle events at the 2012 Olympic Games

Event	Start (s)	Turn (s)	Finish (s)	Stroke count	Stroke rate (SPM)	Stroke length (m)	Velocity (m/s)	Height (cm)	Weight (kg)
50m Freestyle	5.32		2.31	36	62.0	2.05	2.10	194.00	88.75
100m Freestyle	5.65	6.87	2.57	69	51.7	2.34	2.01	197.00	89.80
200m Freestyle	5.99	7.38	2.66	127	43.0	2.56	1.83	191.20	84.60
400m Freestyle	6.26	7.89	2.83	253	39.1	2.68	1.73	188.33	80.00
1500m Freestyle	6.77	8.20	2.67	982	38.0	2.64	1.65	190.25	81.75

Table 22 showed that the males tended to have slower finish times as the race distance increased except in the 1500m where the winner had a final 50m time of 25.68s which skewed the results. This compared with a final split time of 27.42s for the silver medallist and 27.65s for the bronze medallist in the same final. The start time was fastest in the 50m freestyle (5.32s) and slowed as the race length increased so that the 1500m mean start time for men was 6.77s. The turn times showed the same trend with an average of 6.87s in the 100m freestyle and 8.20s in the 1500m freestyle.

Stroke rates and velocities were highest in the shortest races for both males and females while the stroke length tended to increase as the race distance increased. The exception to this was in both of the longest races where the stroke length was slightly lower than in the 400m events (2.18m to 2.21m for the females and 2.64m to 2.58m for the males).

Table 23 Mean competition analysis data for the female freestyle events at the 2012 Olympic Games

Event	Start (s)	Turn (s)	Finish (s)	Stroke count	Stroke rate (SPM)	Stroke length (m)	Velocity (m/s)	Height (cm)	Weight (kg)
50m Freestyle	6.25		2.61	43	63.5	1.80	1.88	178.50	64.83
100m Freestyle	6.41	7.77	2.89	78	53.2	2.03	1.80	177.33	66.33
200m Freestyle	6.80	8.29	2.87	157	46.0	2.18	1.67	178.67	66.83
400m Freestyle	7.00	8.63	2.91	319	43.8	2.21	1.60	180.75	70.00
800m Freestyle	7.27	8.82	3.10	638	43.3	2.18	1.57	178.50	67.50

Pearson Product Moment correlations were performed on the data to determine the relationship between different stroking parameters. Significant relationships were noted in Table 24 and showed that the relationship between height and weight (0.922) was much greater than the relationship between velocity and weight (0.473). The negative value indicated in the relationship between velocity and stroke count indicated that as the velocity increased, the stroke count decreased.

Table 24 Pearson product moment correlations for the freestyle events at the 2012 Olympic Games

	Length	Stroke Count	Velocity	Height	Weight
Length		0.422			
Stroke count	0.422		-0.195		
Velocity		-0.195		0.546	0.473
Height			0.546		0.922
Weight			0.473	0.922	

The length value used in the Table 24 is a value used to normalise the stroke length of the swimmer based on their height (i.e. length = DPS/height). This was used to compare race parameters of shorter swimmers with taller swimmers in the freestyle events such that height did not affect the outcome.

Results of the analysis from the London Olympics in the freestyle events suggest that height and weight have a significant impact on the swimming velocity as well as stroke count to a lesser degree. When normalising the data to allow for the height of the individual swimmers, there was a strong relationship with stroke count. Based on this information, improvements in stroke count and stroke rate should improve performances in the freestyle events.

Starts

Further analysis was then conducted on the skill components of the race in the 100m and 200m events at the 2012 Olympic Games. Table 25 displays the start time to 15m for the winner, medallists and finalists in each of the male events.

Data showed that in all events except for the 100m butterfly the winner had the fastest start time suggesting the importance of the start in the 100m and 200m events at this level of competition. It was interesting to note that in some instances the average time for the swimmers competing in the final had faster start times than the medallists as was seen in the 200m freestyle and 100m butterfly events.

The fastest start time to 15m by the winners in the men’s 100m and 200m events was observed in the 100m freestyle (5.52s) and the slowest start time (6.52s) was measured in the 200m backstroke and 200m breaststroke events. The largest difference between the winner and the average for the finalists was 0.35s in the 200m butterfly event.

Table 25 Start time to 15m for the winner, medallists and finalists in the male 100m and 200m events at the 2012 Olympic Games

		Winner	Medallists	Finalists
Male Starts	100m Freestyle (s)	5.52	5.59	5.65
	200m Freestyle (s)	5.82	6.07	5.99
	100m Backstroke (s)	6.14	6.33	6.35
	200m Backstroke (s)	6.52	6.60	6.65
	100m Breaststroke (s)	6.10	6.21	6.31
	200m Breaststroke (s)	6.52	6.65	6.67
	100m Butterfly (s)	5.70	5.68	5.67
	200m Butterfly (s)	5.66	5.91	6.01

Table 26 displays the start times for the females in the 100m and 200m events at the 2012 London Olympics. The winner of each of the events was not always the swimmer with the fastest start time as was seen in the two backstroke events, the 200m breaststroke and the 100m butterfly which was a world record. In this event the winner had a start time of 6.72s while the average for the medallists was 6.45s and 6.55s for the finalists. The difference of 0.18s was not the largest between the winner and medallists – this was seen in the 100m backstroke where the winner was 0.27s slower than the average start time for the medallists.

Table 26 Start time to 15m for the winner, medallists and finalists in the female 100m and 200m events at the 2012 Olympic Games

		Winner	Medallists	Finalists
Female Starts	100m Freestyle (s)	6.24	6.41	6.41
	200m Freestyle (s)	6.54	6.69	6.80
	100m Backstroke (s)	7.68	7.41	7.34
	200m Backstroke (s)	7.60	7.49	7.52
	100m Breaststroke (s)	7.54	7.81	7.81
	200m Breaststroke (s)	8.00	7.89	7.82
	100m Butterfly (s)	6.72	6.45	6.55
	200m Butterfly (s)	6.54	6.88	6.87

The components of the start for the swimmers in the male events at the 2012 Olympic Games are displayed in Table 27. In addition to the total time to 15m, analysis included the block time (time from the gun until the feet leave the block), head entry time, breakout time and breakout distance. The velocity at which the swimmer exited the underwater phase was calculated at the breakout distance divided by the time to reach that point.

Where the British swimmer was faster than the winner, medallists or finalists in a particular start phase it was highlighted in green. There were four instances where the British swimmer was faster than the winner of the event and included the total start time in the 100m butterfly, block time in the 200m backstroke, head entry time in the 100m freestyle and the breakout time in the 200m butterfly. Seven examples were noted where the British swimmers were faster than the average for the medallists in that event. Three of these were in the 100m butterfly for the head entry time, breakout time and breakout distance. One swimmer had a longer head entry time than the medallists in the 200m backstroke while swimmers in the 200m freestyle had good breakout distances and times when compared to the medallists. There were another ten instances where the British swimmers were better than the group of finalists in the same event. The two start phases in which the male British swimmers tended to be as good or better than the group of swimmers in their event were the breakout time and breakout distance of the start.

Values presented in italics represent the start times as observed in relay events where the swimmer was either second, third or fourth in the relay.

Similar analyses were conducted on the female races at the same competition and are presented in Table 28. There were fewer instances where the British swimmers were better than the entire group of females for the start segments at the 2012 Olympics. One swimmer was faster than the winner in the block and flight phases of the start in the 100m butterfly while a second swimmer had a longer breakout time than the winner in this event. The other two swims where the British swimmer was better than the winner was the breakout time in the 200m butterfly and the head entry time in the 200m freestyle event.

One British swimmer in the 50m freestyle had a better block time, breakout velocity and 15m time when compared to the medallists in the same event. In the 100m butterfly, one British swimmer had a longer flight phase and more appropriate breakout velocity than the medallists. The breakout distance of another female swimmer in the 200m butterfly was also better than the three swimmers who stood on the podium at the end of the race. In general, the British female swimmers did not have as many segments within the start of the race where they were better than others in the same race when compared to the male swimmers.

Table 27 Analysis of the male swimming start phases at the 2012 Olympic Games for the winner, medallists, finalists and British swimmers

			Average of Block Time (s)	Average of Head Entry Time (s)	Average of Breakout Time (s)	Average of Breakout Distance (m)	Average of BO Velocity (m/s)	Average of First 15m Time (s)
50m Freestyle	Winner	Florent Manaudou	0.62	1.00	4.80	14.08	2.93	5.22
	Medallists	n = 3	0.62	1.01	3.80	12.06	3.17	5.24
	Finalists	n = 5	0.66	1.01	3.85	11.83	3.07	5.32
	British		0.73		3.40	10.09	2.97	5.56
100m Backstroke	Winner	Matt Grevers	0.58	0.90	5.60	13.91	2.48	6.14
	Medallists	n = 3	0.59	0.85	5.86	14.13	2.41	6.33
	Finalists	n = 6	0.59	0.85	5.92	14.25	2.40	6.35
	British		0.65	0.94	6.06	14.41	2.38	6.40
			0.62	0.82	6.44	14.33	2.23	6.74
100m Breaststroke	Winner	Cameron van der Burgh	0.63	1.04	5.04	13.14	2.61	6.10
	Medallists	n = 2	0.63	1.00	5.09	13.15	2.58	6.21
	Finalists	n = 3	0.63	0.97	5.07	13.06	2.58	6.31
	British		0.80	1.12	5.20	12.14	2.33	7.04
			0.80	1.12	6.46	14.50	2.24	7.04
100m Butterfly	Winner	Michael Phelps	0.68	1.02	4.48	12.65	2.82	5.70
	Medallists	n = 3	0.67	1.00	4.73	13.21	2.79	5.68
	Finalists	n = 6	0.70	1.05	4.61	12.87	2.79	5.67
	British		0.64	0.94	5.06	13.74	2.72	5.70
			0.65	1.04	4.68	12.98	2.77	5.74
100m Freestyle	Winner	Nathan Adrian	0.66	1.08	3.52	10.80	3.07	5.52
	Medallists	n = 3	0.65	1.01	3.43	10.37	3.02	5.59
	Finalists	n = 6	0.66	1.00	3.52	10.51	2.99	5.65
	British		0.74	1.04	3.84	10.88	2.83	5.80
			0.66	1.00	3.72	10.97	2.95	5.82

200m Backstroke	Winner	Scott Tyler Clary	0.58	0.76	5.92	13.82	2.33	6.52
	Medallists	n = 3	0.61	0.81	5.95	13.82	2.32	6.60
	Finalists	n = 4	0.61	0.82	5.97	13.76	2.31	6.65
	British		0.64	0.82	6.80	14.66	2.16	6.98
			0.58	0.68	6.02	14.08	2.34	6.52
200m Breaststroke	Winner	Daniel Gyurta	0.68	0.96	5.30	12.90	2.43	6.52
	Medallists	n = 2	0.72	1.02	5.57	13.24	2.38	6.65
	Finalists	n = 4	0.71	1.04	5.68	13.51	2.38	6.67
	British		0.76	1.08	5.84	13.57	2.32	6.78
			0.74	1.08	6.04	13.99	2.32	6.90
200m Butterfly	Winner	Chad Le Clos	0.72	1.00	4.74	13.24	2.79	5.66
	Medallists	n = 3	0.67	0.99	4.73	12.87	2.72	5.91
	Finalists	n = 5	0.69	1.02	4.80	12.87	2.68	6.01
	British		0.78	1.16	5.50	14.08	2.56	6.06
			0.66	0.98	4.74	12.48	2.63	6.16
200m Freestyle	Winner	Yannick Agnel	0.66	0.98	4.52	12.65	2.80	5.82
	Medallists	n = 3	0.67	0.97	3.86	10.86	2.81	6.07
	Finalists	n = 5	0.67	1.00	4.17	11.57	2.77	5.99
	British		0.70	1.06	4.46	11.97	2.68	6.04
			0.74	1.12	4.94	12.82	2.60	6.10
			0.71	0.98	4.22	11.22	2.66	6.24
200m IM	Winner	Michael Phelps	0.64	1.00	4.20	12.23	2.91	5.86
	Medallists	n = 3	0.65	1.00	4.30	12.37	2.88	5.82
	Finalists	n = 4	0.66	1.00	4.46	12.56	2.82	5.84
	British		0.68	1.00	4.94	13.15	2.66	5.90
			0.76	1.16	5.24	13.57	2.59	6.06

400m Freestyle	Winner	Sun Yang	0.68	0.98	3.20	8.95	2.80	6.40
	Medallists	n = 2	0.69	0.98	3.47	8.95	2.58	6.26
	Finalists	n = 3	0.69	0.97	3.83	10.42	2.72	6.26
	British		0.67	1.04	4.66	12.39	2.66	6.10
				0.96	4.54	11.89	2.62	6.26
400m IM	Winner	Ryan Lochte	0.62	1.06	4.26	12.20	2.86	5.94
	Medallists	n = 2	0.64	1.02	4.66	12.30	2.64	6.21
	Finalists	n = 3	0.65	1.02	4.57	12.30	2.69	6.08
	British		0.75	1.16	5.08	13.40	2.64	5.98
			0.62	0.96	4.54	11.97	2.64	6.20
1500m Freestyle	Winner	Sun Yang	0.82	1.10	3.52	9.03	2.57	6.80
	Medallists	n = 3	0.81	1.07	3.76	9.65	2.57	6.72
	Finalists	n = 4	0.79	1.07	3.92	10.02	2.56	6.77
	British		0.72	1.06	4.40	11.13	2.53	6.92
			0.78	1.16	3.76	9.71	2.58	6.96

Better than the winner

Better than the finalists

Better than the medallists

Better than the group

Table 28 Analysis of the female swimming start phases at the 2012 Olympic Games for the winner, medallists, finalists and British swimmers

			Average of Block Time (s)	Average of Head Entry Time (s)	Average of Breakout Time (s)	Average of Breakout Distance (m)	Average of Breakout Velocity (m/s)	Average of First 15m Time (s)
50m Freestyle	Winner	R Kromowidjojo	0.70	1.02	4.60	12.19	2.65	6.04
	Medallists	n = 3	0.69	0.99	4.25	11.12	2.62	6.19
	Finalists	n = 7	0.70	0.98	3.92	10.31	2.63	6.25
	British		0.70	0.98	3.80	10.00	2.63	6.24
			0.64	0.98	4.06	10.51	2.59	6.28
100m Backstroke	Winner	Missy Franklin	0.63	0.80	5.38	11.22	2.09	7.68
	Medallists	n = 2	0.61	0.76	5.72	12.19	2.13	7.41
	Finalists	n = 5	0.59	0.80	6.18	13.10	2.12	7.34
	British		0.60	0.80	6.66	13.82	2.08	7.34
			0.68	0.78	6.72	13.82	2.06	7.38
100m Breaststroke	Winner	Ruta Meilutyte	0.60	0.98	4.64	10.97	2.36	7.54
	Medallists	n = 2	0.67	1.02	4.81	10.84	2.25	7.81
	Finalists	n = 2	0.67	1.02	4.81	10.84	2.25	7.81
	British		0.72	1.04	5.60	12.23	2.18	7.86
100m Butterfly	Winner	Dana Vollmer	0.78	0.96	3.98	10.46	2.63	6.72
	Medallists	n = 3	0.69	0.91	4.74	12.11	2.56	6.45
	Finalists	n = 4	0.71	0.92	4.87	12.12	2.49	6.55
	British		0.76	0.96	5.24	12.14	2.32	6.84
			0.62	0.92	4.08	10.21	2.50	6.64
100m Freestyle	Winner	R Kromowidjojo	0.70	0.98	4.90	12.56	2.56	6.24
	Medallists	n = 3	0.72	1.01	4.71	11.75	2.50	6.41
	Finalists	n = 6	0.72	1.02	4.61	11.47	2.49	6.41
	British		0.70	1.02	4.00	10.04	2.51	6.50
			0.68	1.00	4.18	10.38	2.48	6.56

200m Backstroke	Winner	Missy Franklin	0.58	0.74	5.88	12.23	2.08	7.60
	Medallists	n = 3	0.62	0.77	6.50	13.35	2.05	7.49
	Finalists	n = 5	0.62	0.77	6.40	13.14	2.06	7.52
	British		0.66	0.86	7.10	14.62	2.06	7.34
			0.61	0.72	5.96	10.80	1.81	8.34
200m Breaststroke	Winner	Rebecca Soni	0.70	0.96	5.42	11.47	2.12	8.00
	Medallists	n = 3	0.72	1.03	5.87	12.28	2.09	7.89
	Finalists	n = 5	0.72	1.04	5.90	12.46	2.11	7.82
	British		0.78	1.10	5.30	11.30	2.13	8.02
200m Butterfly	Winner	Liuyang Jiao	0.64	0.96	5.02	12.46	2.48	6.54
	Medallists	n = 3	0.67	0.97	5.37	12.47	2.32	6.88
	Finalists	n = 5	0.70	0.99	5.16	12.14	2.35	6.87
	British		0.76	0.94	4.88	11.55	2.37	6.98
			0.66	0.94	5.06	12.23	2.42	6.82
200m Freestyle	Winner	Allison Schmitt	0.68	1.02	4.28	10.97	2.56	6.54
	Medallists	n = 3	0.68	0.97	3.79	9.90	2.61	6.69
	Finalists	n = 6	0.69	0.99	3.88	9.93	2.56	6.80
	British		0.66	1.10	4.12	10.04	2.44	6.92
			0.31	0.62	3.38	9.12	2.70	6.78
			0.46	0.72	4.22	9.87	2.34	6.82
			0.15	0.50	3.98	10.63	2.67	6.46
			0.72	1.02	4.40	10.46	2.38	7.04
200m IM	Winner	Shiwen Ye	0.79	1.14	4.92	11.81	2.40	6.84
	Medallists	n = 3	0.75	1.06	4.80	11.53	2.40	6.85
	Finalists	n = 5	0.74	1.06	4.82	11.37	2.36	6.97
	British		0.70	1.00	4.74	10.97	2.31	7.22
			0.66	1.00	5.46	12.56	2.30	7.12

400m Freestyle	Winner	Camille Muffat	0.68	0.96	4.08	10.29	2.52	6.62
	Medallists	n = 2	0.71	1.02	3.89	9.50	2.44	6.95
	Finalists	n = 4	0.72	1.05	3.74	9.22	2.47	7.00
	British		0.74	1.08	3.70	8.70	2.35	7.28
			0.78	1.12	3.96	9.03	2.28	7.52
400m IM	Winner	Shiwen Ye	0.70	1.04	4.98	11.97	2.40	6.90
	Medallists	n = 2	0.69	1.03	5.21	12.23	2.35	6.98
	Finalists	n = 4	0.71	1.04	4.66	11.07	2.38	7.04
	British		0.68	1.00	3.56	8.70	2.44	7.36
			0.72	1.10	3.92	9.71	2.48	6.96
800m Freestyle	Winner	Katie Ledecky	0.74	1.04	3.90	9.20	2.36	7.26
	Medallists	n = 2	0.73	1.04	3.84	9.08	2.36	7.27
	Finalists	n = 2	0.73	1.04	3.84	9.08	2.36	7.27
	British		0.72	1.04	3.78	8.95	2.37	7.28
			0.75	1.02	4.54	10.13	2.23	7.30

Better than the winner

Better than the finalists

Better than the medallists

Better than the group

Turns

Turn times measured from the head passing the 5m distance during the approach to the wall until the same point passes the 10m distance out from the wall was measured for the winner, medallists and finalists in the 100m and 200m events during the 2012 Olympic Games. These times are presented in Table 29 for the males and Table 30 for the females.

Table 29 Total turn time (5m in and 10m out) for the winner, medallists and finalists in the male 100m and 200m events at the 2012 Olympic Games

		Winner	Medallists	Finalists
Male Turns	100m Freestyle (s)	6.84	6.87	6.87
	200m Freestyle (s)	7.21	7.42	7.38
	100m Backstroke (s)	7.08	7.05	7.14
	200m Backstroke (s)	7.48	7.64	7.72
	100m Breaststroke (s)	8.28	8.48	8.49
	200m Breaststroke (s)	8.87	8.83	8.91
	100m Butterfly (s)	7.52	7.53	7.65
	200m Butterfly (s)	8.24	8.21	8.29

The winner demonstrated faster turns than the average time for the medallists in the freestyle and breaststroke, 200m backstroke and 100m butterfly events. In the events where the winner did not have the fastest turns, there was less than 0.05s difference and the only event in which this would have affected the outcome was in the 200m butterfly where Michael Phelps finished 2nd by 0.05s.

Table 30 Total turn time (5m in and 10m out) for the winner, medallists and finalists in the female 100m and 200m events at the 2012 Olympic Games

		Winner	Medallists	Finalists
Female Turns	100m Freestyle (s)	7.70	7.81	7.77
	200m Freestyle (s)	7.94	8.17	8.29
	100m Backstroke (s)	7.98	8.12	8.16
	200m Backstroke (s)	8.65	8.79	8.82
	100m Breaststroke (s)	9.60	9.62	9.62
	200m Breaststroke (s)	10.03	10.09	10.08
	100m Butterfly (s)	8.40	8.35	8.39
	200m Butterfly (s)	9.04	9.04	9.17

Average turn times were similar between the winner, medallists and finalists in the freestyle and butterfly events as well as the 100m backstroke and 200m breaststroke races. In the 200m backstroke there was 0.54s difference between the average turn time for the winner and the turn times for the other swimmers in the final. The other race to have a large difference in turn times was the 100m breaststroke where the winner had a time of 8.28s while the average for the final was 8.49s.

In contrast to the males, the only event in which the winner did not have the best turns was the 100m butterfly where she also had a slower start time compared to the other swimmers in the event. While this raised the question relating to the importance of skills required to win an Olympic event (in a world record time,) it appears that this was only observed in the minority of 100m and 200m events. Differences between the winner, medallists and finalists were much closer in the female events when compared to the male events. Table 31 displays the phases of the turn analysed during the 2012 Olympic Games in the male events and Table 32 has the information in the female events from the same competition. There were fewer instances where the British males were better than the rest of the group when compared to the start phases.

In the 100m breaststroke one swimmer was faster than the winner in the rotation phase and this was seen for both swimmers in the 200m butterfly. The time from the flags (located 5m from the wall) to the hands touching the wall was faster for one of the British swimmers in the 100m butterfly when compared with the winner. A further swimmer was faster during the out phase to 10m than the winner in the 200m backstroke and the final event where the British swimmer was faster than the winner was the breakout time in the 200m IM. The two phases of the turn that the British swimmers performed the best during the turn component of the race were the breakout time and distance which was the same as the start. Events where British males had faster turn times than the other swimmers in the race were the 100m backstroke, 200m breaststroke, 200m butterfly and 200m IM.

British female swimmers showed faster rotation and breakout times than the others in the race while the areas of weakness were the time out from the wall to 10m and the breakout velocity (Table 32). The only three races where British swimmers were faster than the other females were the 100m and 200m backstroke as well as the 100m freestyle.

The events in which the British swimmers excelled in the majority of the turn phases were the 100m and 200m backstroke although there were no medals achieved in these events. Bronze medals were won by a British swimmer in the 400m freestyle where her turns were not as fast as the winner or finalists although she did have the best approach and rotation phases as well as breakout time and distance within the group. Rotation time was faster than the average for the winner in the 800m freestyle where she also won a bronze medal although this was the only turn segment that was better than the winner. This proves the point that skills are important to event success but are not the only contributing factor.

Table 31 Turn phases for the males competing in the finals at the 2012 Olympic Games

			Average of From 5m To Wall Time (s)	Average of From Wall To 10m Time (s)	Average of Rotation Time (s)	Average of Breakout Time (s)	Average of Breakout Distance (m)	Average of Breakout Velocity (m/s)	Average of Total Time (s)
100m Backstroke	Winner	Matt Grevers	2.96	4.12	1.16	5.80	13.11	2.26	7.08
	Medallists	n = 3	2.96	4.10	1.15	5.73	12.86	2.24	7.05
	Finalists	n = 6	2.96	4.18	1.22	5.82	12.89	2.21	7.14
	British		2.95	4.11	1.39	5.83	13.03	2.23	7.06
			3.01	4.77	1.11	7.11	14.12	1.99	7.78
100m Breaststroke	Winner	C van der Burgh	3.47	4.81	0.74	4.41	9.41	2.13	8.28
	Medallists	n = 2	3.32	5.16	0.63	4.74	9.37	1.98	8.48
	Finalists	n = 3	3.18	5.31	0.64	4.94	9.44	1.91	8.49
	British		2.98	5.74	0.74	4.88	8.74	1.79	8.72
			2.76	5.50	0.66	5.50	10.00	1.82	8.26
100m Butterfly	Winner	Michael Phelps	2.75	4.77	0.58	4.91	10.25	2.09	7.52
	Medallists	n = 3	2.68	4.85	0.62	5.57	11.32	2.03	7.53
	Finalists	n = 6	2.63	5.02	0.71	5.36	10.62	1.98	7.65
	British		2.71	5.11	0.76	5.71	11.01	1.93	7.82
			2.66	5.36	0.72	5.60	10.42	1.86	8.02
100m Freestyle	Winner	Nathan Adrian	2.70	4.14	1.12	2.56	6.81	2.66	6.84
	Medallists	n = 3	2.76	4.11	1.25	2.27	6.30	2.78	6.87
	Finalists	n = 6	2.71	4.17	1.19	2.55	6.79	2.67	6.87
	British		2.78	4.32	1.12	2.68	6.89	2.57	7.10
			2.73	4.27	1.11	1.61	4.78	2.97	7.00
			2.82	4.44	0.86	3.14	7.57	2.41	7.26
			2.76	4.42	1.30	2.48	6.22	2.51	7.18
			2.89	4.47	0.99	2.75	6.81	2.48	7.36

200m Backstroke	Winner	Scott Tyler Clary	2.16	5.32	1.41	6.76	12.34	1.82	7.48
	Medallists	n = 3	2.82	4.81	2.05	5.71	11.45	2.01	7.64
	Finalists	n = 4	2.91	4.80	1.90	5.53	11.19	2.02	7.72
	British		3.39	4.98	1.58	6.93	13.13	1.90	8.37
			3.43	4.45	1.49	6.37	13.01	2.04	7.89
200m Breaststroke	Winner	Daniel Gyurta	3.43	5.44	0.51	5.54	10.15	1.83	8.87
	Medallists	n = 2	3.30	5.53	0.61	5.64	10.16	1.80	8.83
	Finalists	n = 4	3.23	5.68	0.66	5.67	9.98	1.76	8.91
	British		3.16	5.63	0.70	5.74	10.16	1.77	8.79
			3.16	5.85	0.76	5.55	9.58	1.73	9.01
200m Butterfly	Winner	Chad Le Clos	2.88	5.36	0.85	5.16	9.68	1.88	8.24
	Medallists	n = 3	2.88	5.33	0.75	4.53	8.68	1.92	8.21
	Finalists	n = 5	2.85	5.43	0.79	4.46	8.41	1.88	8.29
	British		2.97	5.32	0.84	5.95	10.99	1.85	8.29
			2.97	5.69	0.82	3.98	7.21	1.81	8.67
200m Freestyle	Winner	Yannick Agnel	2.92	4.29	1.41	2.35	6.43	2.74	7.21
	Medallists	n = 3	2.98	4.44	1.38	2.25	6.00	2.66	7.42
	Finalists	n = 5	2.98	4.40	1.32	2.76	7.05	2.55	7.38
	British		3.02	4.61	1.19	2.74	6.60	2.41	7.63
			3.10	4.68	1.25	3.52	8.03	2.28	7.77
			3.12	4.59	1.34	2.36	6.07	2.57	7.71
			3.16	4.72	1.26	2.54	6.23	2.45	7.87
200m IM	Winner	Michael Phelps	3.05	5.28	0.81	4.86	9.18	1.89	8.33
	Medallists	n = 3	3.06	5.36	0.73	5.24	9.79	1.87	8.42
	Finalists	n = 4	3.06	5.42	0.78	5.15	9.57	1.86	8.48
	British		3.07	5.61	0.90	4.87	8.89	1.82	8.68
			3.18	5.22	0.89	6.21	11.58	1.87	8.40

400m Freestyle	Winner	Sun Yang	3.09	4.70	1.46	2.11	5.55	2.63	7.79
	Medallists	n = 2	3.11	4.69	1.58	2.14	5.60	2.62	7.79
	Finalists	n = 3	3.18	4.72	1.52	2.19	5.69	2.60	7.89
	British		3.24	4.89	1.33	2.45	5.78	2.36	8.13
			3.31	4.78	1.40	2.30	5.87	2.55	8.09
400m IM	Winner	Ryan Lochte	3.35	5.30	0.99	5.16	9.66	1.87	8.65
	Medallists	n = 2	3.28	5.39	0.92	5.00	9.30	1.86	8.67
	Finalists	n = 3	3.30	5.43	0.94	5.02	9.26	1.85	8.73
	British		3.42	5.78	1.02	5.20	9.11	1.75	9.20
			3.28	5.64	0.89	4.14	7.70	1.86	8.92
1500m Free	Winner	Sun Yang	3.16	4.87	1.43	2.27	5.76	2.54	8.03
	Medallists	n = 3	3.27	4.84	1.47	2.25	5.76	2.56	8.11
	Finalists	n = 4	3.30	4.90	1.49	2.26	5.70	2.52	8.20
	British		3.37	5.11	1.54	2.30	5.53	2.41	8.49
			3.51	5.09	1.55	2.11	5.42	2.56	8.60

Better than the winner
Better than the finalists
Better than the medallists
Better than the group

Table 32 Turn phases for the females competing in the finals at the 2012 Olympic Games

			Average of From 5m To Wall Time (s)	Average of From Wall To 10m Time (s)	Average of Rotation Time (s)	Average of Breakout Time (s)	Average of Breakout Distance (m)	Av. Breakout Velocity (m/s)	Average of Total Time (s)
100m Backstroke	Winner	Missy Franklin	3.14	4.84	1.22				7.98
	Medallists	n = 2	3.24	4.89	1.23	4.21	8.83	2.10	8.12
	Finalists	n = 5	3.31	4.82	1.29	4.54	9.56	2.11	8.16
	British		3.31	4.61	1.44	4.71	10.17	2.16	7.92
			3.33	4.85	1.04	7.11	13.62	1.92	8.18
100m Breaststroke	Winner	Ruta Meilutyte	3.12	6.48	0.78	4.64	7.40	1.59	9.60
	Medallists	n = 2	3.15	6.47	0.78	4.62	7.36	1.59	9.62
	Finalists	n = 2	3.15	6.47	0.78	4.62	7.36	1.59	9.62
	British		3.33	6.51	0.80	4.00	6.51	1.63	9.84
			3.25	7.09	0.89	4.83	6.89	1.43	10.34
100m Butterfly	Winner	Dana Vollmer	2.87	5.53	0.64	3.14	7.06	2.25	8.40
	Medallists	n = 2	2.92	5.43	0.69	4.88	9.08	1.86	8.35
	Finalists	n = 4	2.89	5.51	0.70	4.95	9.08	1.83	8.39
	British		2.77	5.73	0.70	4.46	9.08	2.04	8.50
			2.93	5.71	0.63	3.79	6.89	1.82	8.64
100m Freestyle	Winner	Ranomi Kromowidjojo	3.20	4.50	1.10	3.08	7.48	2.43	7.70
	Medallists	n = 3	3.05	4.76	1.15	2.69	6.32	2.35	7.81
	Finalists	n = 6	3.02	4.75	1.09	3.01	6.90	2.29	7.77
	British		3.02	4.72	0.96	3.10	7.14	2.30	7.74
			2.93	4.93	0.92	2.53	5.88	2.32	7.86
			3.03	4.95	1.30	2.01	4.96	2.47	7.98
			3.16	5.06	0.96	2.22	5.13	2.31	8.22
			3.15	5.11	1.07	2.23	5.13	2.30	8.26

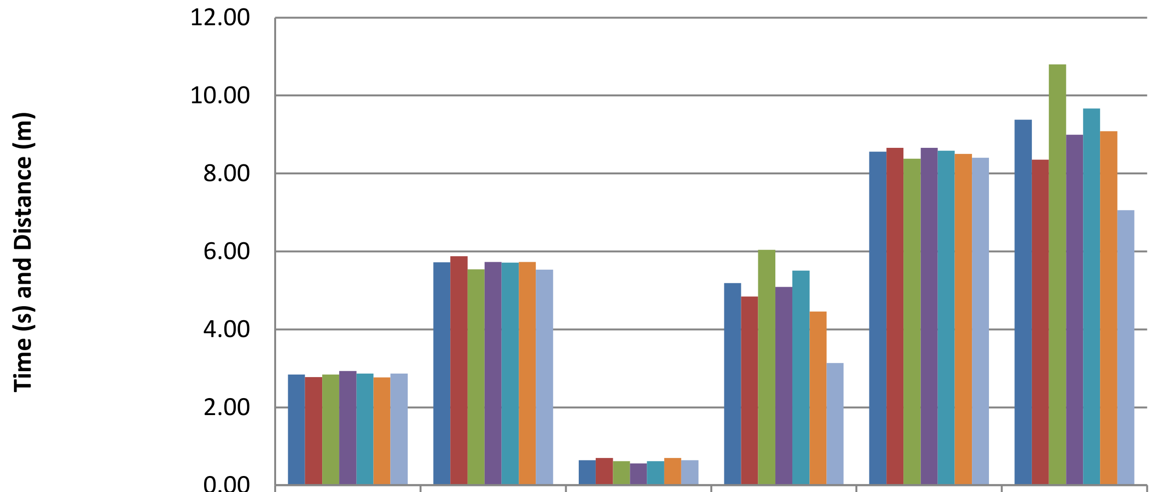
200m Backstroke	Winner	Missy Franklin	3.50	5.15	1.38	3.46	7.44	2.15	8.65
	Medallists	n = 3	3.58	5.21	1.36	3.26	7.03	2.16	8.79
	Finalists	n = 5	3.58	5.24	1.34	3.93	8.00	2.04	8.82
	British		3.48	5.07	1.29	6.67	12.37	1.85	8.55
			3.48	5.52	1.36	3.75	7.36	1.96	9.00
200m Breaststroke	Winner	Rebecca Soni	3.61	6.43	0.60	4.70	7.66	1.63	10.03
	Medallists	n = 3	3.53	6.56	0.72	4.96	7.83	1.58	10.09
	Finalists	n = 5	3.50	6.58	0.76	5.18	8.12	1.57	10.08
	British		3.63	6.93	0.97	5.19	7.83	1.51	10.56
200m Butterfly	Winner	Liuyang Jiao	3.26	5.78	0.57	3.94	7.24	1.84	9.04
	Medallists	n = 3	3.16	5.88	0.59	4.32	7.68	1.78	9.04
	Finalists	n = 5	3.20	5.97	0.71	4.06	7.13	1.76	9.17
	British		3.36	6.41	0.81	4.28	6.95	1.62	9.77
			3.39	6.04	0.93	4.40	7.44	1.69	9.43
200m Freestyle	Winner	Allison Schmitt	3.25	4.69	1.36	2.78	6.82	2.45	7.94
	Medallists	n = 3	3.30	4.87	1.25	2.15	5.47	2.54	8.17
	Finalists	n = 6	3.29	5.00	1.21	2.11	5.24	2.48	8.29
	British		3.44	5.19	1.20	2.26	5.23	2.31	8.63
			3.28	5.24	1.14	2.10	4.96	2.36	8.52
			3.48	5.36	1.08	1.79	4.20	2.35	8.84
			3.26	5.30	1.18	2.35	5.28	2.25	8.56
			3.31	5.30	1.22	1.85	4.41	2.38	8.61
200m IM	Winner	Shiwen Ye	3.25	6.23	0.79	3.86	6.34	1.64	9.48
	Medallists	n = 3	3.24	6.14	0.76	4.56	7.60	1.67	9.39
	Finalists	n = 5	3.30	6.29	0.82	4.26	7.00	1.64	9.59
	British		3.34	6.43	0.88	3.97	6.40	1.61	9.77
			3.55	6.32	0.96	4.61	7.58	1.64	9.87

400m Freestyle	Winner	Camille Muffat	3.50	4.90	1.66	1.67	4.83	2.89	8.40
	Medallists	n = 2	3.44	5.12	1.48	1.91	4.89	2.56	8.56
	Finalists	n = 4	3.41	5.23	1.39	1.83	4.66	2.55	8.63
	British		3.38	5.34	1.31	2.15	4.94	2.30	8.72
			3.48	5.47	1.30	2.03	4.80	2.36	8.95
400m IM	Winner	Shiwen Ye	3.53	6.23	1.18	2.83	5.14	1.82	9.76
	Medallists	n = 2	3.58	6.12	1.05	3.34	6.00	1.80	9.69
	Finalists	n = 4	3.55	6.26	1.01	3.44	5.98	1.74	9.80
	British		3.56	6.35	0.91	3.52	5.94	1.69	9.91
			3.73	6.34	0.89	3.36	5.86	1.75	10.06
800m Freestyle	Winner	Katie Ledecky	3.51	5.17	1.42	2.19	5.32	2.43	8.68
	Medallists	n = 2	3.56	5.26	1.39	2.10	5.05	2.41	8.82
	Finalists	n = 2	3.56	5.26	1.39	2.10	5.05	2.41	8.82
	British		3.61	5.35	1.35	2.01	4.81	2.40	8.96
			3.63	5.61	1.25	1.83	4.25	2.32	9.24

(blue)	Better than the winner
(orange)	Better than the finalists
(yellow)	Better than the medallists
(green)	Better than the group

The one event at the 2012 Olympic Games where the winner did not have the best starts or turns was the women's 100m butterfly and a comparison was made with the turn phase progressions of a British swimmer in this event over a 12 month period (Table 33). During the approach phase the swimmer improved from 2.93s in the heat to 2.77s in the final which was 0.10s faster than the winner of the event. The out time (from the wall to 10m) was on average 5.72s during the 2012 Olympics and 5.88s during the World Championships. This was in contrast to the 5.54s that the British swimmer achieved during the Olympic Trials and was similar to the winner of the event. Large differences were seen in the rotation phase of the turn between the heats (0.56s) and finals (0.70s) with the winner taking 0.64s to complete this phase during the final of the Olympics.

Table 33 Turn progression for a female British swimmer in the 100m butterfly



	5m In Time (s)	10m Out Time (s)	Rotation Time (s)	Breakout Time (s)	Total Time (s)	Breakout Distance (m)
2011 Trials	2.84	5.72	0.64	5.19	8.56	9.38
2011 World Champs	2.78	5.88	0.70	4.84	8.66	8.35
2012 Trials	2.84	5.54	0.62	6.04	8.38	10.80
2012 Olympic Heat	2.93	5.73	0.56	5.09	8.66	8.99
2012 Olympic Semi	2.87	5.71	0.62	5.51	8.58	9.67
2012 Olympic Final	2.77	5.73	0.70	4.46	8.50	9.08
World Record	2.87	5.53	0.64	3.14	8.40	7.06

The average breakout distance and time phases of the turn were much better for the British swimmer when compared with the winner of the Olympics who set the current world record. The race in which the British swimmer achieved their best underwater turn phase was the semi-final where she spent 5.51s and travelled 9.67m. This was in contrast to the winner who spent 3.14s and travelled 7.06m underwater after the turn rotation. Despite having a slower turn time than the average for the final, the winner of the women's 100m butterfly was still 0.10s faster than the British swimmer used in this example.

4.3.5 Race analysis from the 2013 World Championships

Similar analysis was conducted at the 2013 World Championships by a team of Spanish scientists with the mean data for the men's freestyle events presented in Table 34 except for the 1500m that was not analysed. A similar trend to the 2012 Olympic results was observed where the stroke rates decreased from an average of 60.43 SPM in the 50m freestyle to 39.79 SPM in the 400m freestyle. The stoke length in the freestyle events increased from 2.12m in the 50m to 2.58m in the 400m freestyle events. As expected, the velocity throughout the race decreased as the length of the race increased.

Table 34 Mean competition analysis data for the male freestyle events at the 2013 World Championships

Event	Start (s)	Turn (s)	Finish (s)	Stroke count	Stroke rate (SPM)	Stroke length (m)	Velocity (m/s)
50m Freestyle	5.30		2.24	18	60.43	2.12	2.36
100m Freestyle	5.53	9.28	2.57	36	51.02	2.30	2.09
200m Freestyle	5.86	10.08	2.60	67	43.48	2.49	1.90
400m Freestyle	6.30	10.83	2.58	135	39.79	2.58	1.77

The average start time to 15m in the 50m freestyle was 5.30s and increased by 0.23s in the 100m and 200m distances and 0.44s between the 200m and 400m events. The average turn was 9.28s in the 100m event and increased to 10.83s in the 400m freestyle. Interestingly there was very little difference in the finish time for the 100m, 200m and 400m events although it was approximately 0.3s faster in the 50m freestyle.

Freestyle events were also analysed for the females competing at the 2013 World Championships as noted in Table 35. Stroke rates decreased as the length of the race increased from the 50m to the 400m and had similar values in the 800m final. The range of 43-59 SPM in the female events was smaller than that observed in the male events (39-60 SPM).

When examining the stroke rate trends in the female events there was an increase in rate as the length of the race increased except for the 800m freestyle which had an average stroke length that was 0.09m less that the 400m event. The average velocity decreased from 2.06m/s in the 50m race to 1.59m/s in the 800m final. The start time, turn time and finish time all decreased as the length of the race increased.

Table 35 Mean competition analysis data for the female freestyle events at the 2013 World Championships

Event	Start (s)	Turn (s)	Finish (s)	Stroke count	Stroke rate (SPM)	Stroke length (m)	Velocity (m/s)
50m Freestyle	6.19		2.50	20	59.36	1.93	2.06
100m Freestyle	6.46	10.54	2.67	40	50.60	2.11	1.87
200m Freestyle	6.64	11.29	2.84	80	45.60	2.17	1.72
400m Freestyle	6.92	11.75	2.87	164	43.34	2.19	1.64
800m Freestyle	7.00	12.02	2.94	345	43.98	2.10	1.59

The calculated average stroke count was the same per lap for the 50m, 100m and 200m freestyle events and increased by 1 stroke per 100m in the 400m event. The average stroke count for each lap in the 800m freestyle was 20.5 at the 2013 World championships and the consistency between the events was similar to that presented in the male events during the same competition.

Starts

Table 36 showed that in the male freestyle events, the only race where the winner had the fastest start time was the 200m whereas in all of the other freestyle events the mean start time of the medallists was faster than the winner.

Table 36 Start time in seconds to 15m for the winner, medallists and finalists in the male events at the 2013 World Championships

		Winner	Medallists	Finalists	Fastest	Slowest
Freestyle	50	5.28	5.25	5.30	5.16	5.60
	100	5.64	5.57	5.53	5.28	5.72
	200	5.76	5.81	5.86	5.76	6.04
	400	6.36	6.24	6.30	6.04	6.60
	1500			No data		
Butterfly	100	5.63	5.65	5.53	5.16	5.68
	200	5.60	5.69	5.86	5.60	6.20
Backstroke	100	6.20	6.19	6.37	5.96	6.72
	200	6.32	6.45	6.50	6.32	6.68
Breaststroke	100	6.32	6.21	6.31	5.96	6.60
	200	6.52	6.72	6.72	6.52	6.96
IM	200	5.48	5.65	5.86	5.48	6.04
	400	6.12	6.11	6.16	5.88	6.40

The winner of the 200m butterfly had a start time of 5.60s which was faster than the winner of the 100m butterfly. The trend for the backstroke, breaststroke and IM events was that the faster start time was observed in the shorter distance races. The fastest start time in the male form stroke events was performed by the winner in the 200m distances but not the 100m races and in all events the winner did not have the slowest time to 15m.

Table 37 displays the start times for the female finalists competing at the 2013 World Championships that were held in Barcelona. Data is presented for the winner, average of the medallists, average for the finalists as well as the fastest and slowest times within the race.

Table 37 Start time in seconds to 15m for the winner, medallists and finalists in the female events at the 2013 World Championships

		Winner	Medallists	Finalists	Fastest	Slowest
Freestyle	50	5.96	6.09	6.19	5.96	6.32
	100	6.32	6.33	6.46	6.16	6.68
	200	6.64	6.66	6.73	6.56	7.08
	400	6.92	6.96	7.01	6.80	7.28
	800	7.00	7.05	7.19	7.00	7.46
Butterfly	100	6.52	6.49	6.43	6.12	6.60
	200	6.76	6.73	6.96	6.56	7.44
Backstroke	100	7.36	7.32	7.23	7.00	7.36
	200	7.68	7.71	7.63	7.44	7.72
Breaststroke	100	7.12	7.32	7.56	7.12	8.20
	200	7.56	7.65	7.79	7.56	8.12
IM	200	6.36	6.56	6.70	6.36	7.08
	400	6.68	6.88	6.95	6.68	7.16

In all of the freestyle events the winner had a faster start time to 15m than the average of the medallists while the swimmer who won the 50m and 800m freestyle had the fastest start time in the race. Similar trends to the male events were also observed in the female events where the start time was faster in the shorter distances for the form strokes and IM events.

The majority of the races had a range of 0.3-0.5s between the fastest and slowest start times while the largest difference was 1.08s in the 100m breaststroke event. The winner of the 100m breaststroke did break the world record at the time although it was not the only female world record broken at the competition. Katie Ledecky set new world records in the 800m and 1500m freestyle events, Ruta Meilutyte set world records in the 50m and 100m breaststroke while Rikke Moeller-Pedersen broke the world record in the 200m breaststroke.

Turns

Analysis of the turns by the Spanish team conducting the race analysis at the 2013 World championships was measured from the swimmer's head passing the 5m mark leading into the wall and out to the 15m distance after the turn. The total distances used in the analysis were different to those used for analysis at the 2011 World championships and the 2012 Olympic Games so no comparisons could be made. Most FINA competition lane ropes do not include a visible marker at the 10m distance which made it more difficult to use within analysis compared to the 15m distance that must be identified on the lane ropes (rule FR 2.6.2).

Data from the male events is presented in Table 38 and in all of the freestyle events the winner of the race had faster turn times that the average of the medallists although the difference was only 0.01s in the 400m freestyle final. That event was also the only one where the winner had the fastest average turn times in the freestyle events at the 2013 World Championships.

Table 38 Total turn time in seconds (5m in and 15m out) for the winner, medallists and finalists in the male events at the 2013 World Championships

		Winner	Medallists	Finalists	Fastest	Slowest
Freestyle	50					
	100	9.20	9.29	9.28	9.00	9.40
	200	9.89	9.98	10.08	9.89	10.27
	400	10.67	10.68	10.83	10.67	11.04
	1500			No data		
Butterfly	100	9.92	10.13	10.13	9.92	10.32
	200	11.32	11.34	11.37	11.15	11.51
Backstroke	100	9.72	9.85	9.96	9.72	10.28
	200	10.53	10.56	10.75	10.40	11.13
Breaststroke	100	11.72	11.68	11.71	11.59	11.88
	200	12.19	12.32	12.38	12.19	12.51
IM	200	11.16	11.24	11.48	11.16	11.91
	400	11.82	11.88	12.05	11.79	12.33

The average turn time was faster in the shorter distances for the IM and form stroke races and the winner had a faster average time compared with the medallists in all events except for the 100m breaststroke race. The winner had the fastest turn times in the 200m and 400m freestyle, 100m butterfly and backstroke as well as the 200m breaststroke and IM races.

Data presented in Table 39 are the average turn times for the females competing at the 2013 World championships including the fastest and slowest times in each event. As was observed in the male events, the winner in the freestyle events either had the fastest or the same times as the average for the medallists.

Turn times were faster in the shorter distances of the form stroke and IM events as seen in the male events at the same competition. The winner had the fastest turn times in all events except for the 200m freestyle, 100m butterfly and 100m backstroke races.

Table 39 Total turn time in seconds (5m in and 15m out) for the winner, medallists and finalists in the female events at the 2013 World championships

		Winner	Medallists	Finalists	Fastest	Slowest
Freestyle	50					
	100	10.36	10.45	10.54	10.36	10.76
	200	11.21	11.21	11.29	11.19	11.40
	400	11.54	11.61	11.75	11.54	11.87
	800	11.81	11.81	12.02	11.81	12.40
Butterfly	100	11.52	11.48	11.52	11.48	11.60
	200	12.31	12.31	12.52	12.31	12.88
Backstroke	100	11.24	11.27	11.34	11.00	11.78
	200	11.97	11.95	12.12	11.84	12.63
Breaststroke	100	12.92	13.01	13.21	12.92	13.48
	200	13.56	13.69	13.86	13.56	14.41
IM	200	12.65	12.76	12.97	12.65	13.29
	400	13.03	13.13	13.30	13.03	13.59

4.4 Discussion

Information presented within this chapter outlines the development of race analysis within major competitions over time as the technology used becomes more accessible. Details on the way in which a swimmer competes can be useful to both the individual and coach within the competition so that changes can be made between each of the rounds for potential gains in performance. After the competition this information is used within the training environment to improve the weaknesses of the individual and to compare the information to their main competitors.

Researchers have looked at different components of the race since the 1992 Olympic Games with analysis taking 6 months to complete. Today it is possible to provide race statistics to the coaches and athletes within minutes of the completion of the race. Some research groups are very close to automatically analysing the performances of all swimmers in every race so that more time can be spent interpreting the data.

A partnership between British Swimming, UK Sport and Sheffield Hallam University generated a bespoke race analysis system. Strengths and weaknesses of previous systems were discussed so that the new Nemo© software ensured that the data was accurate and appropriate to the needs of the coaches and swimmers. It was also possible to provide the analysis and video to the coaches more quickly than the previous software.

Races are typically divided into three main components: starts, turns and free swimming as noted in Figure 20. Data within the free swimming component provides information on stroke rate, stroke length and velocity. Comparisons between record holders and the British swimmers were made after the pinnacle events between 2010 and 2013 so that changes to the training programme could be made in the next training cycle. The improvements at the next competition were then examined for each individual athlete.

Observations by board members at the 2010 Commonwealth Games were specific to the turns of the British swimmers compared to the Australian swimmers and instigated more comprehensive analysis of this skill. The software used to analyse the races at the time (Greeneye©) provided information on the time to approach the wall from the 5m marker, time from the wall to the 10m distance after the turn as well as the total turn time. Information was then gathered on the distance that the swimmer commenced swimming after the turn and the time at which this occurred. Travelling under the water is faster than swimming so extending the underwater phase of the turn was encouraged.

Competition analysis on the British swimmers then focused on the turns both at National and International competitions from 2010 through to 2013. Detailed analysis included information on the approach (in), rotation, underwater and free swimming phases of the turn. Comparisons were made between the British swimmers and the competitors in the same events at international competitions to highlight the strengths and weaknesses of the individuals. Trends were also made for the British swimmers over the three year period in order to monitor the progress of the individuals to assist in improvements to the race.

The final phase of the enhancement to race analysis software was to include a number of phases within the start component of the race. In addition to the time to leave the block and the time for the head to reach the 15m distance, Nemo© provided information on the flight, underwater and free swimming phases of the start. Data gathered using this analysis system was highly accurate due to the known distances of each lane rope buoy and the swimmer in relation to this. The ability to provide this level of accuracy on performance to the coaches and swimmers ensured that specific changes could be implemented both within training and competitions. One limitation within the system was the inclusion of strokes within the start and turn phases and whilst individual analysis resolves this issue (Veiga et al., 2012) but does not allow for comparisons to be made between swimmers or for individuals at different competitions.

Competition results were assessed from the Olympic Games dating between 1984 and 2012. This competition is the ultimate event within each four year cycle and was deemed to be the optimum when comparing trends over a significant period of time. Data was presented on the percentage difference between the 1st and 8th places in the finals of all events for both males and females. The times for swimmers to qualify for the finals became much faster and the difference between the winner and other swimmers on the podium reduced in the period between 1984 and 2012.

For the British swimmers to make improvements on the world stage their performances during the 2011 and 2012 were monitored. This included their races during the selection event (Trials) as well as the pinnancle event for the year (World Championships or Olympic Games). Those swimmers who continued to improve each year were more successful at the major competition but this was not always guaranteed. The female swimmers were closer to the medal positions than the females. Freestyle was the strongest stroke and breaststroke the weakest for the females while the opposite was observed in the men's events.

In order to improve during the competitions, detailed analysis was performed on all swimmers during the 2012 and 2013 pinnacle events. Data on the stroke rate, stroke count, velocity, stroke length, start time, turn time and finish times were reported. Comparisons were made between the British swimmers and the medallists in each of the phases of the starts and turns during the Olympic Games where strengths and weaknesses were identified.

One of the coaches based at the Loughborough ITC chose to work on the start and turn performances for one session every alternate week during the race specific phases of the training cycle. The swimmer in the 1500m freestyle improved their rotation time by 0.04s with a total turn time 0.12s slower during the 2011 World Championships compared to the Trials. The other swimmer to qualify for the team in 2011 also showed an improvement in the rotation phase of their 400m IM (0.02s) but the overall turn times were on average 0.17s slower.

When comparing the same swimmers in the same events to their compeititors at the 2012 Olympic Games there were some noticeable improvements. The distance swimmer had a longer breakout time than the group (2.30s) and the percentage of total turn time spent during the out phase was lower than the winner of the event. The rotation phase was 0.11s slower than the winner but this did not account for the 0.46s difference in the overall turn time. In contrast, the 400m IM swimmer had a faster in time compared to the average for the finalists as well as the fastest average rotation times for the entire group. The breakout velocity from the turns was also the same as the medallists (2.56m/s) and faster than the average for the finalists (2.52m/s).

4.4.1 Practical implications

Analysis of the best swimmers provides quantitative data that can be used to identify the strengths and weaknesses of athletes within your team. The winners of the events during the major competition for 2011, 2012 and 2013 tended to have the fastest starts and turns compared with the other finalists. These data highlighted the importance of the skills that will be discussed in the following chapters.

Chapter 5 - Starts

Objective 2

To determine the optimal starting position of elite level swimmers training at the five Intensive Training Centres (ITCs) based around the United Kingdom. The best starting position for each individual would result in the highest take off velocity from the block, maximum flight distance and the fastest time to reach the 15m distance from the block. The timing of the peak vertical and horizontal forces on the front and rear legs would also be used with the assessment of the starting performance.

5.1 Introduction

Starting technique within the sport of swimming evolved in 2008 with the introduction of a new design to the swimming starting block after the Beijing Olympic Games. Prior to this time the two main starting techniques were the grab (both feet placed at the front of the block) and the track (one foot towards the front of the block and the other further back). Swimmers utilising a grab start tended to spend a longer period of time on the block and had a steeper angle of entry compared with swimmers using the track start technique.

The governing body of swimming, Federation Internationale De Natation (FINA) state that at least one foot should be placed at the front of the starting platform after the long whistle from the referee[22] while the position of the hands is not regulated (rule SW 4.1). FINA rule 2.7, as of January 2013, allows for the inclusion of a moveable plate at the rear of the block and that the maximum slope of the block should be no greater than 10° with a height of 0.5-0.75m above the surface of the water. The block must be fixed with no springing effect and enable the swimmer to grab the front or side surfaces. For all competitions the dimensions of the block should be 0.5m wide and 0.5m long except in World Championships and Olympic Games where the length is extended to 0.6m (rule FR 3.9). For taller swimmers and those who choose to locate the wedge in position 5, there may be differences in starting performances when using the shorter length starting blocks.

The cost of new starting blocks can be prohibitive for many pool facilities so there are still a large portion of swimmers who do not have the opportunity to practice using the OSB11 type blocks on a regular basis. This would definitely limit their potential to improve the start due to the inability to create a neuromuscular pattern for the movement.

[22] At the start of the race the referee will perform a long whistle to signal to the swimmers that they need to move onto the starting block. After this time they will then instruct the swimmers to “Take your marks” before the gun to signal the start of the race.

Starting blocks used at the World Championships, Commonwealth and Olympic Games since 2009 have been the Omega OSB11 style shown in Figure 21. The angle of the platform increased from 5° in the previous model to 10° and the inclusion of the adjustable wedge at the rear of the block was the other major design change.

Figure 21: Omega OSB11 starting block

Due to the new block design it was important to determine the optimal starting position for each podium level swimmer supported by British Swimming in order to take advantage of the changes to the block. This would enable them to practice their new starting technique in order to improve their performance potential. A number of tests were designed in order to monitor and improve the starting performance of elite swimmers within the daily training environment. These were intended to minimise any impact on training as well as provide realistic situations that were similar to those that would be encountered during competitions.

5.1.1 Phases of the start

The start within a competition environment is defined as the time from the starting signal (gun) until the time when the swimmer's head passes the 15m distance from the wall and comprises a number of phases. These include the block, flight, underwater and stroking phases as displayed in Figure 22. The *block* phase includes the movements from the moment that the swimmer steps onto the block (after the referee's whistle) until the time that their toes leave the block. It includes the time to react to the starting signal as well as the movement of the arms and legs whilst they are on the block. The second phase (*flight*) is the period of time from the feet leaving the blocks until the head enters the water. The head was used in the current research as this is the body part used as a consistent marker to time the total start time through to the 15m distance during competitions. It is also a fixed point that does not alter for each of the swimming strokes.

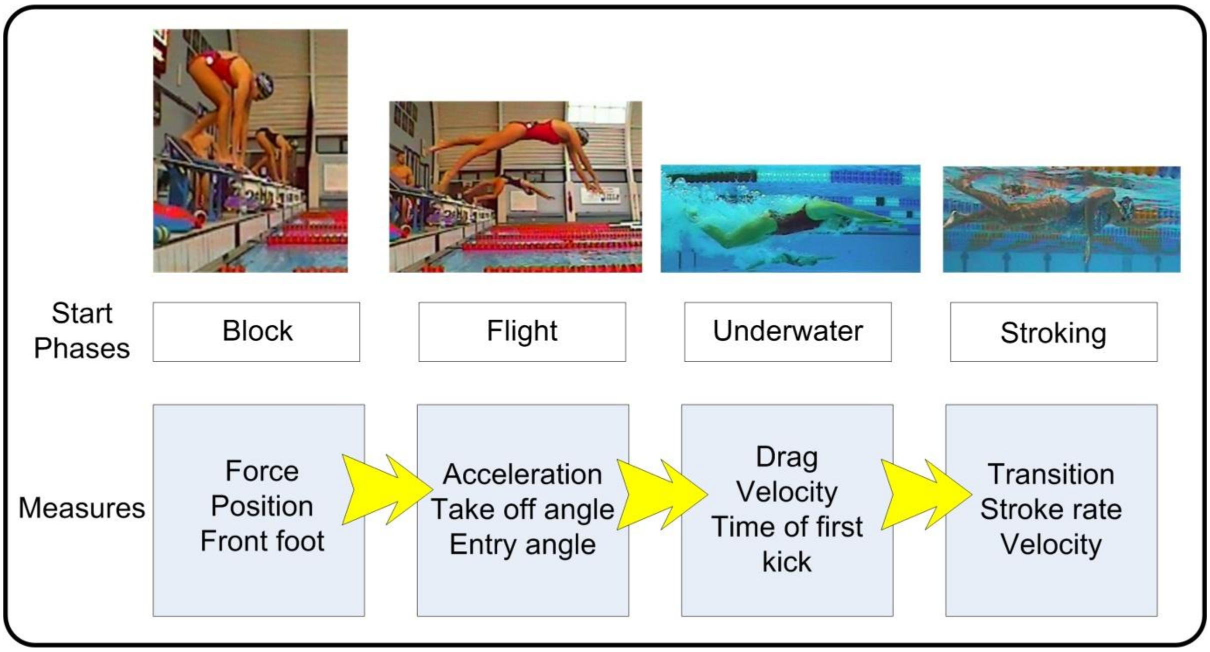


Figure 22: Start phases and measures to assess each of the phases.

After the swimmer enters the water there is a period where the body is streamlined before a number of underwater kicks or strokes are used prior to the head surfacing and this is defined as the *underwater* phase. FINA rules SW 5.3 for freestyle, SW 6.3 for backstroke and SW 8.5 for butterfly state that the swimmer's head must surface prior to the 15m distance from the starting wall. As noted earlier, there is no rule within breaststroke stating that the swimmer's head must break the surface of the water by a set distance but they are only allowed to do one stroke underneath the water (SW 7.1). Previous competition results found that it was faster to travel underwater than to swim in some instances, particularly in the backstroke events. The *stroking* phase from the head surfacing through until the 15m distance varies by individuals and is dependent on the event and the ability of underwater kicking. A change to any one of these phases will have an impact on at least one of the other phases of the start, so it is common practice to optimise the first phase before adapting subsequent phases within the overall starting performance.

5.1.2 Components of a successful start

Within each phase of the start parameters can be defined that contribute to a successful performance. During the block phase it is important for the swimmer to get into a good position on the block that will enable maximum power for the drive off the block. The two main types of starting technique are the grab (both feet at the front of the block) and the track (one foot at the front and one at the rear of the block) starts. In a track start, swimmers choose to place their weight on the rear or the front of the block. If the weight is towards the front then the time spent on the block is shorter than if the weight is positioned to the rear of the block. In this rear weighted stance, a greater period of time is spent developing force during the block phase that has the potential to increase the impulse on the block. A less popular starting technique used within swimming is the swing style as discussed by Galbraith et al. (2008) where one arm is used to assist with the propulsion from the block. Each of these variations is displayed in Figure 23 and highlights the choices that swimmers have when selecting an appropriate starting technique.

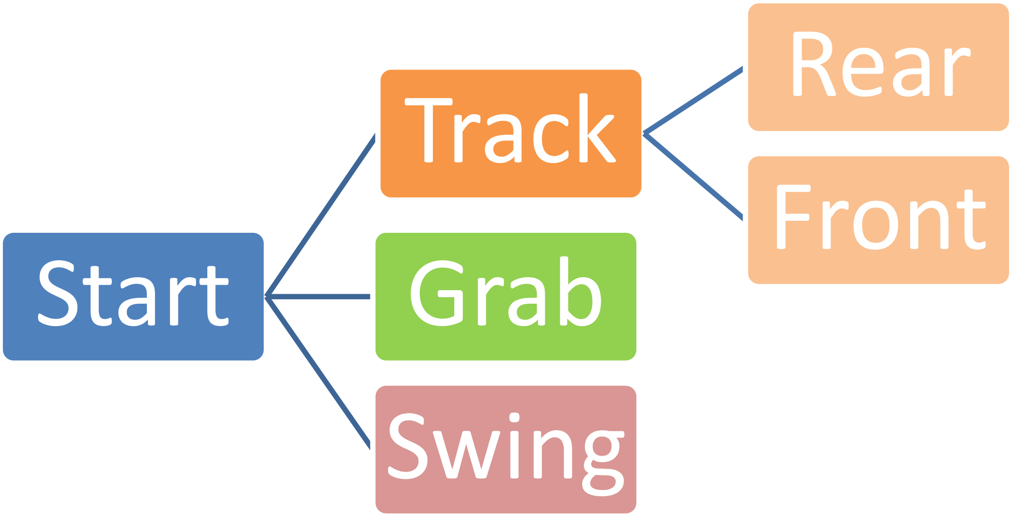


Figure 23: Different swimming start styles

Since the introduction of a wedge on the rear of the starting block the majority of swimmers use the track style technique. Sprinters in athletics use one of three track style techniques – bunched (less than 30 cm spacing), medium (between 30 and 50 cm spacing) and elongated (spacing greater than 50 cm) (Harland and Steele, 1997). These three spacing categories can be loosely applied to swimming where the feet are spaced between 35cm in position one and 53cm in position five with increments of 4.5cm between each wedge position. When the rear foot is placed on the wedge in the first position then it can be classified as bunched, and when the rear foot is in position five then it refers to an elongated position. The middle three wedge positions may be classified as medium styles when compared to athletic starts.

Figure 24: Two swimmers in the set position on starting blocks

The swimmer towards the front of the image in Figure 24 is demonstrating a front weighted track start while the swimmer towards the back of the image is using a rear weighted technique. These differences are highlighted by the angle of the front leg – a larger angle suggests a rear weighted style. Literature supplied by the makers of the OSB11 blocks suggests that the optimal rear knee angle is 90° for optimal starting performance as is shown by these two swimmers.

The initial movement after the starting signal should be the pulling down of the arms on the block and then the raising of the hips to incorporate the benefits of eccentric loading within the hamstrings. The swimmer is able to make use of the stored elastic energy within the muscle through the active stretching of the muscle during the eccentric phase followed by an immediate concentric contraction that is commonly referred to as the stretch-shortening cycle (SSC). Force enhancement during the eccentric stretching is due to an increase in the number of attached cross-bridges, an increase in the force development of each cross-bridge and the recruitment of additional force-bearing elements (Goubel, 1987).

It was hypothesised that the muscle would contract faster if the eccentric tension within the muscle increased while the concentric force decreased (Komi, 1973) therefore a pre-loading within the muscle is employed in rapid movements. Shorten (1987) concluded that the amount of energy stored within a muscle or tendon was the product of the square of the stretch distance and the elastic stiffness. A greater proportion of energy is stored in the tendon as it is more compliant than the muscle and an increase in stiffness favours the release of potential energy due to the shortened coupling time (Aura and Komi, 1987; Goubel, 1987).

Exercises that enhance the SSC capabilities of a muscle are usually reserved for dynamic sports although it has been proposed that there are benefits within the start and turn phases of swimming (Cossor et al., 1999). Reiff (1988) demonstrated some exercises to be used within the water that could enhance the SSC of a muscle which included similar plyometric exercises to those performed on land (e.g. single leg jumps, double leg jumps, and bounding). The major limitation to these exercises was the fact that they could not be performed quickly due to the additional resistance created by performing these in water, minimising the effect of the SSC.

Kanehisa and Miyashita (1983) found that slow velocity training resulted in improvements at slow speeds while high velocity training resulted in increases in power output at both fast and slow speeds. In order to determine the length of time that the stored elastic energy can be used, Wilson et al. (1991) used 12 experienced male weightlifters to perform a series of bench presses at 95% maximum. After 0.20s the mean power curves differed little to the initial movement while the benefits of the SSC movement were lost after 0.37s with an exponential decay resulting in a half-life of 0.85s.

A flatter back position during the set position on the block enables the gluteal muscle groups to contribute to the drive from the legs after the starting signal through the use of the SSC. This position relies on hamstring flexibility so those swimmers lacking in this area tend to move the wedge to a position closer to the rear of the block.

The major difference between athletics and swimming starts is the angle in which they leave the blocks. In athletics the aim is to drive upwards in the forward drive phase from the blocks while in swimming the blocks are 30cm above the surface of the water, resulting in a horizontal or downward movement when leaving the block. It is therefore not possible to make direct comparisons between athletics research on starts to swimming starts but some inferences may be made. Schot and Knutzen (1992) and Slawinski et al. (2012) found that the elongated position of start produced the greatest horizontal displacement and velocity through to 2m so positions four and five on the wedge may be beneficial for improved swimming start performance.

Due to the difference in projection angle from the block it is important for the swimmers to increase the horizontal force generated on the block by both the front and rear legs. With the recent introduction of the wedge to the swimming starting blocks there is a dearth of research in this area and as such it is difficult to determine the optimal forces required in the vertical and horizontal directions for both legs but in particular the rear one. Shinohara and Maeda (2011) tested 18 starting arrangements with one male athlete and found that as the space between the two blocks increased the impulse increased on the rear block and decreased on the front block.

Figure 25: The initial point included in the flight phase of the swimming start

The period between the feet leaving the block until the body enters the water is defined as the flight phase. Researchers have used both the hands (Beretic et al., 2012; Holthe and McLean, 2001; Naemi et al., 2001; Ozeki et al., 2012; Vilas-Boas et al., 2000), the head (Cossor et al., 2010) or the feet (Vantorre et al., 2011) to define the end of this phase and this study used the head in order to be consistent with the following phases. The swimmer in the foreground of Figure 25 is at full leg extension and the toes of the front foot are at the take-off point.

A further variable that is considered to be important to swimming starts is the take-off velocity from the block (Beretic et al., 2012; Guimaraes & Hay 1985; Honda et al., 2010) although Mason et al. (2007) suggested that the take-off angle was more important. It is possible to calculate this automatically from the horizontal and vertical force values obtained from the force platform by subtracting the body weight and integrating with respect to time (Cavagna, 1975) as acceleration is the derivative of velocity.

The design of the instrumented starting block used in this research allowed information on the front and the rear of the block to be determined independently but it was not possible to separate the grab forces generated through the arms pulling downwards on the front of the block and the forces generated by the front leg. While it was possible to derive the take-off velocity and angle from the force platform, the take-off velocity was calculated through the manual digitisation of the hip for each frame of the above water phase of the start. The video cameras were calibrated as noted previously so that the vertical and horizontal displacement was known and this was used along with the timing information to determine the velocity as the swimmer left the block.

The density of air is 784 times less than water at sea level making it easier and quicker for the swimmer to travel through during a start. As it is faster to travel through the air rather than the water due to the resistance of the medium, a greater horizontal entry distance may be beneficial to an improved start. The velocity of the swimmer's hip during the various phases of the start was obtained through manual digitisation using the SwimTrack© software.

The swimmer enters the water with higher velocities (approximately 4-6m/s) than they are able to propel themselves through the water (1.8-2.2m/s in freestyle) due to the propulsion from the block. In order to maintain the high velocity during the start, the swimmer should maintain a streamlined position for an appropriate period of time prior to commencing the underwater kicking action. Analysis of twelve national level swimmers suggested that they should maintain a streamlined position until the swimmer reaches 5.5m from the starting wall where underwater kicking using only the feet and legs should commence at a high frequency (Houel et al., 2010b).

Elipot et al. (2009) reported values of 3.61m/s when commencing the first kick after testing eight elite French swimmers using the grab start technique. The optimal speed in which a freestyle swimmer should commence their first kick during the underwater phase is between 1.9 and 22m/s (Lyttle et al., 2000). These speeds more closely represent those which a swimmer is able to achieve with effective underwater kicking techniques. When analysing the starts of elite French swimmers Elipot et al. (2009) found that the centre of mass was between 5.63 and 6.01m from the wall at the point in which the velocity was within the suggested range of 1.9-2.2m/s.

Figure 26: Underwater phase of the swimming start

The closest swimmer in Figure 26 has commenced their underwater kick when their hip is approximately 5.2m from the wall (the red lane markers represent the 5m distance while each change in colour represents a distance of 67cm). It is possible to see that the upper body is not in a streamlined position and there is still a large amount of drag created from the air bubbles around the body. The angle at which the swimmer approaches the surface of the water during the underwater phase can also affect the drag and lift coefficients of the body so must be considered as part of a successful start (Houel et al., 2010b).

The final phase of the start is the free swimming component after the swimmer surfaces from the underwater phase. The time and distance of this segment varies depending on the distance that the swimmer travels underwater. Cappaert et al. (1995) reported mean swimming velocities of 2.01m/s in elite male swimmers competing in the 100m freestyle during the 1992 Olympic Games. This was similar to the values reported in the final of the same event during the 2012 European Championships (www.swim.ee) where the average velocity for the free swimming segment from the 15m to 25m after the start was 2.03m/s. Individual velocities ranged from 1.98 through to 2.13m/s for this segment of the race and it was not until the final free swimming section of the first lap (35-45m) where the velocity dropped below 2m/s.

As the distance of the race increases the free swimming velocity decreases in all events by elite swimmers (unpublished competition data). In the middle distance events of the 200m and 400m race lengths there is an advantage to spending more time in the underwater phase after the starts and turns. This is due to the fact that it is possible to kick faster using an undulatory technique in the underwater phase than it is to swim in these races. The benefit to spending more time underwater needs to be weighed against the oxygen cost but this is not researched in the current study due to its physiological nature.

When examining aquatic animals it appears that there is a transverse wave along the length of the body from the head to the tail and is referred to as underwater undulatory swimming (UUS). Wu (1971) suggested that the forward propulsion was due to the wave along the length of the body which in turn propels the fluid backwards in an equal and opposite reaction. The specific vortices generated from this movement vary depending on the type and size of fish.

In order to apply this to the human body it is important to consider the addition of limbs to the main body. The legs may be more beneficial than the arms in generating propulsive forces due to the size of the muscles, propulsive surface area and no backward movement throughout the movement (Vorontsov and Rumyantsev, 2008a).

Various forms of technology have been used to determine the metrics used within the analysis of swimming starts as noted in Table 40. These included the use of vision equipment, force transducers and wireless sensor nodes for primary and secondary analysis of the metric. The force transducer was the primary tool used to analyse the block time while it was also possible to validate the data using video and WSN equipment. The primary tool used to analyse the flight time and time to 1st kick was the vision equipment while the WSN was also used. The WSN was the primary form of analysis for the underwater time and 15m time with the vision system used to validate the information.

Table 40 Primary and secondary roles of the various tools used to measure the various times within a swimming start

Metric	Vision Equipment		Force Transducers		WSN	
	Primary	Secondary	Primary	Secondary	Primary	Secondary
Block time		✓	✓			✓
Flight time	✓					✓
Time to 1st kick	✓					✓
Underwater time		✓			✓	
15m time		✓			✓	

5.2 Methods

5.2.1 Experimental design

An experimental design was established to determine: **What is the best starting position for an elite swimmer?** It was necessary to allow for individual differences within this elite population including strength (affected by gender) and anthropometry (height, weight and surface area of the body as they moved through the water). The experimental design comprised three main variables, which were *foot position* (left or right foot forward), *stance* (narrow or wide) and *wedge position* (either position 3, 4 or 5) as displayed in Table 41.

Prior to the commencement of research there was no specific method for determining the foot to be placed at the front of the block and research to date has been inconclusive. Blanksby et al. (2002) and Hardt et al. (2009) proposed that the stronger leg should be placed at the front of the block while Galbraith et al. (2008) found that it should be placed at the rear of the block. The stance was investigated in the current research as it was found that greater power production was produced using a wider leg stance position during vertical jump testing (Carlson et al., 2009; Cossor et al., 1999; Cronin et al., 2007; Garrido et al., 2010; Lyttle et al., 1999; Yu, 2001).

Table 41 Design of experiments to determine the optimal starting position using the OSB11 starting block that included three different factors at two and three different levels

Factor	Factor Name	Level 1	Level 2	Level 3
1	Wedge position	3	4	5
2	Front foot	Left	Right	
3	Width of feet	Narrow	Wide	

Visual observations of swimmers in training and at competitions suggested that the majority placed the wedge in the 3rd position to start from; consequently this location was used as the starting point for this study. It was felt that testing all of the wedge positions would significantly increase the time of testing sessions and potentially decrease motivation of the swimmers. Rather than testing positions 1, 3 and 5 it was felt that positions 3, 4 and 5 would be more appropriate based on observations during competitions. The five set wedge positions were described earlier (Figure 5) with increments of 45mm between each position.

5.2.2 Development of the instrumented starting block

For starting performances to be measured accurately a new instrumented starting block needed to be designed. This would ensure that the information from the front leg would not interfere with the data for the rear leg and provide individual horizontal and vertical force information. The design ensured that the main plate was 10° to the horizontal while the wedge was 30° to the main plate in order to replicate the OSB11 starting block used in competitions.

Vertical and horizontal force measurements for the front of the block were recorded using a Kistler Multi Component Force Plate (Type 9260AA) while the design of the rear wedge component of the starting block incorporated four tri-axial force transducers (Kistler Type 9017B). A slight gap was included in the design of the wedge to ensure that forces measured on the front and rear of the block was independent. The starting block and the associated equipment for measuring the force data are shown in Figure 27 (Slawson, 2010). The weight of the starting block was approximately 90kg and required two people to lift it on to the side of the pool where four bolts were used to attach it to the same positions as used for the OSB11 blocks. A single cable ran from the main plate to the data acquisition (DAQ) box

(Type 5691A1) while another cable ran from the summing box behind the wedge to the charge amplifier. A separate cable attached the 8 amp charge amplifier (model 9865E) to the DAQ box where the data from both force platforms was sent to a laptop through a USB cable. The charge amplifier, DAQ box and laptop were connected to 240v power and located a minimum of 2m from the side of the pool.

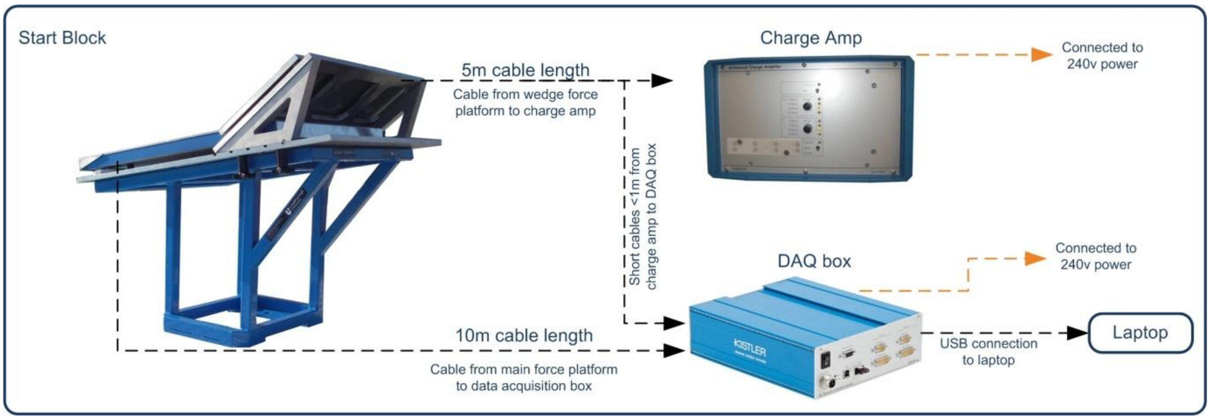


Figure 27: Instrumented starting block set up allowing for forces to be measured on the front and rear of the block independently (Slawson, 2010).

The summation of the forces from the transducers is displayed in Figure 28 along with the interface between the Kistler equipment and the laptop used to capture the data.

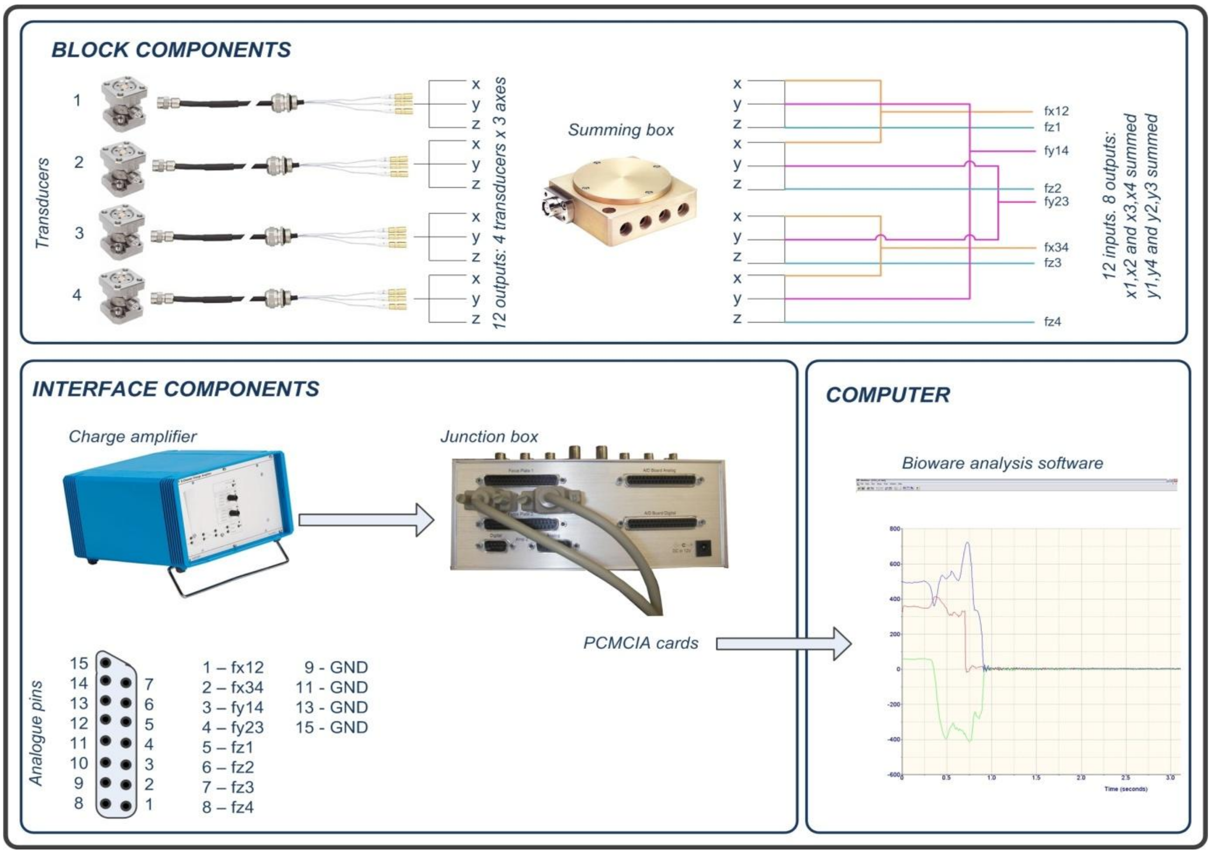


Figure 28: Process to capture the force data from the block onto a computer

5.2.3 Development of a wireless sensor node

In order to measure velocity and acceleration during a swimming start, Loughborough University developed a Wireless Sensor Node (WSN) that was able to transmit data in real time from the small of the swimmer's back to a laptop located on the side of the pool. This WSN included a tri-axial accelerometer, a dual and single axis gyroscope, as well as a store and transmit buffer located within the on-board memory. The size of the WSN was reduced over the period of the study and was 78mm long, 53mm wide and 18mm deep in December 2012. Light emitting diodes (LEDs) were visible on the outside surface to indicate communication, link status and battery charge operations. The dimensions of the WSN are displayed in Figure 29 and the contents are shown in Figure 30 where the data can be stored on board or transmitted real time to the receiver located on the side of the pool. While the WSN was used within the trials for this research the data was presented in separate research (Le Sage et al., 2010a).

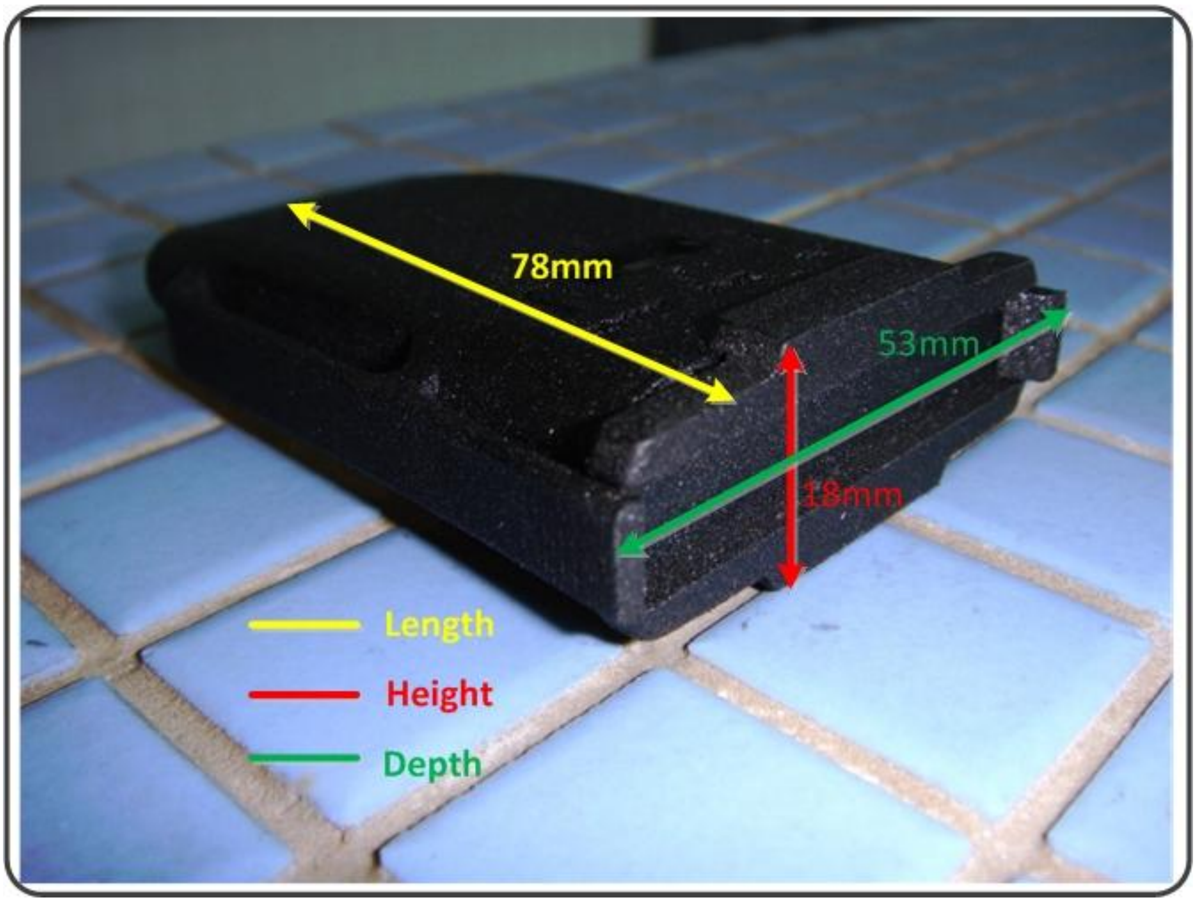


Figure 29: Wireless sensor node (WSN) packaging dimensions in December 2012.

Figure 30: Contents of the wireless sensor node (WSN) in March 2013.

5.2.4 Validation of SwimTrack© calibration

Prior to the initial testing session, each camera was calibrated both in air and water environments using the 3D checkerboard method (Yu and Peng, 2006), in order to determine the focal length and skew of the image. This information was entered into the SwimTrack© software for use within the analysis phase. As the focal length of the cameras did not change it was not necessary to calibrate the cameras prior to each testing session. After capturing an image from each of the three cameras, the only calibration that was required was information on the position of the near lane rope, the far lane rope and the distance of each of the cameras from the pool end. This enabled accurate information to be gathered on the swimmer, regardless of their position within the swimming pool lane. Earlier versions of the software used in swimming analysis (Naemi and Sanders, 2008; Naemi et al., 2010, 2008) required the swimmer to swim in the centre of the lane for positional data to be accurate.

To determine the level of accuracy of the positional information generated from the SwimTrack© analysis, digitisation of known markers placed on the lane ropes took place. Tape was placed on the lane ropes in five positions, located 2.5m, 5m and 7.5m from the side-wall of the pool. These distances are noted in Table 42 and varied slightly for each of the lane ropes.

Table 42 Location of fixed markers along the 2.5m, 5m and 7.5m lane ropes from the side wall of the pool

Lane rope (m)	Marker 1 (m)	Marker 2 (m)	Marker 3 (m)	Marker 4 (m)	Marker 5 (m)
2.5	1.36	2.40	3.51	5.12	6.32
5	1.38	2.43	3.55	5.16	6.29
7.5	1.39	2.49	3.62	5.16	6.29

Each point was digitised ten times and descriptive statistics were generated for all known locations. The average difference between the digitised position and the known location are noted in Table 42 for all of the lane ropes and cameras.

Data presented in Table 43 showed an underestimation of the known distance of 29cm for maker 2 on the lane rope located 2.5m from the side of the pool in the above water image. The greatest over estimation of the position of the known marker was observed in the first underwater camera on the lane rope located 7.5m from the side of the pool and marker 5. Most of the markers tended to underestimate the actual position of the marker located on the lane rope and analysis of the swimming starts and turns took place in the lane located between the 2.5m and 5m lane ropes in order to minimise location errors.

Table 43 Average difference in position between the digitised and known locations for all markers located along the three lane ropes

Camera	Lane rope (m)	Marker 1 (m)	Marker 2 (m)	Marker 3 (m)	Marker 4 (m)	Marker 5 (m)
Above	2.5	-0.03	-0.03	-0.08		
	5.0	-0.22	-0.01	-0.03	-0.11	
	7.5		-0.11	-0.12	-0.17	-0.26
Underwater 1	2.5		-0.29	-0.19		
	5.0	-0.21	-0.14	-0.06	0.08	
	7.5	-0.20	-0.14	-0.09	0.04	0.14
Underwater 2	2.5				-0.02	0.02
	5.0				-0.06	0.02
	7.5			-0.21	-0.10	-0.05

5.2.5 Optimal starting position

Slawson (2010) noted that the starts and turns of elite swimmers were very repeatable so it was possible to see changes to force profiles after changes to technique. As such it was felt that a large number of trials were not required for this subject population but due to the fact that the starting block was different to what the swimmers were used to, three trials in each of the positions were monitored. This allowed for average information in each of the variables to be used as part of the analysis rather than a single sample that may not have been a true representation of the technique. The best trial from each position may have been a random outlier when using the new start and more trials may have provided a better average result but may have introduced fatigue as a factor within the results.

Fifty swimmers (18 female and 32 male) were tested in five British Swimming Intensive Training Centres (ITCs) located in Stirling, Stockport, Loughborough, Bath and Swansea. The weight for the females ranged from 54.55-80.15kg with a mean of 64.73 ± 6.76kg. The group of males had a mean weight of 79.25 ± 6.73kg with a range of 61.25-94.20kg. All swimmers competed at the British National Championships.

More than 1400 dives were filmed and analysed over a two month period. The testing occurred over two consecutive days in each of the centres to ensure that there was minimal impact from fatigue on the results of the study. The order of trials was randomised and no more than 12 dives were conducted in any one training session. All swimmers were provided with detailed information on the testing procedure and completed Informed Consent forms prior to the commencement of testing. The study was approved by the Ethics Committee of Loughborough University prior to testing.

Each of the swimming start phases was examined independently in order to determine the most appropriate measures as listed in Figure 22. It was possible to measure the vertical and horizontal forces of the swimmer during the block phase by utilising a bespoke instrumented starting platform designed and developed within Loughborough University (Slawson, 2010). Within the current research the focus was on the block and flight phases of the start.

During the flight phase of the swimming start information on position, time, velocity and acceleration could be measured through the use of various technologies. A vision system component of the start system was developed in conjunction with Sheffield Hallam University (SHU) that enabled three separate video images to be combined into one playback screen. Three Sony HQ2 fixed focal length analogue cameras were used as part of the vision system – one fixed to a tripod 60cm above the surface of the water and two cameras each attached to poles 1m below the surface of the water. The cameras operated at 25Hz and were connected to individual Canopus ADVC55 analogue to digital converters.

The first image captured the movement of the swimmer during the block and flight phases and was located approximately 4.2m from the horizontal movement plane of the swimmer and 2m from the starting wall. The second and third images focused on the entry and underwater phase of the start and were positioned 2m and 5m from the end wall respectively. The software for the start and turn analysis was named SwimTrack©.

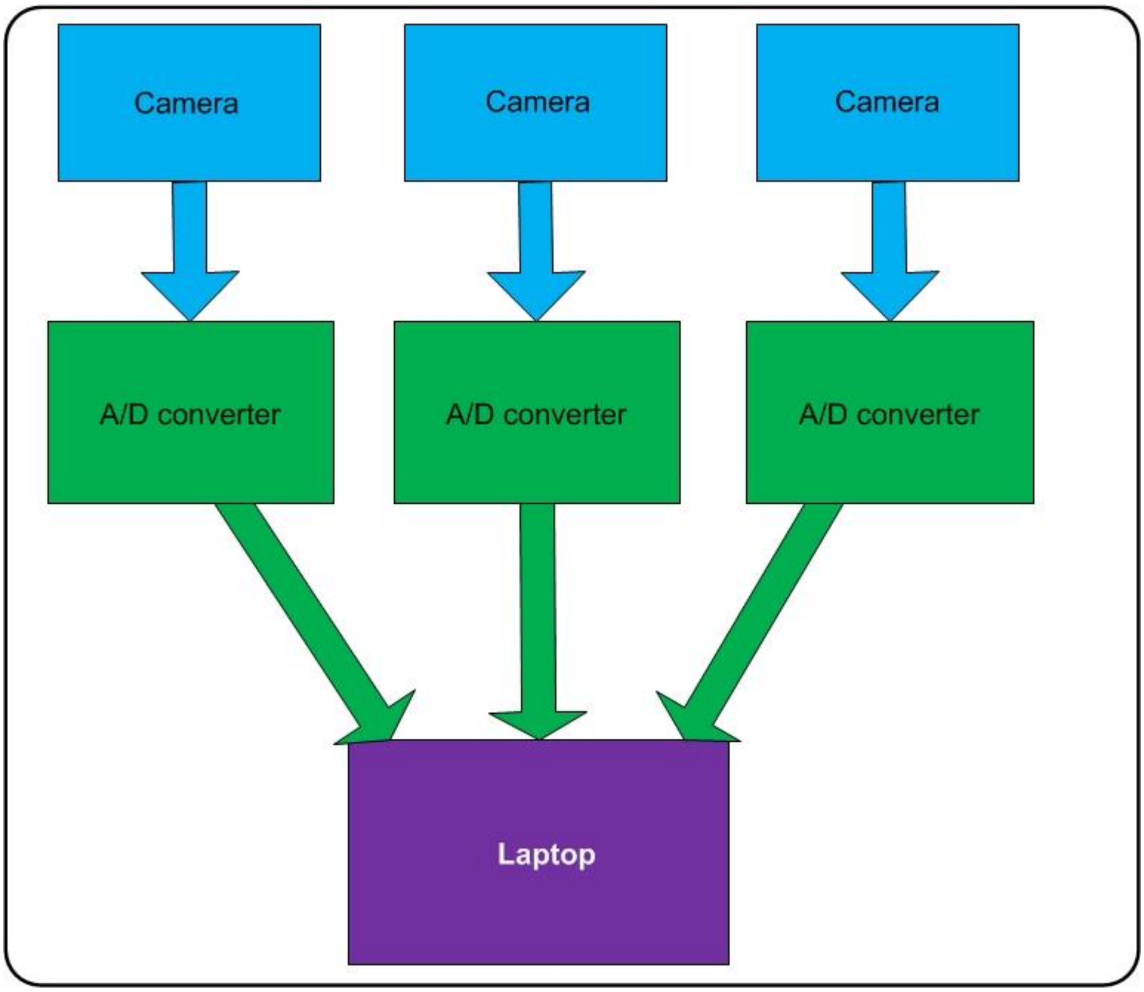


Figure 31: Representation of SwimTrack© set up and data capture.

The design of the cameras did not allow for direct synchronisation between each camera through a traditional genlock system but the software was able to synchronise the images. In approximately one trial in every 100 tests it appeared that the images were not correctly synchronised and these trials were not used for analysis purposes. The digital signal was connected to a laptop with Firewire (IEEE1394) cables into three separate ports for video capture, represented in Figure 31.

Measurements used in the underwater phase of the start included position, time, velocity and acceleration with the inclusion of the SHU SwimTrack© software and vision system along with the WSN. The acceleration data was used to determine the time of the first kick after entering the water along with the kick rate and number of kicks prior to the swimmer surfacing. The time to 15m was manually calculated with a timer attached to the starting trigger and operated by an experienced timer. Stroke rate information was determined using the WSN in the stroking phase of the start due to restrictions with the camera images. Raw acceleration data was passed through a low order Butterworth filter and embedded signal processing was used to determine the kick rate, number of kicks, stroke rate, and number of strokes during each trial (Le Sage et al., 2010a, 2010c).

No previous literature has reported the kick rate or frequency during swimming start research so it was not possible to make comparisons with previous data. Coaches are typically able to measure stroke rate through the use of a stop watch where the time for three complete stroke cycles[23] is measured and this information is displayed as the number of strokes per minute if the swimmer continued at the same stroke rate. Swimmers are asked to count their strokes both in training and competition but the use of the WSN enables both the coach and swimmer to focus on other areas as the stroke data is provided automatically.

Visualisation of the testing set up is displayed in Figure 32 and includes the instrumented starting block, WSN and vision system. All three of these components were linked to an external 5v TTL (transistor-transistor logic) trigger that was also connected to an audio and visual signal for synchronisation purposes.

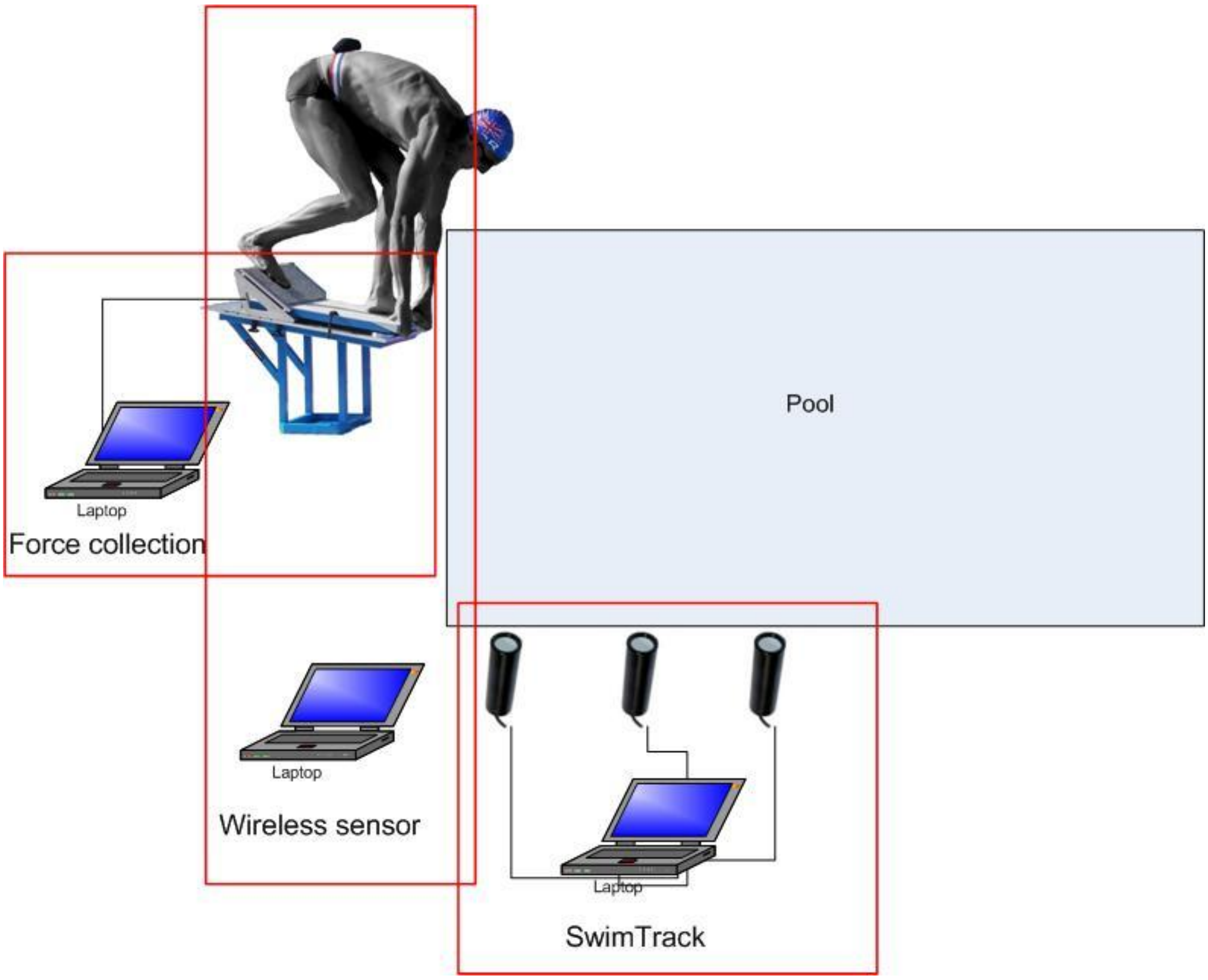


Figure 32: Testing set up for multi component analysis of swimming starts

[23] Swimming strokes are measured in cycles rather than counts. In freestyle and backstroke a stroke cycle is defined as the right hand entry through until the following right hand entry. The stroke cycle is considered to be one complete stroke in butterfly and breaststroke.

Swimmers were instructed to stand on the instrumented block after it had been calibrated and then position themselves in the "set" position[24]. A starter then instructed them to "take your marks" and the audio buzzer was their signal to commence the start. Each trial was performed at maximal speed until the swimmer's head passed the 15m mark from the starting wall. The same starter was used for all trials within each ITC to ensure consistency.

All starts were tagged at the key times and the hip was digitised using the SwimTrack© software so that times and positions for key points were determined. A light was used to indicate the exact gun time and feet lift-off was measured to the last frame prior to the toes no longer being in contact with the block. Entry times were recorded for the hand, head and feet such that comparisons could be made with previous research although the head was used in this research as it was also used to measure the total start time. The first downward movement of the leg after maximal knee flexion was defined as the first kick. Values derived from the analysis included the take-off velocity, horizontal distance from the wall as the head entered the water, maximum vertical depth of the hip, horizontal velocity and distance during the first kick as well as the hip throughout the block, flight and underwater phases.

After the testing session, the hip was used as a marker for the analysis process and digitised from 0.08s prior to the starting signal until the hip was no longer visible in the camera images. Data extracted from this analysis included the horizontal velocity at take-off, horizontal position of the hip at the time of head entry, maximum depth, as well as the horizontal distance and velocity of the hip at the commencement of the first kicking action during the underwater phase. The velocity was calculated through the use of the positional data in each frame with a known time difference of 0.04s between successive images.

Force data was captured at 100Hz as this had previously been shown to provide measurable differences in performance for elite and sub-elite swimmers (Slawson, 2010). Analysis from this data showed the repeatability of the starting technique for elite swimmers in the force traces sampled at 100Hz while there was variation between trials for individual sub-elite swimmers.

Fast Fourier Transforms (FFT) of a swimming start captured at 1000Hz on the instrumented starting block also indicated that the minimum capture rate required was less than 100Hz for the horizontal, vertical and lateral directions (Figure 33). This method was used to ensure that no key data was missed during the capture and analysis during the block phase of the swimming start as previous research had used higher sampling rates of 200Hz (Arellano et al., 2005) and 500Hz (Benjanuvatra et al., 2007; Galbraith et al., 2008). The majority of research into swimming starts using force platforms did not report the sampling rate of the equipment although Honda et al. (2010) did note that the force data was subject to a 10Hz Butterworth digital filter prior to analysis.

[24] A swimmer is required to be bent over prior to the start with no movement and this is referred to as the set position. The starter is then able to give the signal for the race to commence.

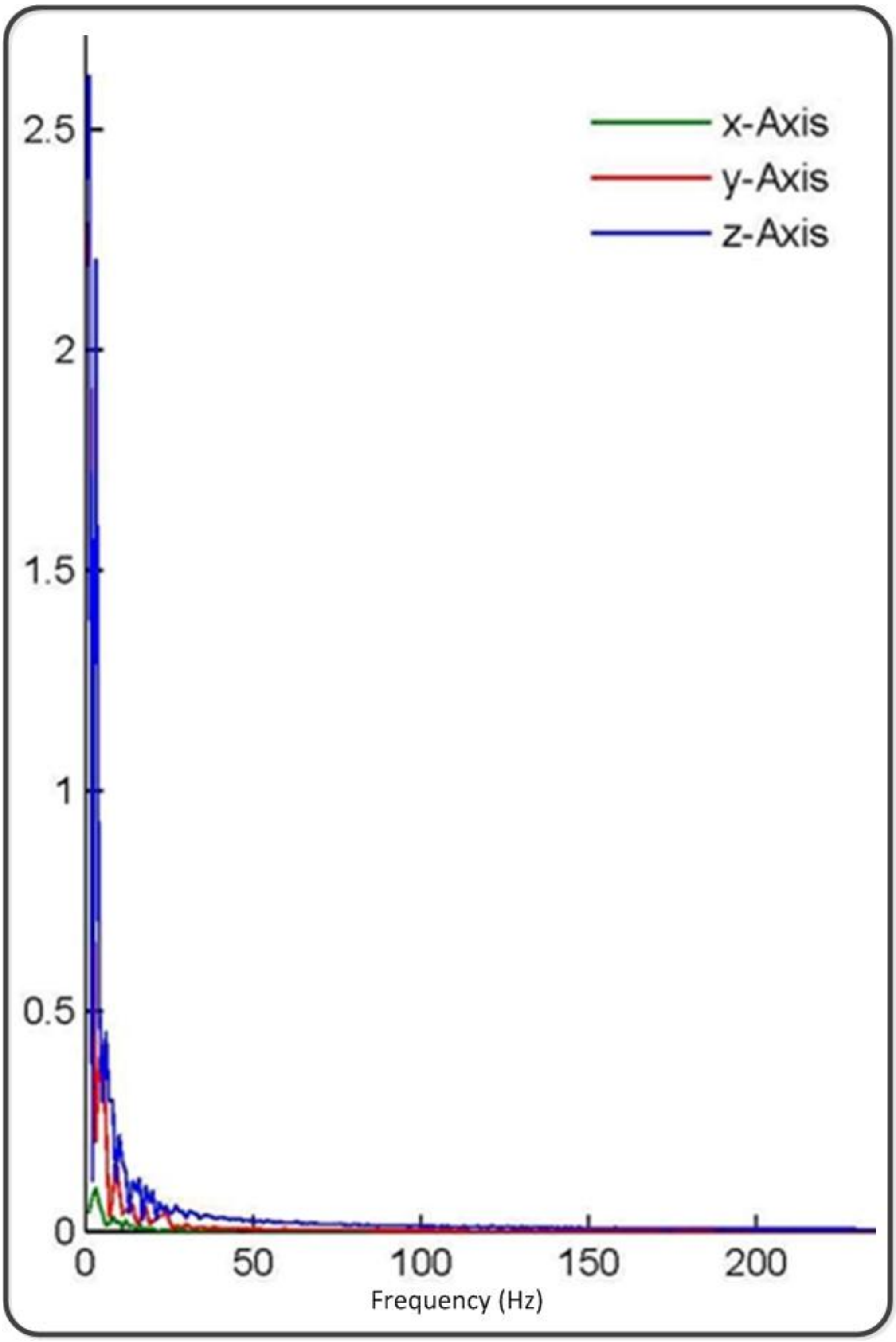


Figure 33: Frequency spectrum of a swimming dive using an instrumented starting block capturing at a sample rate of 1000Hz

5.3 Results

Data obtained from the instrumented starting block included the peak force and time at which this occurred in the horizontal (Y) and vertical (Z) planes for both the front and rear legs with calculations included to allow for the angle of the block and the wedge as displayed in Figure 34. Lateral (X) forces were disregarded due to the minimal variations between trials and minimal influence on starting performance.

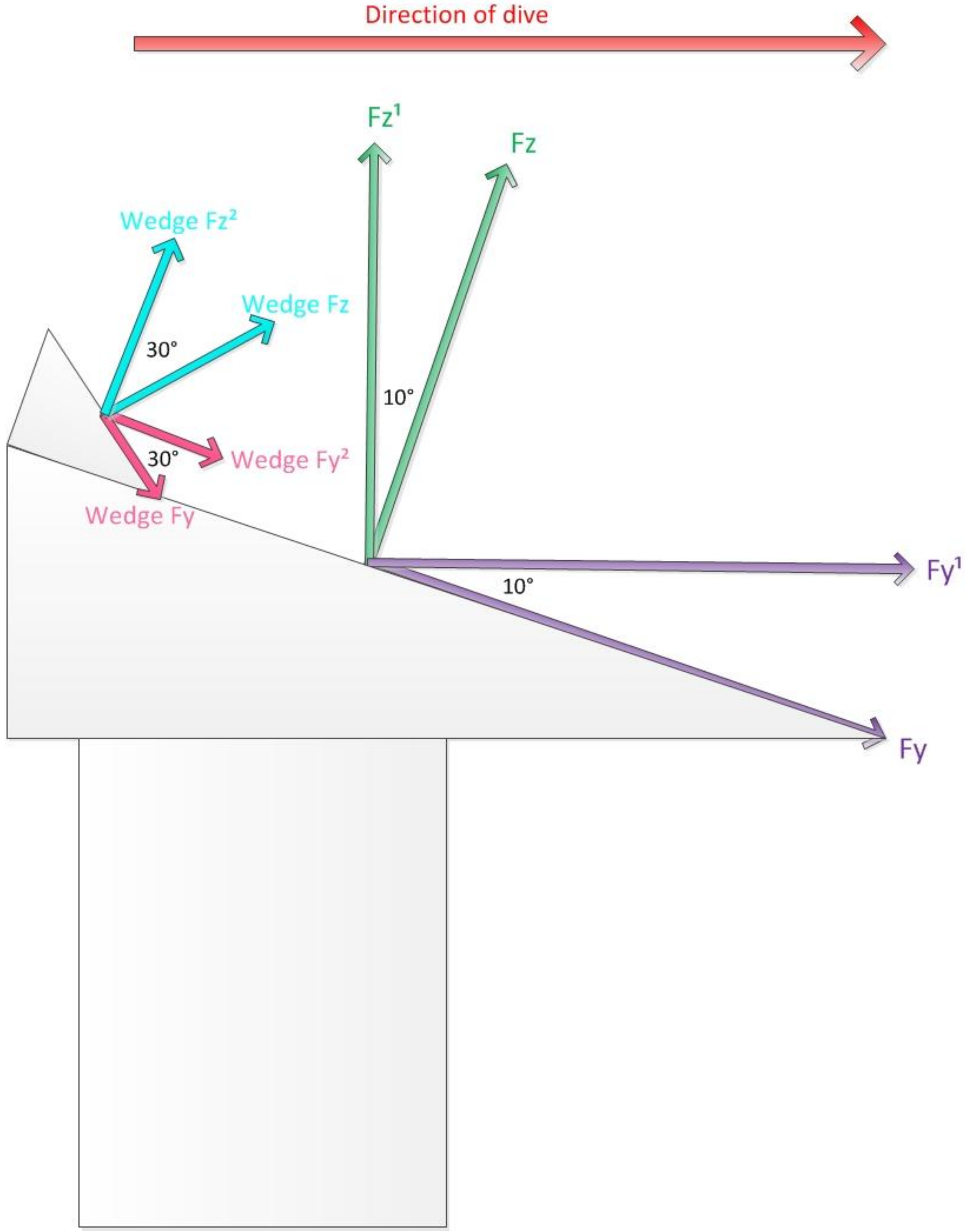


Figure 34: Vertical and horizontal force calculations on the main plate and wedge of the starting block

5.3.1 Optimal starting position

Data gathered from 48 swimmers (Table 44) showed that the majority of the group (42%) should have the rear wedge located in position 4 in order to produce the most effective start. The number of swimmers with the left leg in the forward position was 27 with 21 swimmers recommended to have their right leg at the front of the block. Interestingly, 76% of the swimmers produced better starts in the block and flight phases when they used a narrow stance[25] on the block.

Table 44 Summary of data to determine the optimal starting position on the OSB11 block

	Wedge position	Front leg	Width of stance
Position 3	11		
Position 4	20		
Position 5	16		
Left		27	
Right		21	
Wide			11
Narrow			35

One swimmer had not used the track start previously so there was no clear wedge or stance position to use but the best results were seen when starting with the left foot in the forward position. Prior to the 2008 Beijing Olympic Games the starting block design had been adapted so that the block was 10° from the horizontal compared with 5° in previous competitions using earlier starting block designs. The rear wedge had not yet been introduced to the design of the block yet all swimmers in the final of the 200m butterfly final used a track style technique. It was suggested that the swimmer noted above should adapt to the track style technique in order to be competitive during the start in his main event (200m butterfly). Times to leave the block are faster using the track technique (Issurin and Verbitsky, 2003), which can result in lower impulses (as determined by the force and time parameters on the block) when compared to the grab start.

A linear stepwise regression analysis was performed on the data in order to determine the contribution of the wedge position, front leg and width of stance with the only predictor related to the dependent variable of the 15m time being the stance. The results of the model are displayed in Table 45 with an R value of 0.092, adjusted R square of 0.008 and standard error of 0.686. The ANOVA results are displayed in Table 46.

[25] Narrow stance was defined as approximately 5cm between the left and right legs and a wide stance was when the legs were shoulder width apart on the block.

Table 45 Stepwise regression analysis measuring the impact of the wedge position, front leg and width of stance on the 15m time

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	0.092[a]	0.009	0.008	0.686

a. Predictors: (Constant), Stance

Table 46 ANOVA data for the stance position on the 15m time

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	5.35	1	5.35	11.36	0.001[b]
	Residual	622.72	1322	0.47		
	Total	628.07	1323			

a. Dependent Variable: 15m time (s)
b. Predictors: (Constant), Stance

This trend can be seen more clearly when examining the data within Tables 47-49 which compare the mean 15m times and standard deviations for each of the independent variables.

Table 47 Descriptive statistics for each of the wedge positions tested

Wedge position	Mean	N	Std. Deviation
3	7.09	439	0.69
4	7.10	442	0.69
5	7.11	443	0.69

Table 48 Descriptive statistics for the front leg

Front leg	Mean	N	Std. Deviation
Left	7.08	654	0.69
Right	7.12	670	0.70

Table 49 Descriptive statistics for the width of stance

Wide / Narrow	Mean	N	Std. Deviation
Narrow	7.05	853	0.67
Wide	7.19	471	0.72

While fewer trials were conducted using the wide stance position (471 compared with 853) it was clear that the mean time of 7.19 ± 0.72s was slower than the narrow stance position that had a mean 15m time of 7.05 ± 0.67s.

Data was then grouped in to each of the 12 testing variables for further comparisons (Table 50). The fastest 15m time was performed when the left foot was forward using a narrow stance and the wedge in position 3 (5.84s). The slowest time of 9.39s was generated when the right foot was forward using the same stance and wedge position.

Table 50 Descriptive statistics for all 12 starting positions used within the study

	N	Minimum Time (s)	Maximum Time (s)	Mean Time (s)	SD
Right Narrow 3	143	6.02	9.39	7.06	0.67
Left Narrow 3	139	5.84	9.27	7.03	0.67
Right Narrow 4	142	5.90	9.14	7.03	0.66
Left Narrow 4	143	5.84	9.21	7.05	0.67
Right Narrow 5	145	5.98	9.03	7.08	0.67
Left Narrow 5	141	5.92	9.28	7.07	0.68
Right Wide 3	80	6.10	9.08	7.19	0.74
Left Wide 3	77	6.06	9.33	7.14	0.72
Right Wide 4	80	6.17	9.20	7.28	0.76
Left Wide 4	77	6.01	9.33	7.15	0.69
Right Wide 5	80	6.29	9.07	7.21	0.72
Left Wide 5	77	6.00	9.29	7.16	0.69

5.3.2 Individual analysis during the original testing session

Descriptive statistics generated for one male subject are displayed in Table 51 and include information on the minimum, maximum, mean and standard deviation values for all 36 trials. These were conducted over three different training sessions on two consecutive days in a randomised order so that fatigue did not influence the results. The 15m time was defined as the period from the starting signal until the head passed the 15m mark from the wall and the block times were the period from the starting signal until the feet left the force platform. Peak vertical (Max Fz) and horizontal (Max Fy) forces were recorded on both the main plate and the wedge and the time at which these occurred is also provided (MP Fz and MP Fy time).

Table 51 Example of the descriptive statistics for one swimmer when determining the optimum starting position

	N	Minimum	Maximum	Mean	Std. Deviation
Wedge position	36	3.00	5.00	4.00	0.83
15m time (s)	36	5.95	6.53	6.22	0.14
Block time on main plate (s)	36	0.71	0.85	0.76	0.03
Max Fz on main plate (N)	36	761.00	1086.00	956.69	77.57
MP Fz time (s)	36	0.58	0.76	0.64	0.04
Max Fy on main plate (N)	36	357.00	461.00	410.53	26.84
MP Fy time (s)	36	0.65	0.78	0.69	0.03
Block time on wedge (s)	36	0.61	0.76	0.66	0.04
Max Fz on wedge (N)	36	740.00	874.00	819.42	32.71
Wedge Fz time (s)	36	0.28	0.56	0.43	0.10
Max Fy on wedge (N)	36	181.00	250.00	213.72	15.48
Wedge Fy time (s)	36	0.52	0.67	0.57	0.03

Data presented in Table 51 show large variations between the minimum and maximum values for the maximum vertical force produced by the front leg (761-1086N) and the time at which this occurred (0.58-0.76s) highlighting the fact that some of the start positions were more appropriate than others. The differences were not as large for the peak forces generated by the rear leg although the timing did show significant differences (0.26-0.56s) in the vertical direction on the wedge plate.

These data were then investigated further to examine the differences in peak forces on the main plate (Figure 35) and wedge (Figure 36) when the left and right legs were in the forward position.

From these graphs it is possible to see that the highest peak vertical forces are generated when the left leg is at the front of the block. The mean peak force on the main plate was 1009N when the left leg was forward and 903N when the right leg was at the front of the block. These were higher than the mean peak forces generated on the wedge component of approximately 835N and 804N for the left and right legs respectively.

The time that it took for the swimmer to reach 15m from the starting wall was also measured for all 36 trials (Figure 37) where results showed that when the right leg was at the front of the block, the average time was slower (6.31s) that when the left leg was at the front of the block (6.14s). Within the group there was an outlier with the right leg in the forward position on the block with a start time to 15m of 5.00s and this occurred when the swimmer moved prior to the starting signal (i.e. a false start).

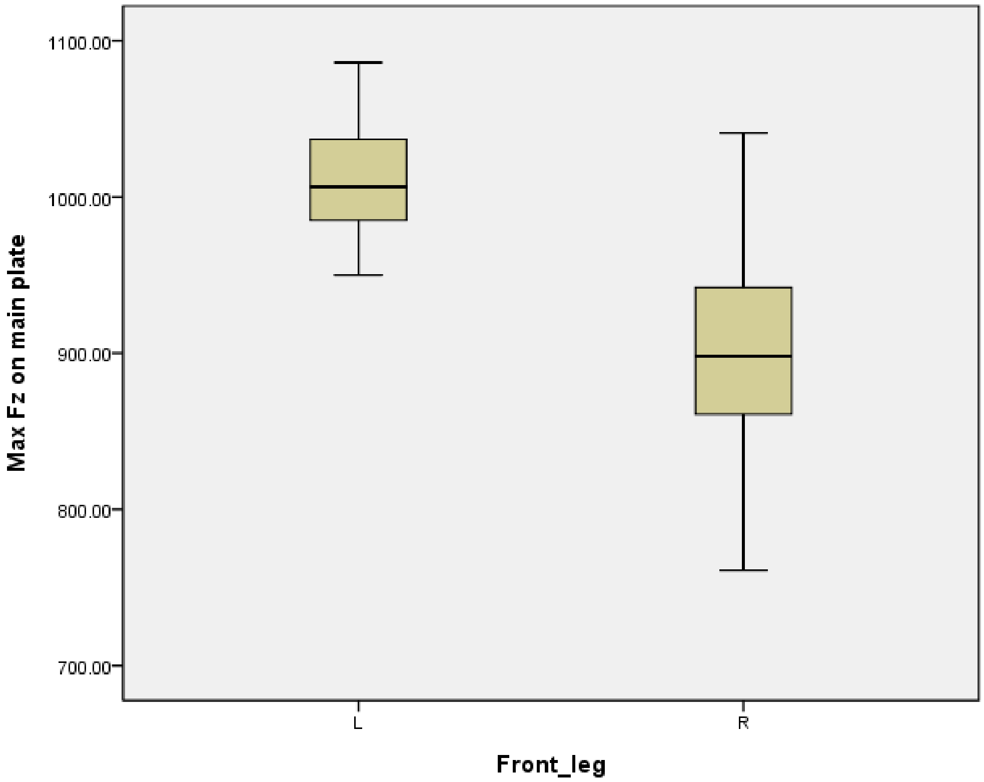


Figure 35: Box plot diagram showing the mean and SD values of peak vertical forces in Newtons on the main plate with the left and right leg at the front of the block

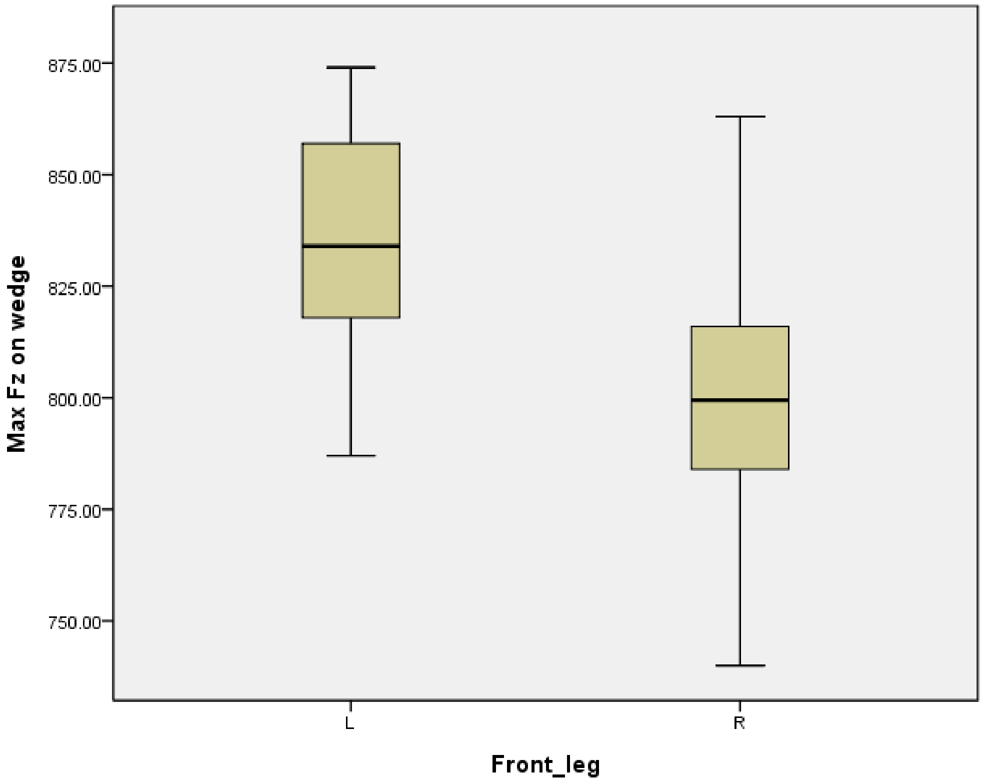


Figure 36: Box plot diagram showing the mean and SD values of peak vertical forces in Newtons on the wedge with the left and right leg at the front of the block

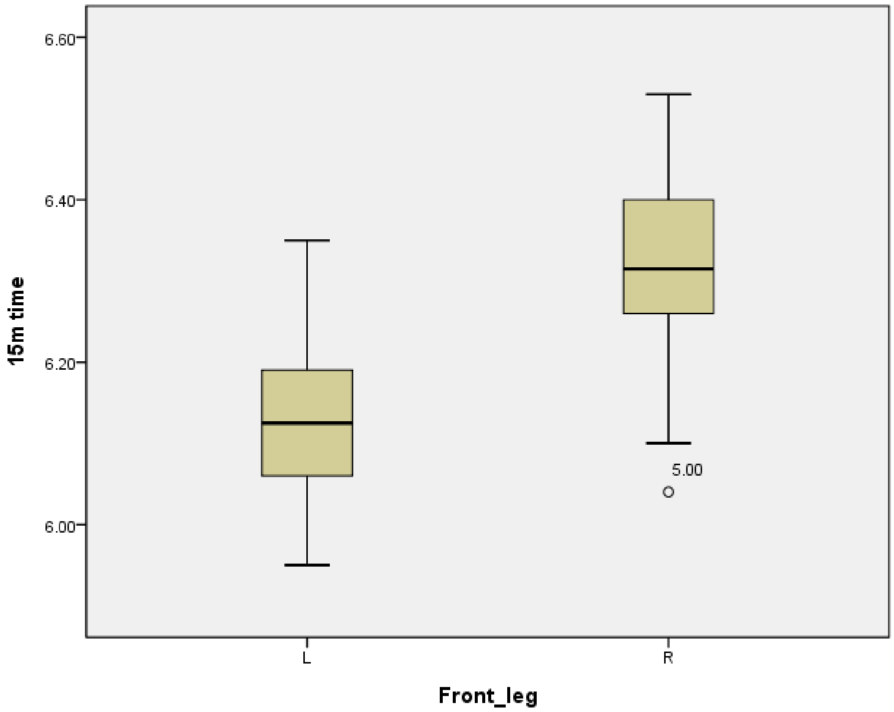


Figure 37: Time in seconds for the head to pass 15m after the starting signal with the left and right legs at the front of the block with a noted outlier indicated when the right leg was at the front of the starting block

Results from both the peak force and time data indicate that this swimmer should start with the left leg in the forward position on the block for the best diving performance. A 0.17s difference in the start time to 15m is less than the difference in time between the gold and silver medals in the 50m and 100m freestyle events for the previous three Olympic Games leading into London 2012 (www.omegatiming.com).

5.3.3 Case study progression

After examining the force, velocity and timing information of the twelve different starting positions feedback was provided to each individual swimmer as to the position which was predicted to provide the optimal start. In the majority of these instances the positions were similar to those currently used, so the results may have been influenced by a learning effect. The results of one subject suggested that they should change their position from the right leg forward with the wedge in position two to the left leg forward and the wedge in position four. This subject was selected as a case study in order to determine the influence of using technology to improve starting techniques.

Longitudinal trials were conducted over an 11 month period to monitor the progression of swimming starts after the optimal position had been determined for each swimmer. The aim of this research was to ensure that there was continued improvement to the starting performance within the daily training environment.

Table 52 Longitudinal data for one swimmer measuring the head entry distance as well as information on the first kick

	Head entry distance (m)	First kick time (s)	First kick distance (m)	First kick velocity (m/s)
Nov-10	2.54	2.99	7.49	1.55
Apr-11	2.55	3.39	8.28	1.71
Oct-11	2.71	3.42	8.06	1.63

Table 52 displays the data for one swimmer over the 11 month period. The distance of the hip as the head enters the water is the same for the November 2010 and April 2011 sessions but increased by more than 10cm during the October 2011 testing. The time and distance at which the first kick commenced increased during the testing period and resulted in a higher (1.71 compared to 1.55m/s) velocity at the same time. Lyttle et al. (2000) proposed that the first kick should commence when the swimmer is travelling between 1.9-2.2m/s in freestyle turns. Those figures are higher than seen for the current case study individual who was swimming breaststroke, so it is not possible to make direct comparisons. The progression from 1.55-1.71m/s over this time period shows that this swimmer is now utilising the streamlined position more effectively in the underwater phase of the start and is commencing their kick at similar velocities to the average first 25m race analysis data (1.65m/s) in the men's 100m breaststroke final at the 2011 World swimming championships (unpublished competition data).

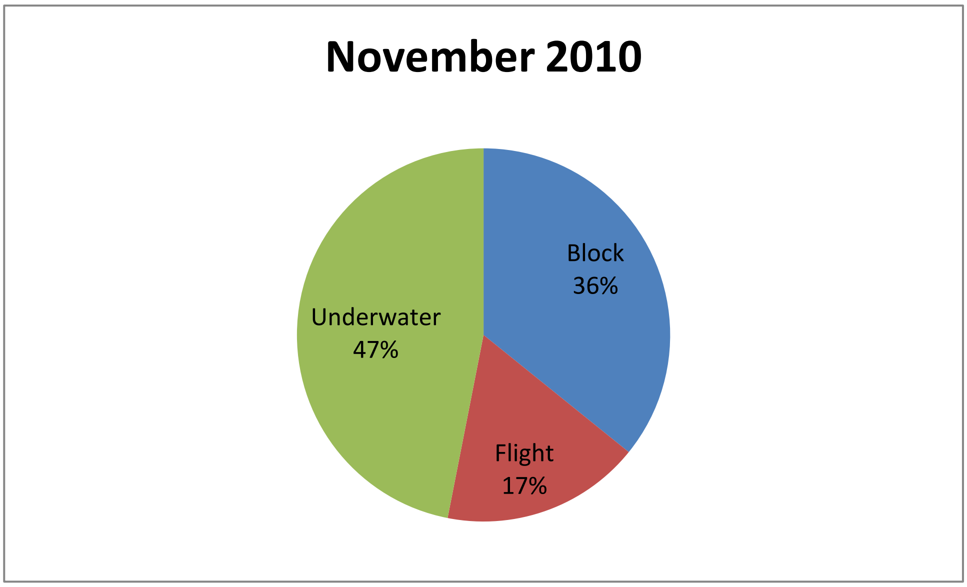


Figure 38: Percentage of the start spent in the block, flight and underwater phases during testing November 2010

The initial phase of the investigation was to examine the timing information over a 12 month period. Information was measured using the SwimTrack© analysis system, as described previously, where the timing information was synchronised with the audio signal for the start.

During the initial testing, three starts were performed in the recommended starting position during three training sessions over a two day period. This was one of twelve starting positions that were tested in a randomised order as part of the original research. In order to dismiss any outliers within the data, the average of all three trials was used for the analysis of the starting technique. The percentage of time spent in the block, flight and underwater phases of the start for the subject are displayed in Figure 38.

Starting performance was measured again in April 2011 where the swimmer was able to use both their preferred as well as the predicted optimal positions on the starting block. The total number of dives on this occasion was five and all were performed during one training session. Block, flight and underwater phase times are represented as a percentage of the overall start time (Figure 39).

These two figures highlight a 1% decrease in both the block phase and flight phase between the original testing in November 2010 and the follow up testing conducted in April 2011. These data therefore suggested that the subject spent a longer proportion of time in the underwater phase of the start during the second round of testing.

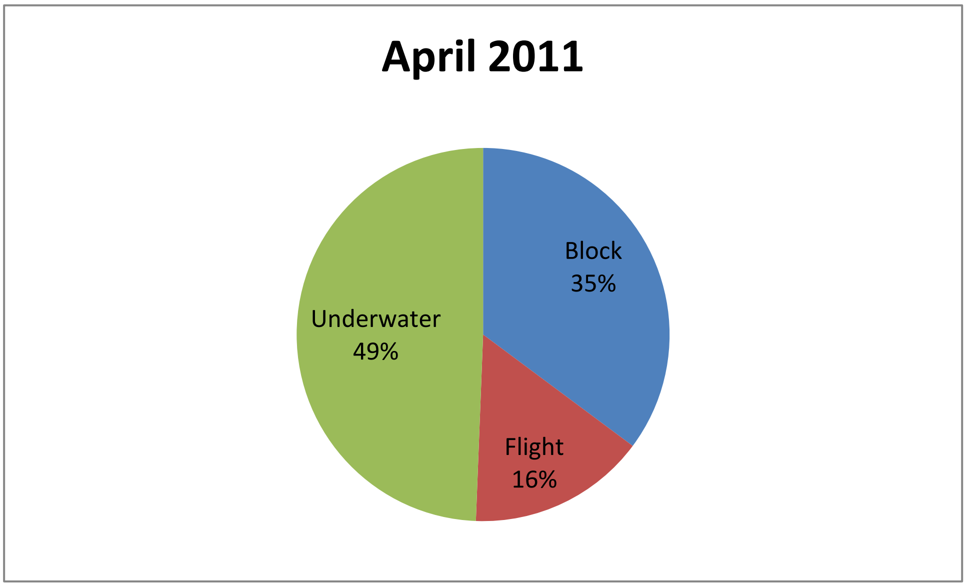


Figure 39: Percentage of the start spent in the block, flight and underwater phases during testing April 2011

The subsequent testing session occurred in October 2011 after the swimmers had regained some of their fitness following the annual summer break from training and competition. On this occasion three maximal starts were performed using the predicted starting position on the instrumented block (Figure 40).

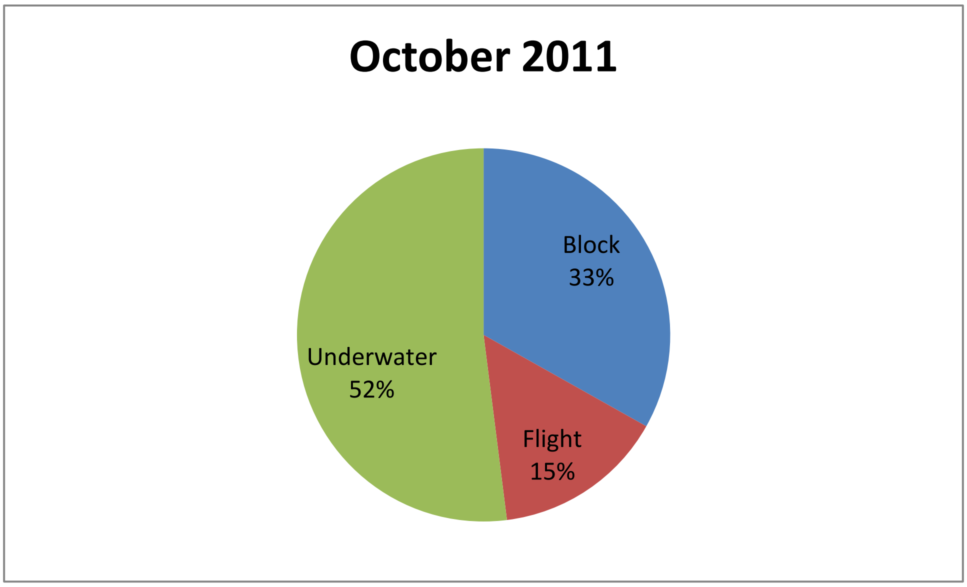
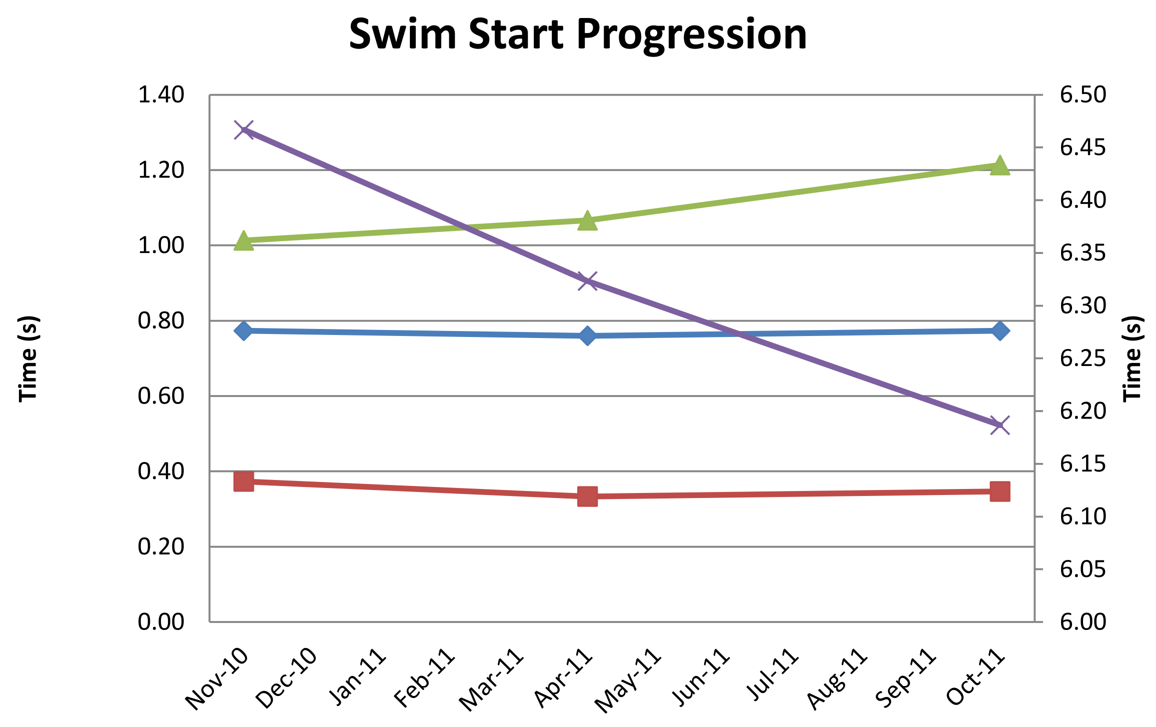


Figure 40: Percentage of the start spent in the block, flight and underwater phases October 2011

Results from the third round of testing showed that the underwater phase contributed to 52% of the time spent performing a maximal start and this had increased from 47% in November 2010. Over the same time period the block phase changed from 36% down to 33% of the start while the block phase was reduced by 1% on each consecutive testing session.

In order to determine the impact of a greater time spent in the underwater phase of the start, the timing information for each of the phases was compared with the 15m start time. The values calculated within each phase for the November 2010, April 2011 and October 2011 testing sessions are displayed in Figure 41.

The average block time was 0.77s in November 2010, 0.76s in April 2011 and 0.77s in October 2011 showing no real change during this phase. The 0.04s time difference between the average flight time in November 2010 (0.37s) and April 2011 (0.33s) may be explained by the limitation with the video equipment used within the testing sessions. The Sony HQ2 cameras used during the research captured the starting technique at 25 frames per second, which equates to a 0.04s time difference between successive frames. Results from the testing session in October 2011 (0.01s) fell within the range discussed above so it is plausible that there was no change in the time of the flight phase over the three testing sessions.



	Nov-10	Apr-11	Oct-11
Block	0.77	0.76	0.77
Flight	0.37	0.33	0.35
Underwater	1.01	1.07	1.21
15m Time	6.47	6.32	6.19

Figure 41: Representation of the time for the various start phases over a 12 month period

From earlier discussions it was noted that there was a large change in the percentage of time spent in the underwater phase from the original testing in November 2010 to the final testing in October 2011. The subject spent 1.01s in the underwater phase (time from head entry through to head surfacing) in the first testing session and increased this to 1.07s in the second testing session. By the final testing in October 2011 the time spent in the underwater phase had increased to 1.21s.

During the same time period the average start time to 15m after the starting signal was 6.47s in the first testing session and this was reduced to 6.32s during the second testing session. There was little practice using the new starting position during the period between the first and second testing sessions but results from the April 2011 testing showed that the starts were faster using the predicted optimal starting position. After this point the subject used the new position within the daily training environment on a regular basis. Results from the starts measured in October 2011 showed that the average of the three trials resulted in a start time of 6.19s. The improvement of 0.28s of the start time to 15m is significant considering the difference between the gold and silver medallists in the men's 100m freestyle event was 0.14s on average from the 2000, 2004, 2008 and 2012 Olympic Games.

This level of competition was used for comparative purposes as it is the event in which our subject used within the case study competed in.

Results from this case study showed a relationship between the underwater time and the 15m time after the starting signal. During the 11 month period the subject increased the time that was spent underwater from 1.01s to 1.21s. This 0.20s time difference was less than the 0.28s decrease in the overall start time but the trend suggested that the longer that the swimmer spent in the underwater phase, the faster the overall start time as noted by Cossor and Mason (2001).

5.3.4 Relationship with land testing

A study was designed to determine the relationship between land tests and starting performances. While previous researchers examined the effect of land training on starts (Arellano et al., 2005, Benjanuvatra et al., 2007, Breed and Young, 2003 and West et al., 2010) none were conducted using the OSB11 type block.

Six elite male swimmers were used for the study and performed three maximal swimming starts using the instrumented block as well as three trials on a single axis force platform operating at 200Hz for the land based tests. Markers were placed on the force platform to indicate the size of the starting block and the swimmers held their hands on their hips throughout each of the counter movement jumps. Trials with the left or right foot forward were randomised both in the pool and on land in order to minimise any learning effects.

Pearson Product Moment Correlations were used to determine the relationships between the land and pool tests with significant trends at the $p \leq 0.05$ level displayed in Table 53.

Table 53 Significant correlations (p=0.05) between land and pool tests for starting performance

	Right Jump Height	Left Jump Height	Right Vertical force land	Left Vertical force land
Right Fz main			0.526	0.596
Left Fz main	-0.478	-0.515	0.647	0.636
Right Fz wedge			0.653	0.741
Left Fz wedge			0.792	0.830
Right dive depth			0.885	0.794
Left dive depth			0.765	0.771
Right entry distance				
Left entry distance	-0.694	-0.593	0.500	0.600

Positive correlations were observed between all of the vertical forces generated on the land and the pool parameters except for the entry distance when the right foot was at the front of the starting block. Vertical jump height was negatively correlated with the peak vertical force on the main plate as well as the entry distance when the left foot was at the front of the block. These results would indicate that it may be possible to perform jump testing on the land instead of using expensive instrumented starting blocks for information on starting performance in swimming.

5.4 Discussion

During the 2012 London Olympics the time differences between the first and second swimmers ranged from 0.01s (men's 100m freestyle) to 0.38s in the women's 100m freestyle. This highlights the potential importance of the start in the sprint freestyle races at the highest level of competition with the winner of the gold medal achieving a faster time to 15m in all four events when compared to the other medallists as seen in Table 54. The fastest times are highlighted as green, the second fastest are orange and the slowest start times to 15m for the medallists in each event are red.

Table 54 Start time to 15m in the 50m and 100m Freestyle events at the 2012 London Olympic Games

	London Olympic Start times for podium swimmers (s)		
Event	**Gold**	**Silver**	**Bronze**
Men's 50m Freestyle	5.22	5.20	5.30
Men's 100m Freestyle	5.52	5.60	5.64
Women's 50m Freestyle	6.04	6.38	6.14
Women's 100m Freestyle	6.24	6.54	6.46

With the introduction of a new starting block to international level competitions it was important to determine the best starting position for each individual swimmer. The new blocks had two major modifications to the previous model:

1. The inclination increased from 5° to 10°
2. The introduction of a wedge at the rear of the platform

A combination of these three systems (force, WSN and vision) enabled the optimum starting position for each swimmer to be identified. The key parameters used to define good starts include the take-off velocity (Arellano et al., 2005; Welcher et al., 2008), flight distance (Houel et al., 2010a), underwater distance (Cossor and Mason, 2001; Lyttle and

Benjanuvatra, n.d.; Mason and Cossor, 2000), and position of the centre of mass (CoM) on the block (Kraan et al., 2001; Miller et al., 2003; Welcher et al., 2008).

Throughout this research systems have been developed to monitor and record the starting performances of elite swimmers within the training environment. These multi-component systems include force data derived from instrumented starting blocks, inertial sensors to monitor the kick rate, number of kicks, stroke rate and number of strokes, as well as vision systems to derive timing and positional information. Data could then be linked to competition performances to ensure that the correct phase of the skill was targeted.

Optimal starting positions were determined for 48 elite swimmers using an instrumented version of the OSB11 starting block. Vertical and horizontal forces for the front and rear legs were measured separately under numerous conditions. The OSB11 block has five positions for the rear wedge to be located on the block ranging from 350mm to 530mm from the front of the block. Swimmers were asked to perform three trials in wedge position 3, 4 and 5, with either the left or right leg foot on the front of the block, and both narrow and wide stances. The testing order was randomised and took place over a two day period before the data from the force platform and vision systems was analysed and an optimal starting position was recommended for each swimmer.

A case study was performed on the swimmer whose suggested change was the greatest from their preferred starting position. No practice was performed on the suggested starting position between the original testing and the follow up testing that compared the preferred and suggested starting positions. Results showed faster starting times to 15m when the swimmer used the suggested position compared to their preferred position. Two more testing sessions were performed on the swimmer over an 18 month period and the subject continued to improve their starting performance with the new position.

Comparisons were also made between the force data generated on the starting block and the force data that was monitored in the gym. Vertical force with the left and right leg in the forward position was measured for jump tests in the pool and on land. Strong positive correlations were found between these measures on the main plate and wedge with the land tests. There were also significant positive correlations with the land tests and the maximum dive depth of the swimmer. When comparing the land tests with the entry distance from the starting block, significant positive correlations were also observed when the left leg was in the forward position for the swimming start. Data was significantly negatively correlated with the jump height on land with the vertical force and entry distance when the left leg was at the front of the block. All of these were significant at the $p \geq 0.05$ level. This would suggest that the swimmers limited their vertical force and flight distance when the left foot was forward during a swimming start so it may be more beneficial for them to place the right foot forward.

Fast Fourier transform (FFT) analysis also showed no significant differences in the peak force and timing information of start performances when capturing the data at 100 or 1000Hz. Previous research on swimming starts was completed using single and tri-axis force platforms with capture rates ranging from 250-1000Hz. Strength and conditioning coaches suggested a capture rate of 1000Hz was required to determine the rate of force development but results of the FFT proved that it was possible to capture at 100Hz and not miss any relevant data.

5.4.1 Feedback to swimmers and coaches

Feedback on the force measures using the instrumented starting block can be provided back to the swimmer and coach within 2 minutes of the testing session through the use of a graphical user interface (GUI) written by Slawson (2011, unpublished) as displayed in Figure 42. During the original research start testing utilising the bespoke instrumented block it was not possible to display the video and force data simultaneously and made the feedback process time consuming and difficult.

On the left side of the screen the horizontal and vertical force profiles were displayed for the capture period along with information on the sampling rate and body weight of the athlete. To the right of the screen is the above water image of the swimmer performing the start that was synchronised with the force data through the inclusion of a light that was attached to the starting audio signal and displayed in the video image within the GUI. The tabs allowed the user to select key variables within the force traces and see where the swimmer was in the block phase of the start that corresponded to these values.

The calculated values for the reaction time (time to first movement) and the contact time with the force plate are listed on the display along with the peak forces and times at which these occurred.

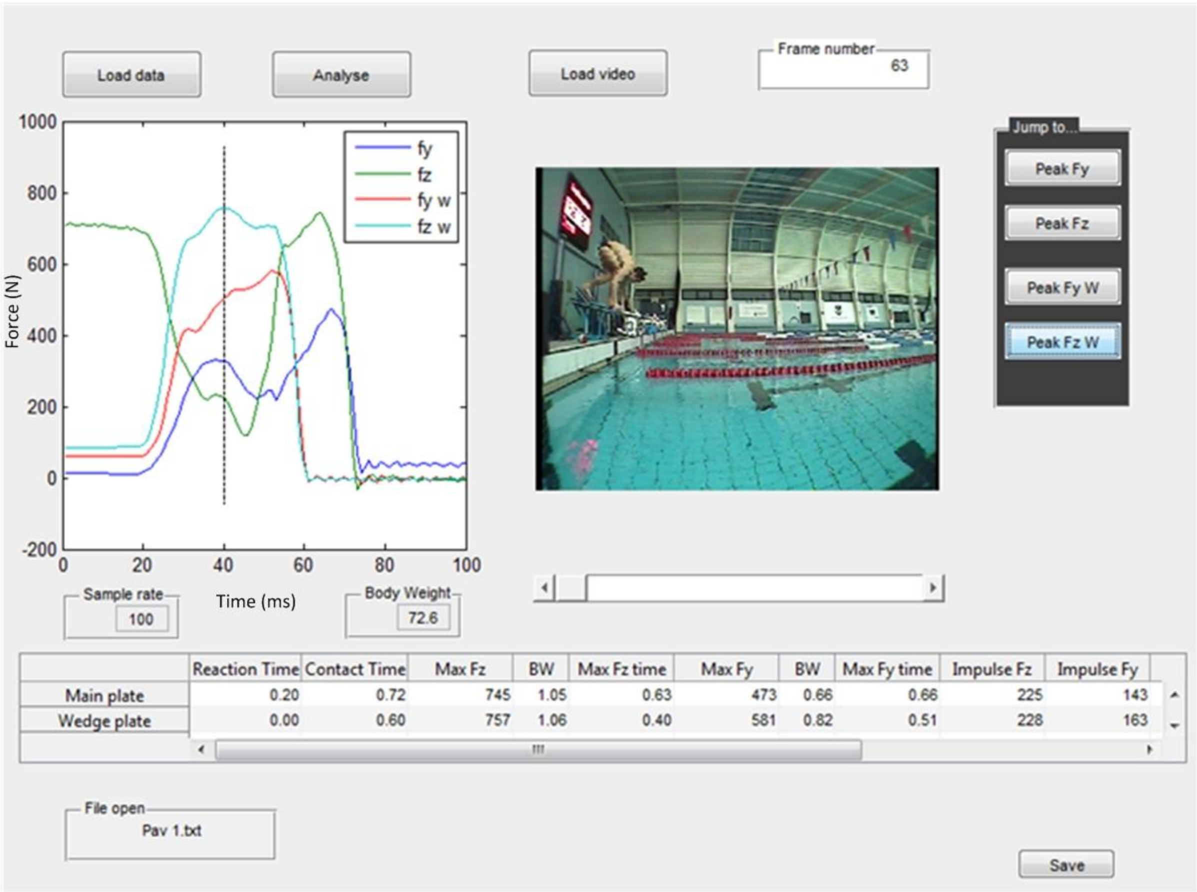


Figure 42: Screen shot displaying the force and video analysis of a single swimming start

Graphical data could be used to demonstrate the trends for the velocity as the swimmer leaves the block as well as the velocity during the first kicking action in the underwater phase. Figure 43 shows that the highest flight velocity was seen during trial 6 and while this resulted in the highest velocity when leaving the block, the swimmer felt uncomfortable and this led to poor technique when entering the water and a faster reduction in hip velocity.

The other important factor that Figure 43 demonstrates is that the swimmer commences their first kick when they are still travelling faster than they can propel themselves using an UUS technique in the underwater phase. They should be aiming to commence their first kick when travelling between 1.9 and 2.2m/s based on the earlier reported research, and the only start in which this occurs is during trial 6 (the second point on the graph). This type of feedback clearly shows that the underwater phase is an area in which the swimmer can improve their starting technique with no additional work – all they need to do is maintain the streamlined position for a longer period of time prior to commencing the underwater kicking action.

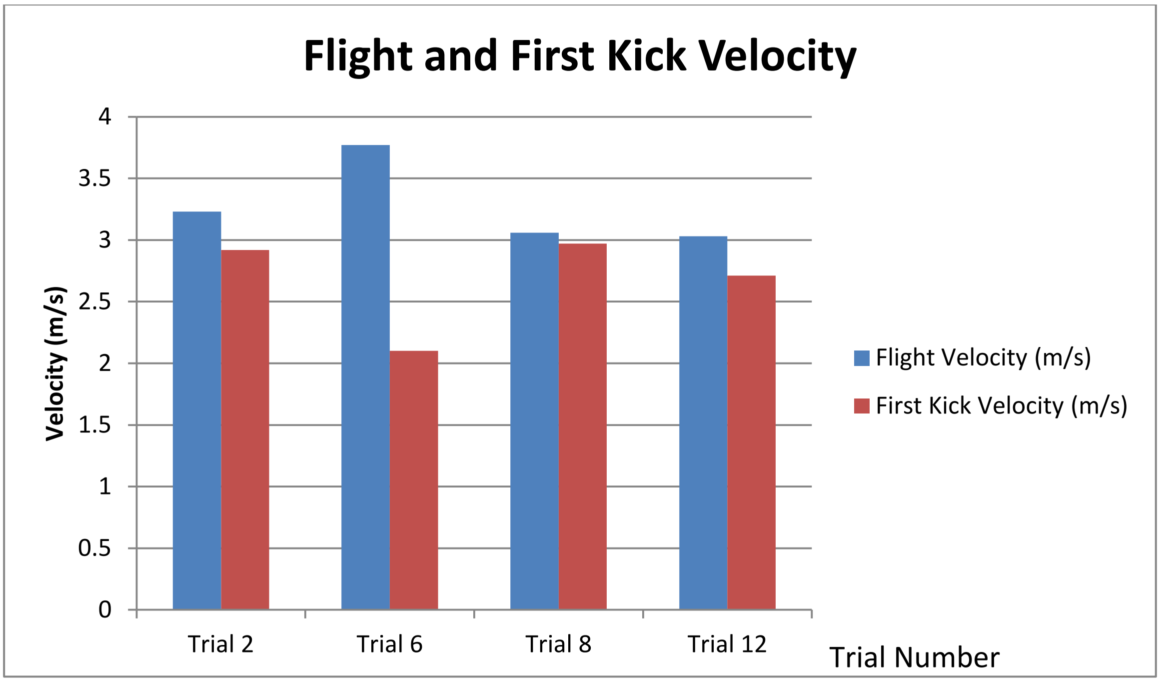


Figure 43: Graphical representation of the flight and first kick velocity for a swimmer during a single testing session

Another style used to feed back information to the coaches and swimmers was to present the information in tabular format but include more detail as seen in Table 55. The variables presented include information gathered from the SwimTrack© software including the take-off from the block, entry into the water, timing of the first kick and maximum depth of the hip throughout the start. Total start time to 15m was noted for comparisons to be made when changes to any of the start phases were implemented.

Quantitative data from the instrumented starting block was also displayed in the report so that comparisons could be made between the different trials. Information was then separated into the front foot and the rear foot and included the peak horizontal (Fy) and vertical (Fz) forces in Newtons (N) and when resolved for body weight (BW).

The time at which these peaks occurred was noted along with the total contact time on each of the individual plates. At the bottom of the table, information was included on the stroke, mass, front foot position and wedge positions.

These examples of feedback to the coaches and swimmers that have been described above show how the feedback of the start testing may be adapted to suit the needs of the individual coaches and swimmers. All information was provided to the coaches within one week of the testing session such that changes could be implemented within the following training cycle. The data presented as part of this feedback process could also be linked to tests that were performed on land, particularly around the strength phases in the gym.

Table 55 Kinematic and kinetic information on two swimming starts for one swimmer

	Variable	Trial 1 Time (s)	Trial 1 Distance (m)	Trial 1 Velocity (m/s)	Trial 1 Force (BW)	Trial 2 Time (s)	Trial 2 Distance (m)	Trial 2 Velocity (m/s)	Trial 2 Force (BW)
	Take off	0.70	0.89	3.95		0.71	0.78	3.41	
	Head entry	1.00	2.09	3.78		1.04	2.13	3.57	
	1st kick	1.28	4.02	4.24		1.32	4.09	4.78	
	Total start time	6.34				6.33			
	Maximum depth		1.23				1.23		
Front foot	Reaction time	0.12				0.13			
	Contact time	0.70				0.71			
	Peak force (Fz)	0.22	910		1.13	0.25	951		1.18
	Peak force (Fy)	0.27	530		0.66	0.28	534		0.66
Rear foot	Contact time	0.58				0.59			
	Peak force (Fz)	0.23	803		0.99	0.24	837		1.04
	Peak force (Fy)	0.23	656		0.81	0.33	649		0.80
	Stroke			Butterfly				Butterfly	
	Mass (kg)			82.30				82.30	
	Front foot			Right				Right	
	Wedge position			3				3	

5.4.2 Practical implications

Analysis of the swimming starts using the instrumented block has shown differences between the left and right legs during the block phase. Results showed that the optimal starting position was not related to the preferred leg and that the narrow stance position was more effective than a wide stance position.

The equipment required to measure forces during the starts is expensive and not readily available so it was good to note that it was possible to get similar results when measuring the jumping ability of swimmers on land.

The research on optimal starting position was new knowledge gained for this group of elite level swimmers who then went on to compete at major international competitions throughout the duration of the research. The ability to differentiate between the left and right legs had not been analysed prior to this time and with the information gained from the instrumented block it was possible to generate a more effective start with the measures on vertical and horizontal forces.

With measureable differences observed between the left and right legs in the start it was felt that it was important to measure these within the wall contact phase of the turn.

Chapter 6 - Turns

Objective 3

To determine the position of the feet on the wall that resulted in the fastest turn times as measured from the head passing the 5m distance in to the wall and back to the same position after the swimmer had completed the turning motion. There is currently no research to suggest that the foot position effects turning performance but it is an assumption made by swimming coaches.

6.1 Introduction

A swimming turn enables the athlete to change direction when they reach the end of the lap in the fastest possible method. The technique used varies between the different strokes but all aim to use the momentum from the stroke coming into the wall during the rotation phase. This is more appropriate in freestyle and backstroke where there is a change from linear to angular momentum when changing the swimming direction. The mechanics of the turns are discussed by Maglischo (2003, 1993) for each of the strokes and for each of the phases.

6.1.1 Phases of the turn

As with starts, the skill of turning in swimming can be divided into a number of different phases. These include the:

- Approach (In) phase
- Rotation phase
- Wall contact phase
- Underwater phase and the
- Stroking phase

The *approach phase* is defined as the period from when the swimmer's head passes the 5m distance coming in to the wall at the end of the lap, until their last hand enters the water. The final arm stroke tends to occur between 1.7 and 2.0m before they reach the wall (Chow et al., 1984). An example of the last hand entry position is shown in Figure 44 and is similar for both freestyle and backstroke turns. In breaststroke and butterfly the end of the approach phase is the time at which the hands touch the wall prior to the rotation.

Figure 44: Representation of the approach (in) phase of the freestyle swimming turn

In Figure 44, the swimmer has the forward arm in a streamlined position along with the head in a neutral position (i.e. not looking upwards or downwards). This position enables them to maintain the velocity from the free swimming component within the lap prior to the change in direction.

After the last hand has entered the water or touched the wall, the swimmer commences the *rotation phase* (Figure 45) which ends when the feet touch the wall in all strokes. The mechanics vary depending on the stroke but in freestyle and backstroke the front arm is used as an anchor point over which the body rotates. This is generally more successful if the swimmer drops their head downwards soon after the last hand enters the water to assist with a more continuous movement between the arms and the body.

Figure 45: Rotation phase during a freestyle turn

The body is tucked during this phase in order to increase the speed of rotation. In order to be more tucked than piked (straighter legs) during the rotation the swimmer must be closer to the wall while the swimmer in Figure 45 is quite piked at this point. A piked turning position has resulted in faster 5m round trip times (RTT) which measure less of the swimming component and more of the turning action (Cossor et al., 1999).

Figure 46: Side rotation in a breaststroke turn

Figure 47: Rotation underneath the body during a breaststroke turn

In breaststroke and butterfly the swimmers can choose to rotate to the side (Figure 46) or underneath (Figure 47) their body and this will affect their position on the wall. In either variation it is important for the legs to be tightly tucked and to keep the majority of the body underneath the surface of the water to reduce the negative effects of wave drag.

When the swimmer's feet contact the wall there is a period of time before the feet leave the wall and this is referred to as the *wall contact phase*. Various positions have been discussed relating to the foot position on the wall during a turn – particularly in freestyle and backstroke (Lyttle and Benjanuvatra, 2007; Troup, 1999).

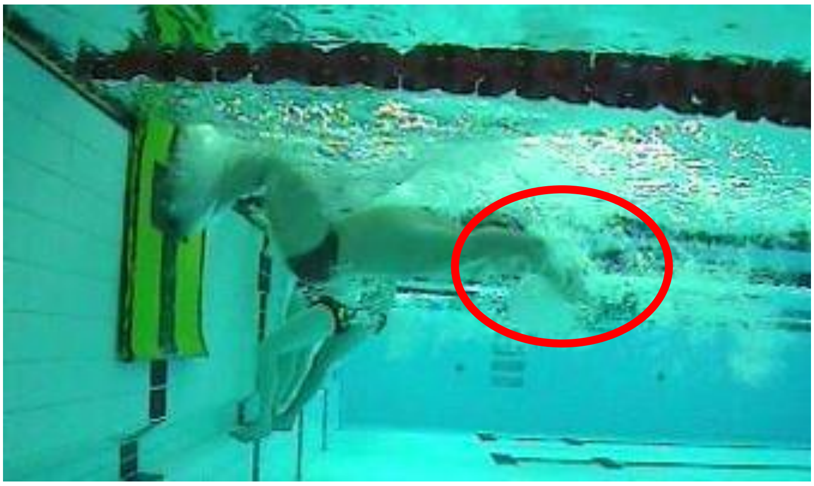


Figure 48: Toes pointing towards the surface of the water during the wall contact phase of a turn

One method is to contact the wall with the toes pointing upwards (Figure 48) and does not require any additional rotation in the longitudinal axis[26]. On the other end of the continuum, some swimmers contact the wall with their feet at 90° (Figure 49) so that the toes are pointing to the side wall of the swimming pool rather than towards the surface of the water.

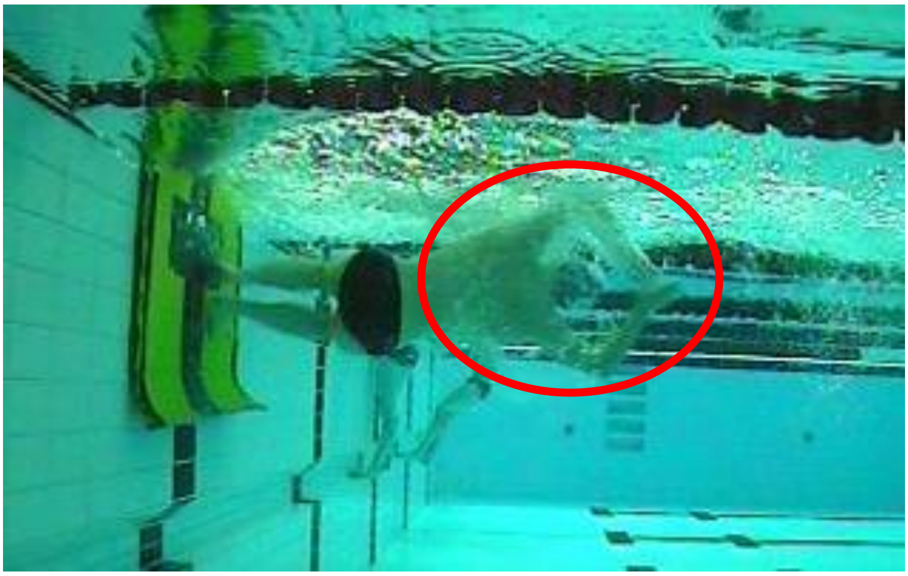


Figure 49: Feet rotated to face the side wall of the pool during the wall contact phase in a turn

The different feet orientations on the wall should not affect the period of time that is spent during this phase but will be examined during the current research. Regardless of the position of the feet on the wall, the athletes should ensure that there upper body is in a streamlined position prior to pushing off the wall in order to minimise the drag and hence maintain the velocity for a longer period of time. The red circle in Figures 48 and 49 reveal that the swimmers are not in an appropriate position with the bent arm position

[26] The longitudinal axis divides the body into left and right sides.

contributing to the frontal resistance. Swimmers do not need to spend a long period of time in contact with the wall but do need to ensure that they are able to generate enough power to increase their velocity when leaving the wall (Lyttle and Benjanuvatra, 2007). Studies on age group swimmers found average wall contact times of 0.6s in backstroke (Blanksby et al., 2004) and 0.39s in breaststroke (Blanksby et al., 1998).

Plyometric training is designed to improve the SSC capabilities for movements that are shorter than 0.40s in duration (Komi and Gollhofer, 1987). Results of a 20 week investigation on tumble turns by adolescent swimmers found an improvement of wall contact times by both the control (swimming only) and test group who practiced plyometric movements in addition to swimming training (Blanksby et al., 1998; Cossor et al., 1999). The control group averaged 0.60s prior to the study and reduced this to 0.48s after the 20 weeks while the swimmers who performed low to mid level intensity plyometric jumps decreased their wall contact times from 0.58s to 0.50s.

The swimmer should also ensure that their body is in a streamlined position prior to leaving the wall as seen in Figure 50 in order to maintain the higher velocity off the wall for as long as possible (Miyashita and Tsunoda, 1978). The knee angle is slightly less than 90° during the foot plant and the upper body is flat and parallel to the surface of the water. The arms are outstretched and in line with the upper body while the head is between the arms.

Figure 50: Upper body in a streamlined position prior to leaving the wall during a swimming turn

The distance between the surface of the water and the hip was measured at its maximum point during the turn and is determined by the position of the feet on the wall. A swimmer will move towards the bottom of the pool if the feet are higher than the hips when pushing off the wall. Likewise they will maintain a parallel position to the surface if the feet and hips are in line and go towards the surface of the water if the hips are higher than the feet during the wall contact phase. When swimmers were towed at 0.4 and 0.6m below the surface of the water there were no significant differences in the passive drag measures for speeds ranging from 1.6-3.1m/s (Lyttle et al., 1998a) suggesting that there is no need for the swimmers to be too far below the surface of the water when pushing off the wall after a turn.

After the swimmers lose contact with the wall and prior to the head surfacing after the turn is referred to as the *underwater phase*. During this phase the swimmer will hold a streamlined position initially and then commence some form of kicking action in order to maintain the velocity generated during the wall contact phase. The dolphin kick in the prone position is the most common form of kick during the underwater phase of turns but was not significantly faster than the prone freestyle kick or lateral dolphin kick in a study of 16 elite male swimmers (Lyttle et al., 2000). This kicking technique can be performed with large amplitude and low frequency actions or a small amplitude and high frequency. Swimmers will tend to vary the relationship between amplitude and frequency at different stages during the underwater phase. The most popular technique used by elite swimmers is to use a large amplitude kick initially and then move to a smaller amplitude as they approach the surface of the water but there are individual differences at the elite level (Elipot et al., 2010).

Results using computational fluid dynamics (CFD) modelling suggested that the larger amplitude kicks were more effective at minimising momentum reduction when travelling at 2.40, 2.18 and 1.50m/s (Lyttle and Keys, 2006). Similar conclusions were reported by Sugimoto et al. (2006) using their own "SWUM" model to show that the trunk and head contribute to the thrust of the body during underwater kicking.

Gavilan et al. (2006) conducted a two dimensional analysis of the UUS technique of 20 national and international swimmers for 15m after a pool entry. Digitisation of a 13 point model was used to determine the frequency and amplitude of the kicking motion used by the swimmers in this group. Results found an average frequency of 2.17 ± 0.32Hz and kick length of 0.76 ± 0.13m for the group. As a consequence of the vertical displacement information reported, the authors concluded that there is the chance that the energy generated from the UUS transfers along the entire length of the body rather than from the hips to the toes.

The least common kicking action during the underwater phase is the freestyle flutter kick and is used by those swimmers who are not proficient as the dolphin kick. Swimmers competing in the breaststroke events are permitted to take one underwater stroke prior to surfacing from the start or turn and this includes one large dolphin kick movement after the hands have separated.

As the velocity leaving the wall during a turn is not as high as that generated during a swimming start, the athlete commences their initial kicking action much closer to the wall when they are travelling between 1.9 and 2.2m/s in freestyle and backstroke. Exact values for breaststroke and butterfly have not been reported in the literature but butterfly swimmers are encouraged to use similar values as the free swimming velocities are similar to the other strokes.

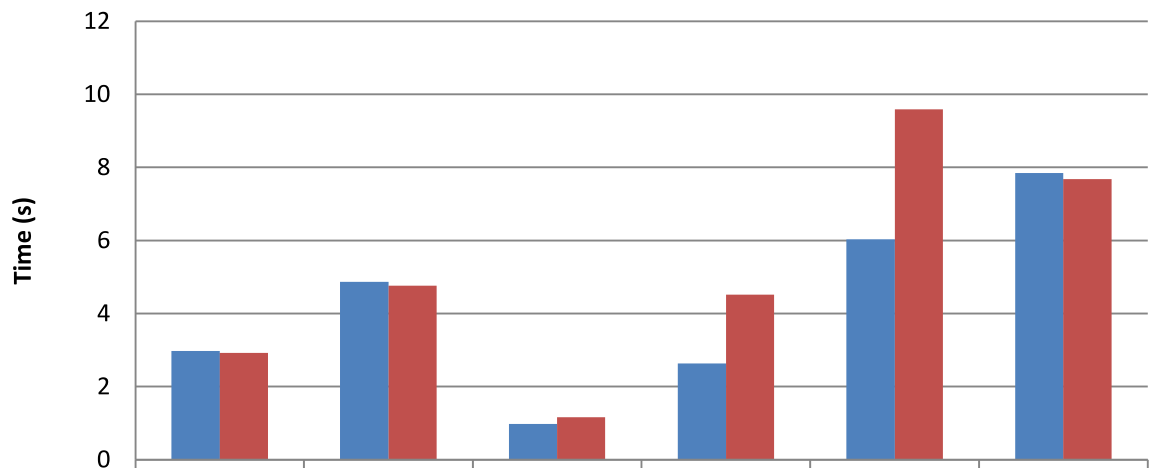
The angle at which the swimmer ascends to the surface of the water should be gradual in order to minimise the frontal resistance of the body as well as to ensure that the first stroke is propulsive (Pease and Vennell, 2010). Swimmers that utilise more of the regulation 15m distance during the underwater phase tend to have deeper starts than those who surface more quickly. Due to the number of turns in the distance events, these swimmers maintain a streamlined position that is parallel to the surface of the water as they tend to only do one or two dolphin kicks prior to the first stroke.

The final phase of the swimming turn is the *stroking phase* and is the period from the swimmer's head breaking the surface of the water until they pass the 10m distance out from the wall after the turn. As has been noted earlier, it is generally faster for swimmers to use the UUS technique than swimming along the surface of the water so ideally swimmers will have no, or little, stroking phase within their turn for optimal performance.

6.1.2 Impact of turns on race performances

Slawson et al. (2010) noted that a 1% improvement in turn times would affect the podium places in the 100m and 200m swimming events based on results from the Beijing Olympic Games. The turning performance of individual British swimmers was examined after the 2011 World Championships to determine any weaknesses. Table 56 shows the turning phases in the women's 100m freestyle and Table 57 is the men's 100m backstroke.

Table 56 Differences in turning phases between the winner and British swimmer in the women's 100m freestyle at the 2011 World Championships



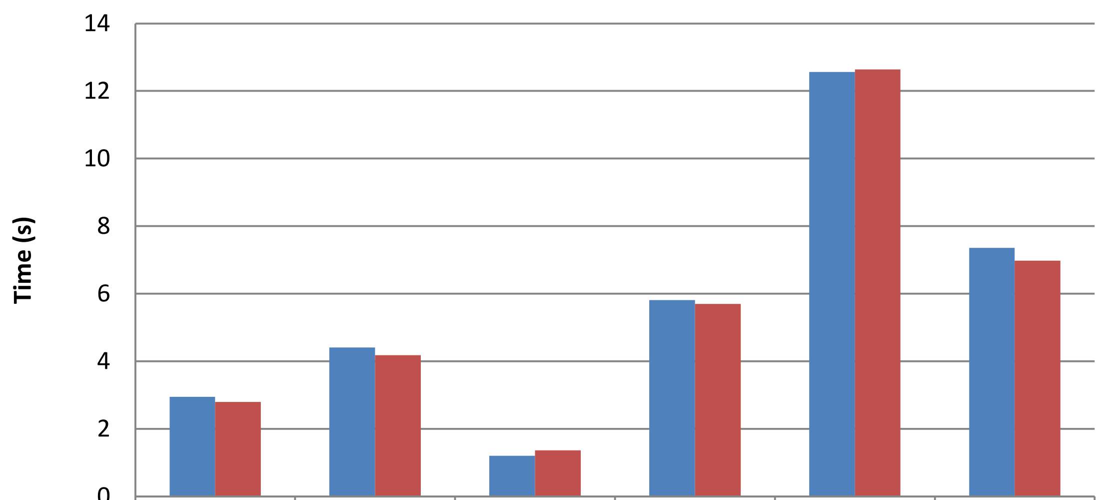
	5m In Time (s)	10m Out Time (s)	Rotation Time (s)	Breakout Time (s)	Breakout Distance (m)	Total Time (s)
British	2.97	4.87	0.98	2.63	6.03	7.84
Winner	2.92	4.76	1.16	4.52	9.59	7.68

The blue bar in the graph represents the times for the British swimmer and these are compared to the winner of the event, shown as a red bar in the graph. In the women's 100m freestyle the time taken to approach the wall from the 5m distance was similar for the two swimmers (2.97s British swimmer and 2.92s for the winner). The British swimmer had a much faster rotation time of 0.98s compared to the winner of the race who took 1.16s from the time that their last hand entered the water until their feet touched the wall. The turning phase which showed the greatest differences between the two swimmers was the underwater phase where the winner of the event spent longer (4.52s) and travelled further (9.59m) than the British swimmer (2.63s and 6.03m).

Swimmers are able to travel faster under the water than they are able to swim and the most effective turns are where swimmers are able to maximise the underwater phase (Mason and Cossor, 2001, 2000). In the women's 100m freestyle example from the 2011 World Championships, the British swimmer would benefit from further work on the underwater phase. By travelling further and for a longer period of time under the water in the turn the British swimmer would be more competitive in this event.

In contrast, the example provided in the men's 100m backstroke final (Table 57) shows that the British swimmer was similar to the winner of the event in both the underwater distance and the breakout time during the turn. The British swimmer also had a faster rotation time (1.20s) than the winner (1.36s) suggesting that the approach phase (5m distance in to the wall) and the 10m distance in the opposite direction were where the swimmer could make the greatest gains to turning performance (0.15s and 0.23s respectively).

Table 57 Differences in turning phases between the winner and British swimmer in the men's 100m backstroke at the 2011 World Championships



	5m In Time (s)	10m Out Time (s)	Rotation Time (s)	Breakout Time (s)	Breakout Distance (m)	Total Time (s)
British	2.95	4.41	1.2	5.81	12.56	7.36
Winner	2.8	4.18	1.36	5.7	12.64	6.98

During the approach phase it is important to maintain the velocity from the free swimming component of the lap into the rotation phase in order to maximise the turning performance. Some swimmers may decrease their stroke rate during the final few strokes on a lap which in turn may slow them down. In backstroke events the swimmer is able to use the flags that are positioned 5m away from the wall to adjust their stroke rate and length as they approach the turn. For all other strokes the swimmers are able to use the "T" mark located on the bottom of the pool which is always 2m from the end of the wall. The depth of the water can influence the perception of distance which can impact on turning performance, particularly if the depth of the pool is different at each end of the pool.

To date the research into swimming turns has been through the use of vision systems, bespoke analysis software, towing equipment and force platforms. The combination of kinetic and kinematic measures has enabled information to be inferred from the analysis such that turning techniques can be adjusted for improved performances.

Blanksby et al. (2004) noted that there were limitations to the measurement of forces in the water due to the inability to separate the effects of water during the turn. It is possible to subtract the static water pressure but there is a moving mass of water during the turn as the swimmer approaches the wall and then changes direction.

The majority of the platforms used have been uni-directional and are capable of measuring information on the force, impulse and centre of pressure for the body during the contact phase of the turn.

The projection of the force platform from the wall of 4.5-20cm can also affect the approach of the swimmer prior to the rotation and wall contact phases of the turn such that various pool markers that are used during competition cannot be used in testing conditions. In the research where the platform was 20cm from the wall, new markers were placed along the bottom of the pool for the swimmers to use (Pereira et al., 2006).

No research to date has been found where information on each leg has been separated during the analysis of a swimming turn. It would be possible to determine this detail through the use of a pressure sensor which was also much thinner and more portable than traditional force measuring devices. **The purpose of this phase of testing was to determine the differences between the left and right feet during the wall contact phase of swimming turns.**

6.2 Methods

6.2.1 Equipment

A pressure mat was developed at Loughborough University to monitor the foot and leg placement on the wall during a swimming turn. A high pressure sensor with flexible design (Xsensor model IX500:40:64.02) pressure mat was encased within a waterproof bag that was then painted to replicate a touchpad used during competitions.

The active area was 81cm wide by 51cm high as displayed in Figure 51. The pressure range was set as either 10-200psi or 5-100psi and there were 2,560 individual sensing elements with a resolution of 12.7mm within the pressure mat. When the pressure mat was set at 5-100psi the pressure range was 3.4-69N/cm^2 and at the 10-200psi range was 7-138N/cm^2. Capacitive pressure imaging sensors were aligned in perpendicular grids in order to detect changes to the strain when pressure was applied (Cork, 2007).

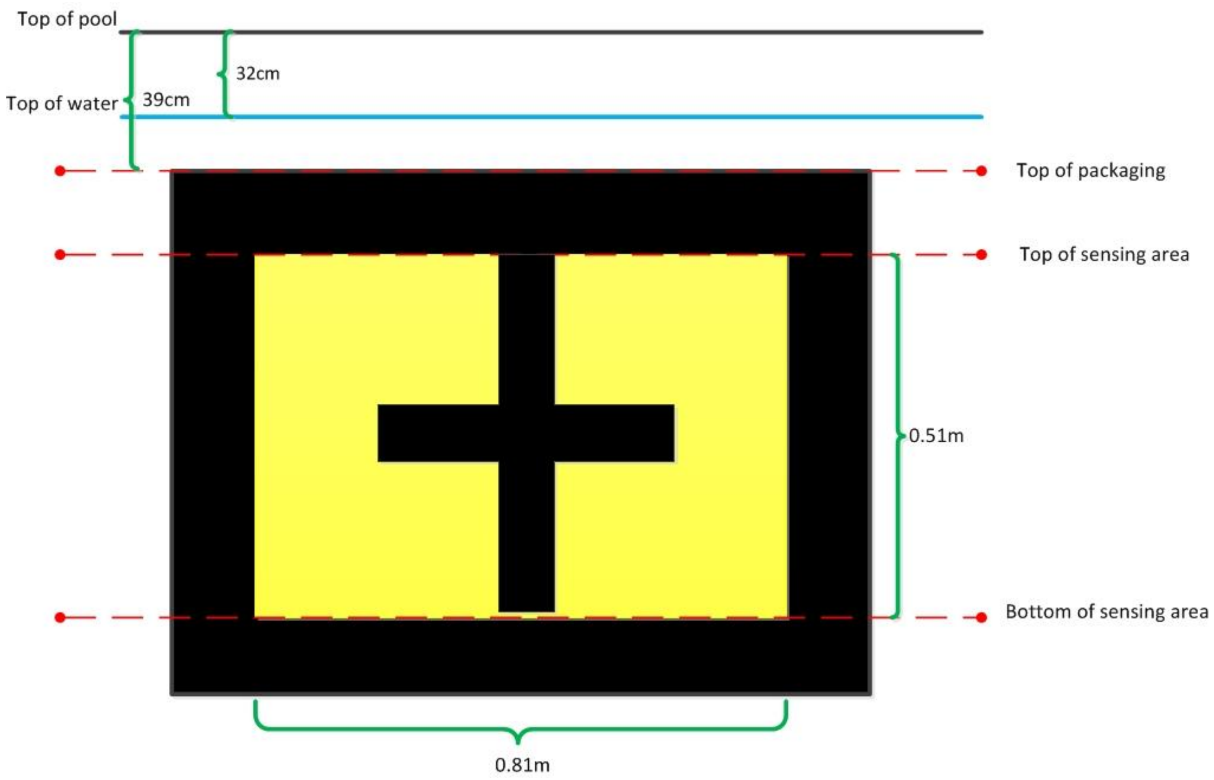


Figure 51: Original turn pressure mat dimensions and the location on the wall of the swimming pool

Pilot testing indicated that it was important for elite swimmers to spot the wall during their rotation phase of the turn even though this may increase their frontal drag. Long axis (freestyle and backstroke) turns showed little variation in the measuring area while short axis (butterfly, breaststroke and medley) turns had large vertical and horizontal displacement differences between the hands and feet contacting with the wall as well as between swimmers.

As such, a larger pressure mat with dimensions of 81cm x 81cm was used for the second phase of testing. This ensured that there was no need to adjust the height of the mat within a testing session and minimised any disruption for the swimmers and coaches. The waterproof casing and painting were similar to those used in the original design of the turn pressure mat. Mechanical Velcro was used to attach the pressure mat to a polycarbonate backing for rigidity. Two pieces of stainless steel were used to attach the polycarbonate to the end of the swimming pool using the standard holes used for attaching touchpads during competitions. In all testing the capture rate of data was set to 25Hz which matched the sampling frequency of the cameras that were used as part of the testing set up.

The design of the pressure mat allowed for attachment at various pools with different lane widths as well as vertical displacement changes to allow for different types of turns. It was possible for one person to carry the equipment used for the turn pressure mat and fitted easily within a car so it was possible to transport between different pools for testing. The software used for the analysis of the turns continues to be developed within the University but used Matlab code and some manual digitisation throughout this research.

6.2.2 Testing set-up

As with the starts, a multi-component approach was used for the analysis of turns that included the pressure mat and vision systems. The two underwater cameras monitored the "in" and "out" phases of the turn while the above water camera viewed the rotation phase of the turn and these were located 2m and 5m from the end wall of the pool. The SwimTrack© software enabled the turn to be divided into the various phases noted earlier (Figure 8).

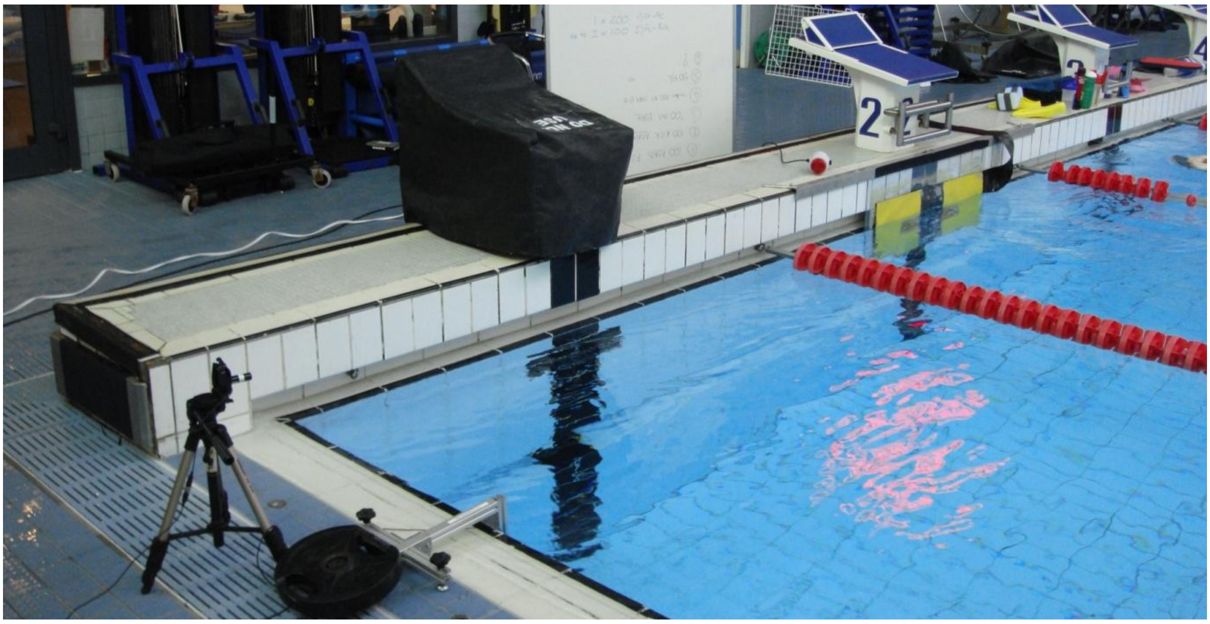


Figure 52: Turn testing set up including the vision system

Staff involved in the testing sessions had specific roles relating to their component within the system so it was necessary to have one person instructing and timing the swimmers, one to operate and record the vision system, one to record data on the pressure sensor and a final person working with the WSN.

Cameras were set up in similar positions to the start testing such that one camera observed the action above the wall during the rotation phase while two cameras monitored the turning performance below the surface of the water. The three analogue cameras (Sony HQ2) were connected to Canopus AD55 boxes to convert the images to a digital signal that were directly input into the laptop that was located on poolside. These images were captured and displayed in the SwimTrack© software with an example shown in Figure 53.

Figure 53: SwimTrack© software located on poolside for use during turn testing

The pressure mat was attached to the end wall of the pool with a cable running from the pressure mat to a laptop to capture information on each turn (Figure 54). As the swimmer passed the 5m distance when approaching the wall a light was triggered and was visible in the above water video.

Figure 54: Pressure mat capture station for turn testing

In a similar format to the start testing, a wireless sensor node (WSN) was placed on the lower back of the swimmers during some of the trials. Data was transmitted in real time to a laptop located on the poolside for the parts of the turn where the WSN was located less than 15cm below the surface of the water. During the underwater phase of the turn the data was stored on the WSN and was then wirelessly transmitted to the laptop at the end of the trial. The real time display of the acceleration data on a laptop along with the receiver box is shown in Figure 55.

Figure 55: Wireless sensor node (WSN) capture during turn testing

6.2.3 Testing protocols

Swimmers during each of the turn testing sessions conducted their own warm up both on land and in the water before any trials were recorded. They were asked to perform a minimum of three trials at maximum effort where the time was recorded as their head passed the 5m mark approaching the end wall until the head passed the 10m distance when travelling in the opposite direction after the turn. These times were measured by the same practitioner for consistency with feedback provided after the testing session rather than after each trial so that there was no influence on the peformances.

6.2.4 Measurements

Information derived from the pressure sensors included wall contact time, vertical displacement of the hands and/or feet, horizontal displacement between the two hands and/or feet, angle between the hands and/or feet, and force derived from information on the pressure and area of contact.

These details were determined automatically but there were some concerns that the software was not measuring the correct blobs on the pressure mat due to the attachment of the mat to the end wall. Complete details on the methods and calculations used for the automatic processing are reported elsewhere (Chakravorti et al., 2012a). In all instances it was the centre of the blob that was used for the calculations. When analysing the foot contact it was the balls of the feet rather than the full foot used within the calculations as the heels were generally not in contact with the wall.

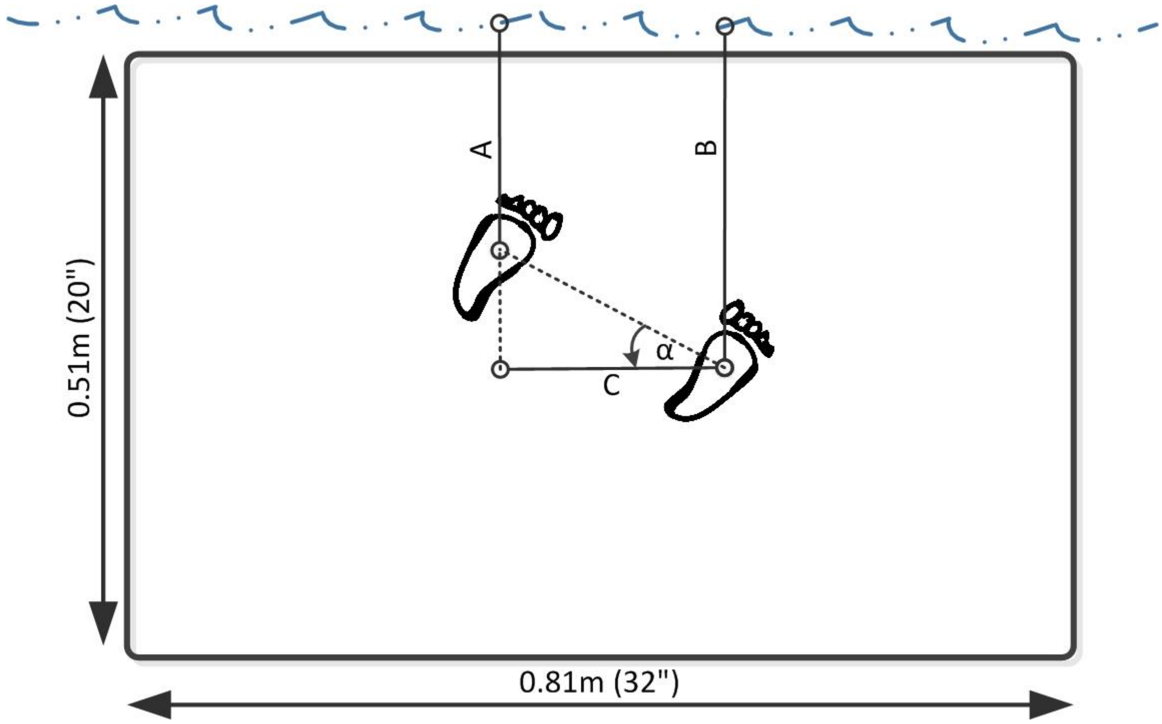


Figure 56: Measurements calculated from the original turn pressure mat

A schematic of the feet contacting the pressure mat during the turn is represented in Figure 56 with spacing between the feet and orientation calculated automatically. Line A in is the distance from the surface of the water to the centre of the left foot while line B is the vertical distance measured for the right foot from the surface of the water. Line C is the horizontal distance between the centre of the left and right foot while α is the angle between the two feet (approximately 45° in this example). The foot orientation will determine the rotation that is required along the body during the push-off component in the underwater phase of the turn. It is felt that a larger rotation will result in greater resistance by the body moving through the water and will minimise the benefits of the drive phase from the wall during the turn but is not measured in the current research.

The second version of turn analysis software was able to measure the same details that were noted above after the user has clicked on the centre of each blob and took less than one minute to analyse each turn. Currently only the information on the legs is used as part of the analysis of the short axis turns but future work will analyse the position and contact time of both the hands and feet and the time between these points (rotation time).

Vision systems were again used to analyse performance with the hip digitised for each frame from the period before the swimmer's head reached the 5m distance during the approach to the end wall through to the point when the hip was no longer visible after the turn. Data exported from the SwimTrack© analysis included information on times for each of the phases with the 5m distance from the wall during the approach phase used as the starting reference. The rotation time, wall contact time, maximum depth during the underwater phase, as well as the velocity and position of the hip at the commencement of the first kicking action have been used as part of the feedback to the swimmers and coaches.

6.3 Results of investigations

6.3.1 Turn study 1

Early trials for turn analysis utilising the pressure mat and vision systems provided information on the velocity of the hip at the time of the first kick, maximum depth, wall contact time, rotation time, peak pressure and peak force measured in body weights (BW). This was conducted on three swimmers over a number of testing sessions such that turn profiles could be developed as well as the reliability of the pressure mat. Information from these tests is presented in Table 58 for the three swimmers who competed in freestyle (swimmer 1), backstroke (swimmer 2), and individual medley (swimmer 3).

Data for the freestyle swimmer showed large variations in the peak pressure values on the final testing session (33.38-54.21psi) as well as the peak force (0.88-1.43BW). During the second testing session the peak pressure was the same for the second and third trial but there was a variation of 0.15BW as a result of the number of cells used within the calculations (i.e. a larger portion of the ball of the foot was used). There were also variations observed with the backstroke swimmer within each testing session and between testing sessions.

Comparisons for the medley swimmer were more complicated due to the number of different turns to be tested but it appeared that there were higher peak pressure values during the second testing session. The peak force was higher for the butterfly to backstroke, butterfly, backstroke and breaststroke turns during the second session indicating that there may have been a practice effect involved in the testing results.

The benefits of using a pressure mat compared with the more traditional force platform when monitoring the turn performance of swimmers are highlighted during the wall contact phase. Information can be separated into left and right feet and the position between the feet can also be determined when using a pressure mat. This is not possible when using the more traditional method of a force platform attached to the end wall of the pool where the time and force data is for the entire body. By separating the information to left and right feet it is feasible to determine the importance of the positioning of the feet on the wall in relation to the overall turn performance.

Within the Xsensor software it was possible to determine the size and position of each blob for calculations to be made. The number of cells, average pressure value (in pounds per square inch - psi), peak pressure (psi), area (inches²), vertical and horizontal positions for each blob were measured for each frame that the feet were in contact with the wall.

Figure 57 is an output from the Xsensor software representing of the foot height and foot width measures during the wall contact phase of a turn using a pressure mat. The cells within the pressure mat were calculated from the top right corner as indicated by the red dot on the image.

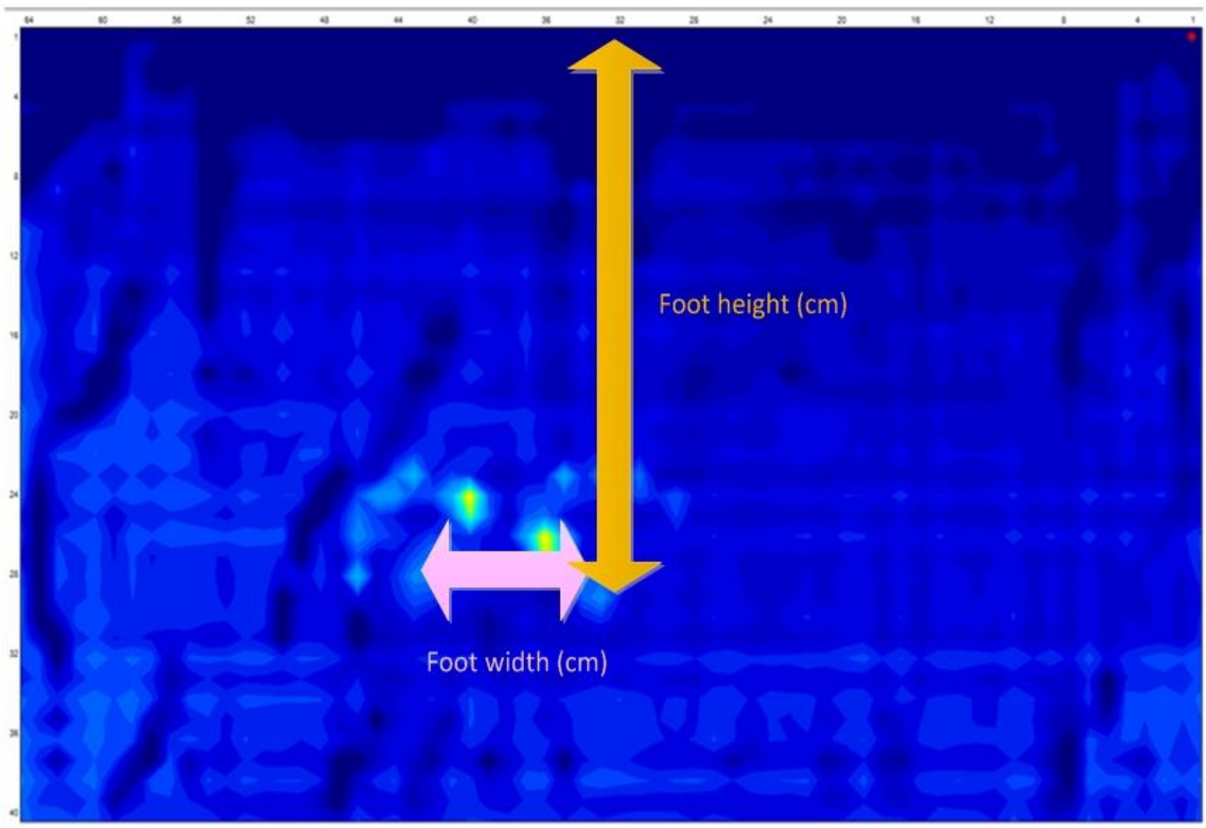


Figure 57: Foot placement on the pressure mat during the wall contact phase of the turn

The output of the original software used to analyse the data from the pressure mat is portrayed in Figure 58 with each foot represented by a red blob. The image shown is looking towards the end wall of the pool so that the blob on the left is the left foot and the blob to the right of the image is the right foot. In this example the centre of the left ball of the foot was 35.3cm below the surface of the water while the centre of the right ball of the foot was 30.5cm deep. The distance between the two feet was 17.6cm and the orientation between the centres of the two feet was 15.5°.

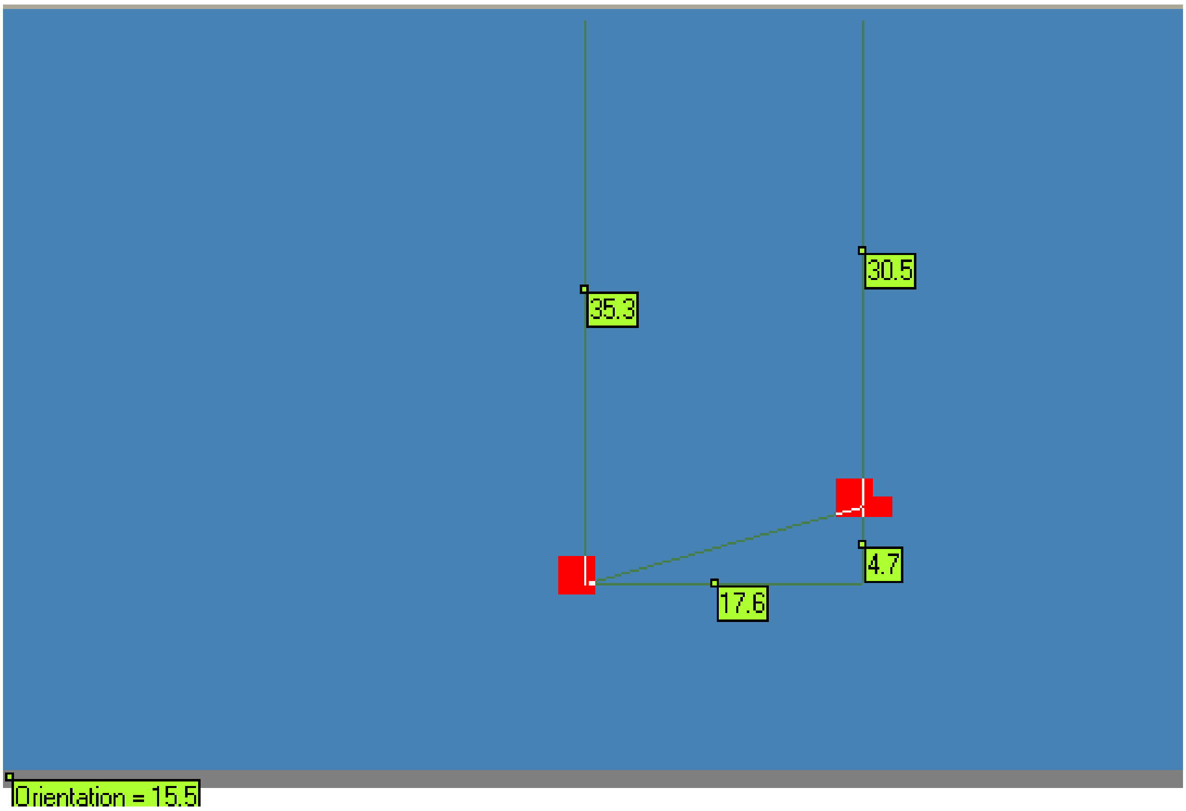


Figure 58: Automated output from the turn pressure sensor displaying feet position and orientation information

The image presented in Figure 58 shows that the swimmer has commenced the rotation around the sagittal plane prior to contacting the wall due to the 15.5° orientation angle between the left and right feet.

Similarities between the automated and manual versions of the feet contacting the wall during the turn can be observed in Figures 57 and 58.

Table 58 Analysis of the turn using vision and pressure systems

	Date	Stroke	1st kick velocity (m/s)	Max depth (m)	Wall contact time (s)	Rotation time (s)	Peak pressure (psi)	Force per BW
Swimmer 1	22.11.11 AM	Free	2.03	0.82	0.32	1.28		
	22.11.11 PM	Free	2.05	0.77	0.35	1.71		
	24.11.11 PM	Free	1.85	0.82	0.20	1.12	46.01	1.41
		Free	2.03	0.80	0.24	1.36	24.35	1.38
		Free	1.93	0.82	0.32	1.16	24.35	1.23
	29.11.11 AM	Free			0.30		33.38	1.28
		Free	1.25	0.67	0.28	1.36	54.21	1.43
		Free	1.76	0.80	0.32	1.16	43.97	0.88
Swimmer 2	22.11.11 AM	Back	1.52	1.23	0.27	1.33		
	24.11.11 PM	Back	1.56	1.75	0.28	1.36	18.99	1.62
		Back		1.51	0.28	1.28	23.33	1.72
		Back	1.40	0.26	0.32	1.52	19.02	1.72
	29.11.11 AM	Back	1.49	1.04	0.36	1.28	11.51	1.50
		Back	1.25	1.23	0.28	1.44	26.58	1.84
		Back	1.19	1.02	0.28	1.36	20.69	1.94

	Date	Stroke	1st kick velocity (m/s)	Max depth (m)	Wall contact time (s)	Rotation time (s)	Peak pressure (psi)	Force per BW
Swimmer 3	22.11.11 AM	Fly/Back	1.83	1.08	0.47	0.98		
		Back/Breast	2.04	0.88	0.27	0.84		
		Breast/Free	1.99	0.89	0.42	1.11		
	24.11.11 PM	Fly/Back	1.74	1.04	0.36	1.00	29.36	0.91
		Back/Breast	1.66	0.87	0.36	0.84	31.19	1.27
		Breast/Free	2.30	0.86	0.40	1.00	28.98	0.66
		Fly	2.64	0.88	0.36	0.92	38.21	1.03
		Back	1.20	1.28	0.36	1.36	29.90	1.06
		Breast	2.05	0.84	0.36	1.00	33.50	0.85
		Free	2.03	1.02	0.40	1.40	18.38	1.70
	29.11.11 AM	Fly/Back	1.36	1.15	0.40	0.92	50.37	1.13
		Back/Breast	2.32	0.77	0.36	0.84	55.13	1.15
		Breast/Free	1.67	0.80	0.44	1.00	31.16	0.63
		Fly	2.14	0.77	0.40	0.92	66.60	0.86
		Back	1.78	1.25	0.32	1.28	42.60	1.28
		Breast	1.86	0.82	0.40	0.96	45.91	1.14
		Free	1.28	0.81	0.40	1.28	24.34	1.64

It has been proposed by elite coaches that rotation times (from the last hand entry until the feet contact the wall) should be less than 1s and that the most effective turns have wall contact times of less than 0.30s (personal discussions). From the data presented in Table 58 it was possible to see the differences in technique of swimmer 1 between the morning session where just the turn was monitored and the afternoon session where the 400m swimming repeat was recorded. The rotation time varied between 1.28s and 1.71s although the first kick velocity, maximum depth and wall contact times were similar between the two testing sessions. In order to calculate the force in body weights the pressure value was converted to Pascals (Pa) where 1 Pa = 1.450377×10^{-4} and the area was converted from inches² to metres² where 1 inch = 0.0254m. These values were then used to calculate the force in Newtons where Force = Pressure x Area. The body mass of each athlete was then converted from kilograms to Newtons with the value divided by the force value to determine the force per body weight for each swimmer.

It was felt that three trials for each swimmer would be appropriate to determine the trend for the turning performance when using a pressure mat. However as the sensing area was quite specific there were some instances where both feet did not contact the correct area on the pressure mat. In hindsight it may have been more appropriate to have the swimmers perform 7-10 trials of each turn for validation of the data.

6.3.2 Pressure mat analysis validation

The variation of the data from the automated pressure mat analysis software suggested that the data should be validated with manual analysis. Data for one swimmer was analysed on 10 consecutive days with the descriptive statistics presented in Table 59 including the cell count, average pressure (psi), peak pressure (psi), area, and position of the feet.

The two variables with the largest variations were the cell counts for both feet. The left foot varied from 41-51 with a mean of 45.50 and standard deviation of 3.87 cells. The range was between 32 and 40 on the right foot with a mean of 35.20 ± 2.30 cells. Normalised curves for the area of the left and right feet are displayed in Figures 59 and 60.

Table 59 Descriptive statistics for the analysis of one turn over 10 days

	N	Minimum	Maximum	Mean	Std. Deviation
Left foot cell count	10	41	51	45.50	3.87
Right foot cell count	10	32	40	35.20	2.30
Left foot average pressure (psi)	10	34.03	36.63	35.26	0.87
Right foot average pressure (psi)	10	33.65	38.50	36.71	1.43
Left foot peak pressure (psi)	10	72.73	72.73	72.73	0.00
Right foot peak pressure (psi)	10	94.47	94.47	94.47	0.00
Left foot area (cm^2)	10	10.25	12.75	11.38	0.97
Right foot area (cm^2)	10	8.00	10.00	8.80	0.57
Left foot horizontal position (cell location)	10	36	36	36.00	0.00
Left foot vertical position (cell location)	10	14	14	14.00	0.00
Right foot horizontal position (cell location)	10	23	23	23.00	0.00
Right foot vertical position (cell location)	10	21	21	21.00	0.00

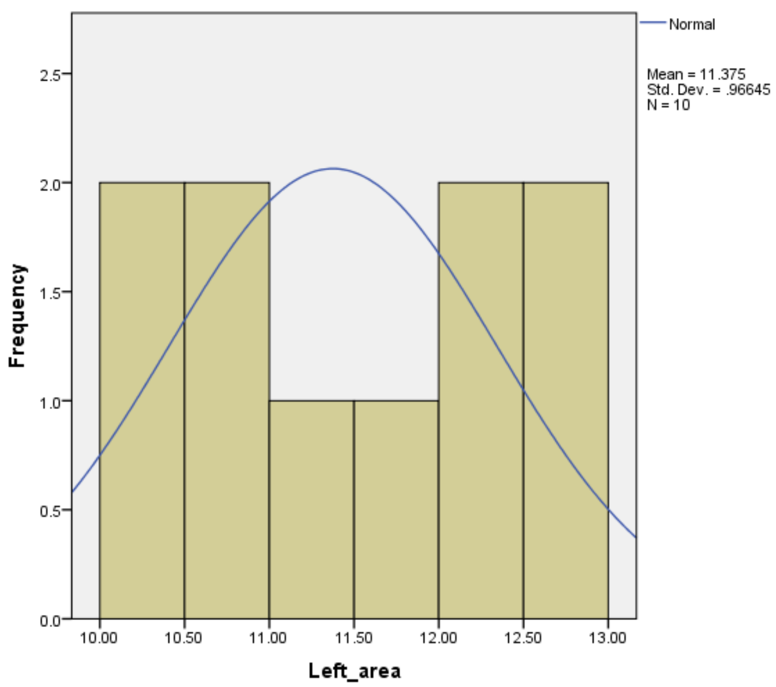


Figure 59: Normalised curve for the left foot using manual digitisation

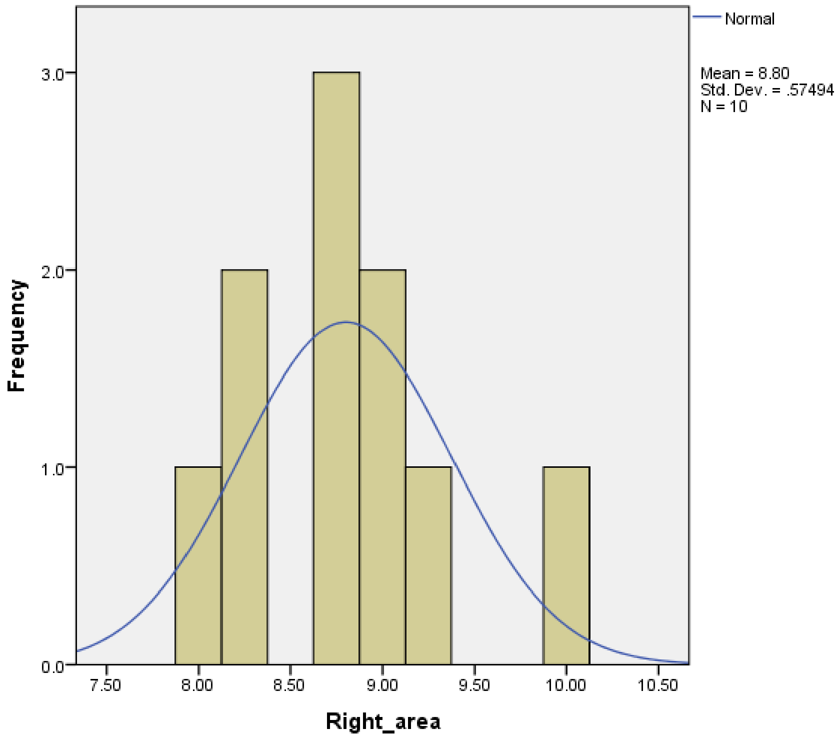


Figure 60: Normalised curve for the right foot area in cm² using manual digitisation

6.3.3 Pressure mat and force validation

With the differences in peak pressure and force values generated during the initial turn testing it was felt that validation on the pressure mat was required to determine the level of accuracy when extrapolating the force data from the pressure sensors. The pressure mat was laid flat over a calibrated Kistler force platform and a known mass of 15cm diameter disc was attached to the bottom of a robot leg (Figure 61). Forces generated by the robot were within a range of 200-1500N and five trials in each of five differing contact times (0.20-0.60s) were used for the exploration. The force platform captured data at 150Hz and the pressure pad sampled at 25Hz.

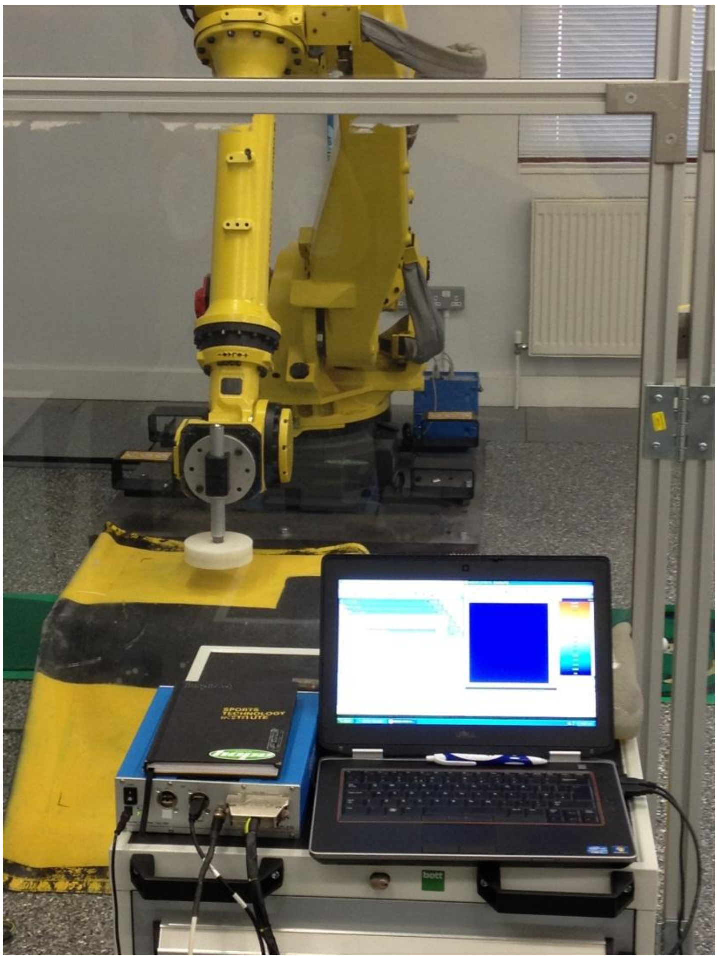


Figure 61: Pressure mat validation using a robotic arm and force platform

It was noted that there were differences in calculated variables between the pressure mat and the force platform so the current feedback to swimmers and coaches only provides information on the position and pressure of the feet rather than an extrapolation of force. The errors were related more with the force rather than contact time and area values as shown in Figures 62-64. A proposed explanation for these differences is that the size of the measuring area in the testing conditions was much larger than those used by a swimmer during a turn, so future tests will replicate the experiment with a smaller known weight.

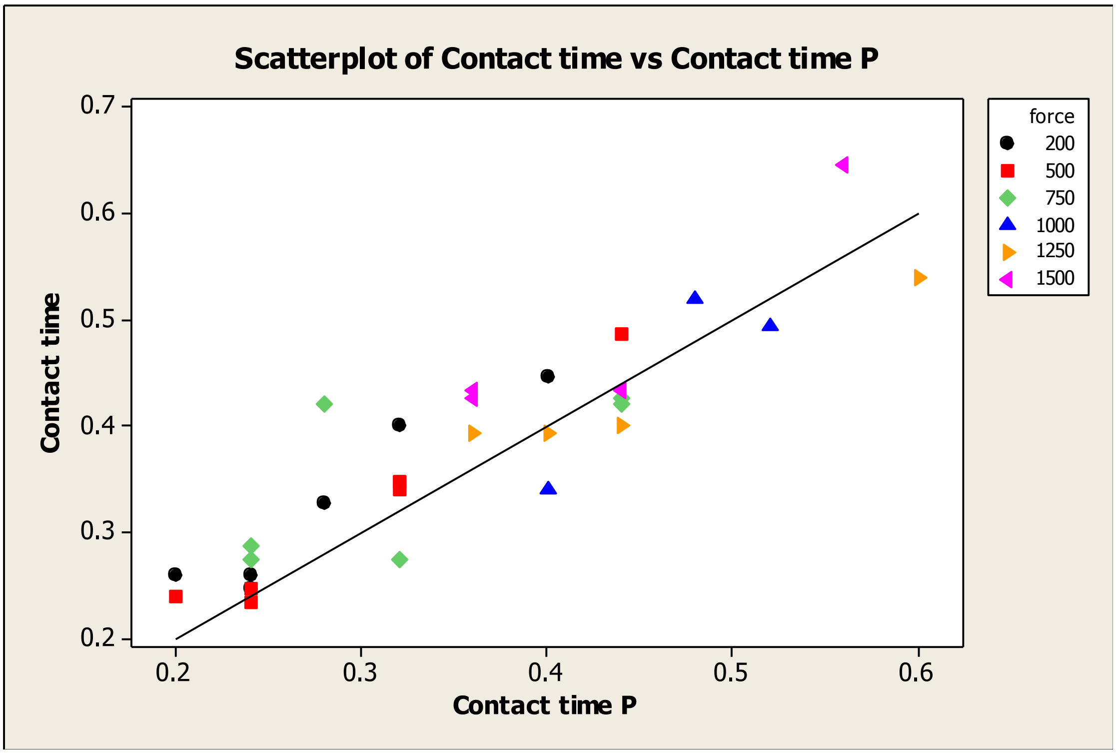


Figure 62: Comparison of contact times in seconds calculated on the pressure mat (horizontal axis) and force platform (vertical axis)

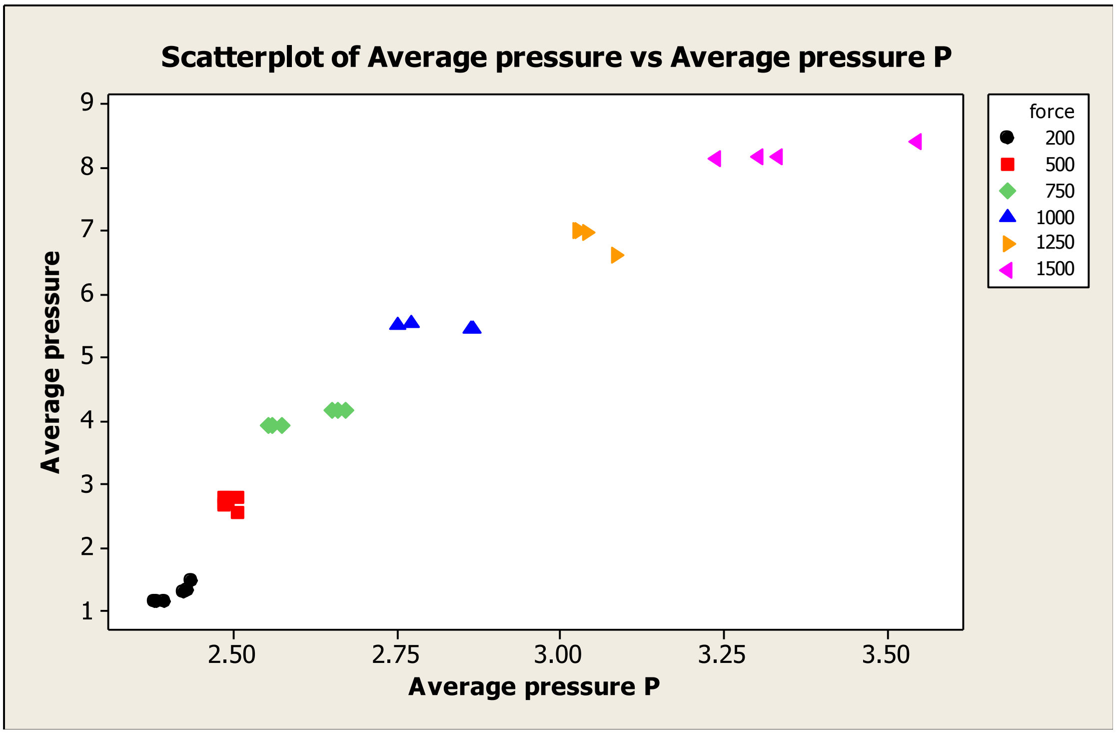


Figure 63: Comparison of the pressure values in Pascals calculated on the pressure mat (horizontal axis) and force platform (vertical axis)

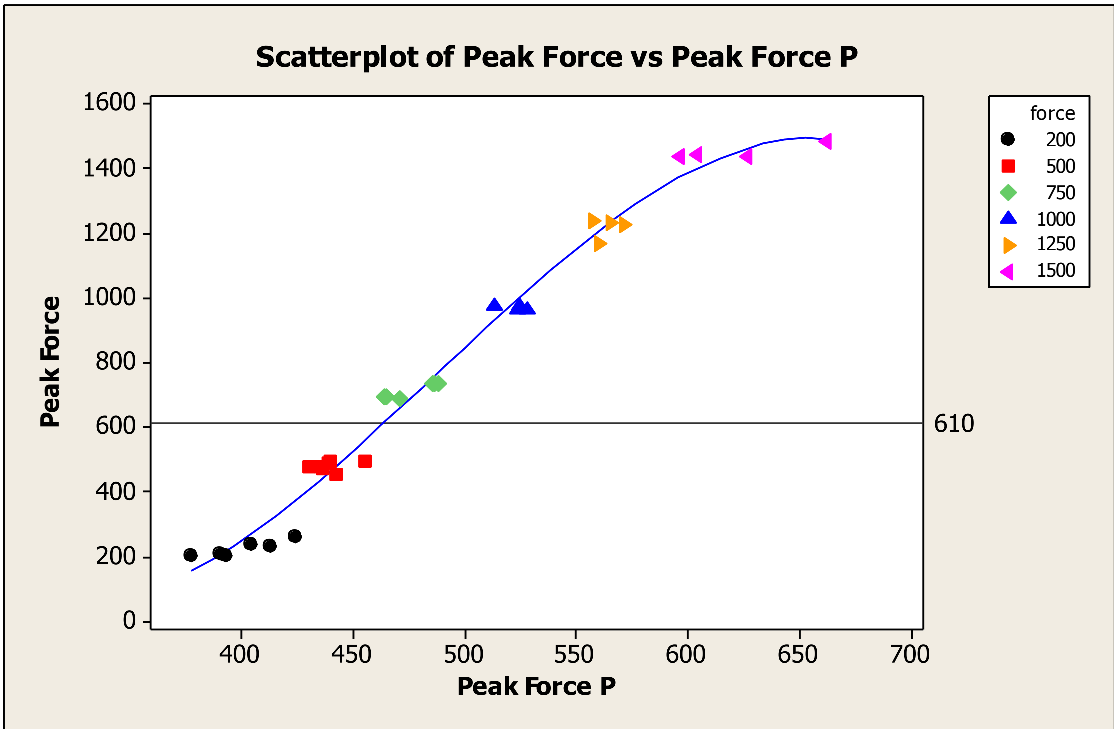


Figure 64: Comparison of peak force values in Newtons calculated using the pressure mat (horizontal axis) and force platform (vertical axis)

6.3.4 Turn study 2

After the pilot work using the turn pressure mat, a period of three months was spent constructing the newer model that was large enough to ensure that there was no need for adjustments to the vertical position of the mat within a testing session. Data was then collected on elite level swimmers in a camp situation using the original analysis software. The use of the new mat ensured that more turns were valid during the data capture process and information was fed back to the coaches and swimmers and coaches.

Written feedback provided information from both the pressure mat and vision systems analysis for a more complete understanding of the turn. Data within the report included details of the stroke as well as time, distance and velocity information for key variables. These variables were: hands on the wall, feet on the wall, feet off the wall, timing of the first kick, total turn time (5m in and 10m out) as well as the maximum depth of the hip during the turn.

Specific data on the wall contact phase of the turn included information on the: peak pressure, peak force normalised for body weight, and position of the feet on the wall. The depth of the left and right feet from the surface of the water was reported as well as the distance between them and their orientation to each other. Comparisons were made between all of the trials for each individual swimmer and suggestions made for improvements to the turning technique.

An example of the quantitative feedback provided to the swimmers and coaches is seen in Table 60 where information is divided into the vision system data and then the data collected from the pressure mat. When examining the results there was a great deal of variability between each of the three trials for the approach to the wall. This varied between 2.76 and 3.04s and was not expected for this elite level swimmer. One explanation for the large values may have been due to poor skills at spotting the wall[27] during this turn phase.

The wall contact time ranged from 0.32 and 0.44s during this testing session. Results also showed that the only trial in which the correct velocity for the first kick was achieved on the third trial where they were 2.96m from the wall with a velocity of 1.92m/s.

Peak pressure varied between 23.46 and 37.32psi while the distance between the balls of the feet ranged from 2.35 to 4.70cm. The depth of the left foot was between 15.25 and 25.00cm below the surface of the water while the right foot depth ranged between 26.47 and 28.66cm. The orientation of the feet was 14.54° on the first trial, 27.41° on the second trial and 57.27° on the final trial of the testing session. Part of the success of breaststroke and butterfly turns during competition is the ability of the swimmer to ensure consistent timing of their hands when touching the wall. On some occasions there may be a glide until the wall contact and in other instances swimmers may be too close to the wall resulting in bent arms at wall contact.

As force is a product of pressure and area it was interesting to note that the trial with the lowest peak pressure value resulted in the largest peak force when normalised for body weight. This was due to the fact that the measurement area of the feet was larger on the third trial when compared to the first two turns as a result of the sensor size. The feet appeared to have square edges due to the size of the sensors so it may be more accurate to have more sensors on the mat resulting in smaller areas for each cell.

[27] Swimmers must judge the exact distance of the wall as they make their final approach to ensure that there is no glide. This is referred to as spotting the wall.

Table 60 Example of quantitative feedback on butterfly turns by a female swimmer

		Trial 1			Trial 2			Trial 3		
	Variable	Time (s)	Distance (m)	Velocity (m/s)	Time (s)	Distance (m)	Velocity (m/s)	Time (s)	Distance (m)	Velocity (m/s)
Vision systems	Stroke	Fly			Fly			Fly		
	Hands on wall	3.04	1.14	1.36	2.76	1.18	1.55	2.92	1.20	1.26
	Feet on wall	3.88	0.70	0.30	3.60	0.62	0.17	3.80	0.69	0.13
	Feet off wall	4.28	1.23	2.68	4.04	1.21	2.81	4.12	1.14	2.55
	1st kick	5.20	3.22	1.74	4.92	3.19	1.83	4.92	2.96	1.92
	Total turn time	9.10			8.69			8.61		
	Maximum depth		1.11			1.09			1.08	
Pressure mat	Peak pressure (psi)	33.50			37.32			23.46		
	Body mass (kg)	61.70			61.70			61.70		
	Peak force (normalised BW)	1.11			1.04			1.65		
	Left foot depth (cm)	15.25			22.56			25.00		
	Right foot depth (cm)	16.47			25.00			28.66		
	Horizontal distance between feet	4.70			4.70			2.35		
	Orientation between feet	14.54			27.41			57.27		

Figure 65 shows the position of the hip during the approach, rotation and push off phases of the turn for the butterfly swimmer over a number of trials. Observation of the final 2m during the approach into the turn shows various patterns of the hip suggesting that the timing onto the wall during the final stroke was not consistent for all trials. Once the swimmer came into contact with the wall then the rotation and the path of the hip leaving the wall was similar for all trials.

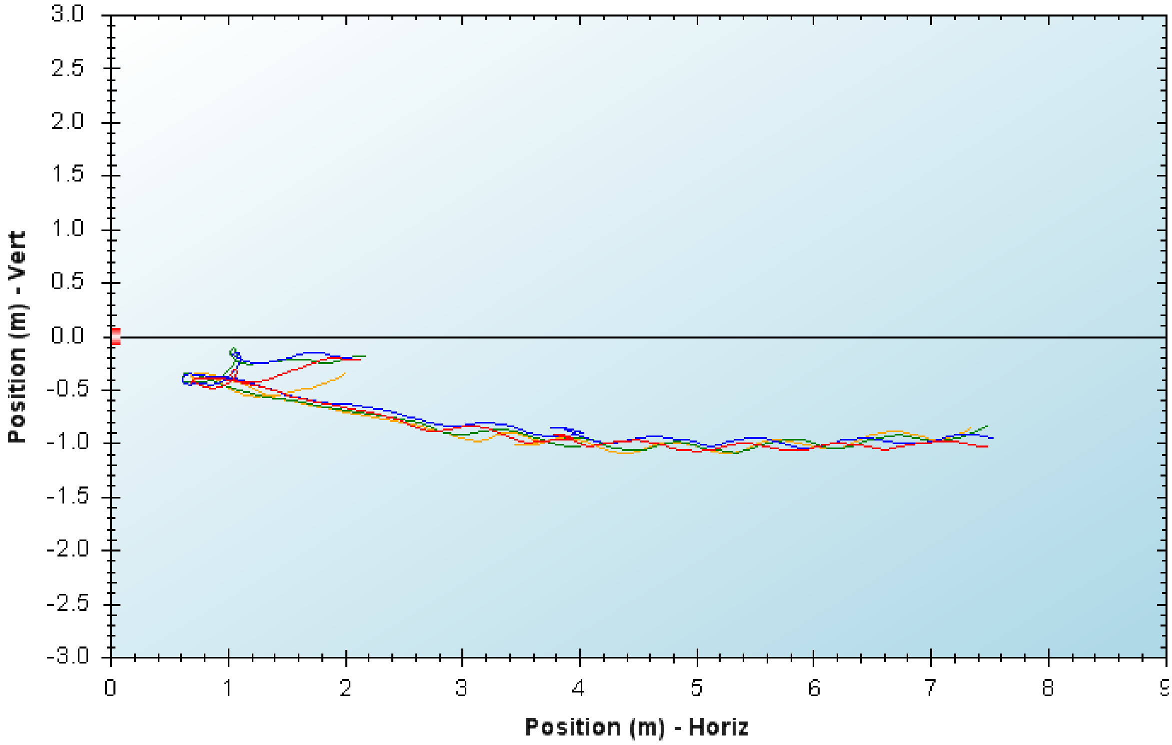


Figure 65: Position of the hip for each of the butterfly turns analysed on one swimmer

A comparison of the data was then made with a different elite female butterfly swimmer that showed more consistent results between the three trials (Table 61). The time from the 5m into the wall during the approach phase varies by 0.04s (2.80-2.84) in all three trials and the same difference is noted for the time for the feet to contact the wall. The rotation times were 0.84 and 0.88s for all trials while the time that the feet remained in contact with the wall was 0.40s in all instances.

The swimmer commenced their first underwater kicking action between 2.77 and 2.90m from the wall after the turn where the velocities ranged between 1.31 and 1.74m/s, suggesting that this kick should start sooner in order to maximise the benefits of the push off from the wall. Surprisingly the total turn time ranged from 8.65 to 8.91s for the period between the 5m in and 10m out from the wall after the turn. Between all three trials there was a 7cm difference in the maximum depth of the hip from the surface of the water.

Table 61 Quantitative feedback for a second female elite butterfly swimmer on three turns

		Trial 1			Trial 2			Trial 3		
	Variable	Time (s)	Distance (m)	Velocity (m/s)	Time (s)	Distance (m)	Velocity (m/s)	Time (s)	Distance (m)	Velocity (m/s)
Vision systems	Stroke	Fly			Fly			Fly		
	Hands on wall	2.84	1.27	1.26	2.80	1.31	1.26	2.80	1.31	1.12
	Feet on wall	3.68	0.84	0.57	3.68	0.82	0.43	3.64	0.83	0.57
	Feet off wall	4.08	1.38	2.76	4.08	1.26	2.91	4.04	1.40	2.48
	1st kick	4.76	2.90	1.33	4.76	2.87	1.31	4.64	2.77	1.74
	Total turn time	8.81			8.91			8.65		
	Maximum depth		0.83			0.90			0.85	
Pressure mat	Peak pressure (psi)	24.40			29.28			16.38		
	Body mass (kg)	59.35			59.35			59.35		
	Peak force (normalised BW)	1.51			1.47			1.19		
	Left foot depth (cm)	22.56			25.00			25.00		
	Right foot depth (cm)	26.22			28.66			28.66		
	Horizontal distance between feet	2.35			3.53			2.35		
	Orientation between feet	57.27			46.05			57.27		

As with the first swimmer there were variations in the peak pressure values recorded although the first two trials showed similar results for both pressure and force when normalised for body weight. During the third trial the peak pressure and force values were lower than the first two trials although the foot position was similar for the three trials.

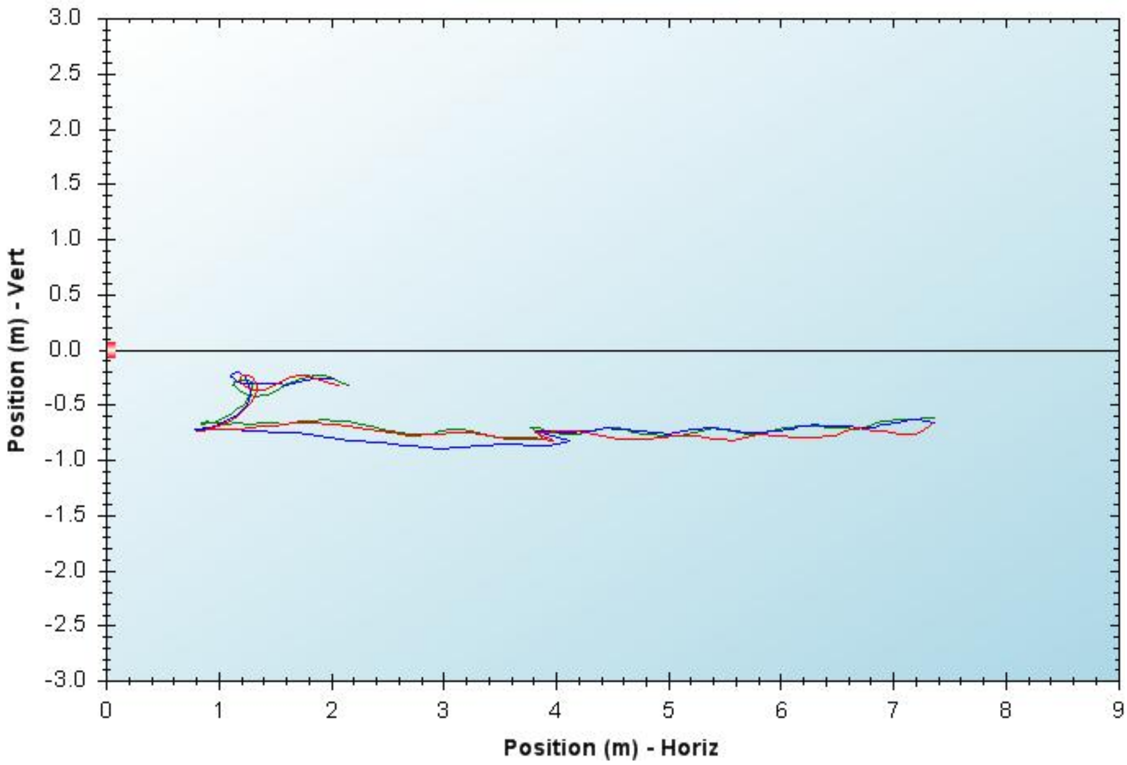


Figure 66: Position of the hip during three butterfly turns by a second elite female swimmer

In contrast to the first swimmer, Figure 66 shows similar trends during the final 2m in to the wall by the second female swimmer. The differences in the graph are seen in the initial drive phase when leaving the wall where the hip marker is deeper during the trial shown by the blue line.

Results from this section of the research highlight the individual differences between swimmers when examining the turn performance using a pressure mat and vision systems.

6.3.5 Turn study 3

After the testing protocol had been refined and the size of the pressure mat developed to be suitable for all turs, testing a larger subject population was required to determine trends of the foot placement during the wall contact phase of the turn. A group of 33 university level swimmers were asked to perform three maximal freestyle turns so that they were travelling at competition speed when their head reached the 5m distance on the way in to the turn and were travelling at race speed when their head passed the 10m distance out from the turn.

Anthropometric data for the group as well as the 5m RTT are displayed in Table 62. Mean data and standard deviations are presented for the entire group as well as separated by gender. The females were shorter (172.77 ± 4.87cm) than the males (185.94 ± 6.41cm) and had smaller trochanter heights (90.47 ± 2.50cm compared to 94.70 ± 4.25cm).

Table 62 Anthropometric and 5m RTT statistics for the swimmers used in turn study 3

	Trials (N)	Standing height (cm)	Trochanter height (cm)	Tuck index	Mass (kg)	5m RTT (s)
Group	99	181.42 ± 8.62	93.24 ± 4.24	0.94 ± 0.11	76.70 ± 8.56	4.91 ± 0.41
Females	34	172.77 ± 4.87	90.47 ± 2.50	1.01 ± 0.11	68.17 ± 4.60	5.39 ± 0.23
Males	65	185.94 ± 6.41	94.70 ± 4.25	0.90 ± 0.09	81.16 ± 6.51	4.66 ± 0.22

The tuck index for the females was 1.01 ± 0.11 compared to 0.90 ± 0.09 for the males showing that they contacted the wall with straighter legs than the males did. The females were lighter (68.17 ± 4.60kg) than the males (81.16 ± 6.51kg) and had slower turn times when measured from 5m in to the wall and back to the same distance (5.39 ± 0.23s females and 4.66 ± 0.22s males).

When Pearson Product Moment correlations were performed on the freestyle turn data using the SwimTrack© software there were a number of significant results (at the $p \leq 0.01$ level) found with the 5m RTT criterion measure as presented in Table 63. These included negative correlations with the hip velocity at the last hand entry, head down, feet on wall, feet off wall and the timing of the first kick.

Swimmers who had higher velocities at these times had faster turn times from 5m in to the wall and back to the same distance. There was also a significant positive correlation with the rotation time and 5m RTT indicating that those swimmers who spent less time from the last hand entry until their feet contacted the wall had a faster 5m RTT. The only variable that did not have a significant relationship with the 5m RTT was the maximum depth of the hip during the turn suggesting that there is no benefit from travelling closer to the surface of the water or the bottom of the pool after the wall contact phase in this case. It would make more sense to swim closer to the surface of the water to limit the distance travelled in the underwater phase of the turn.

Table 63 Correlations between the 5m RTT and velocities of the hip at different stages of the turn

		Last Hand	Head Down	Feet On Wall	Feet Off Wall	1st Kick	Max depth	Rotation time	5m RTT
Last Hand	Pearson Correlation	1	.313**	.156	.425**	.258**	.082	-.380**	-.557**
	Sig. (2-tailed)		.002	.124	.000	.010	.417	.000	.000
Head Down	Pearson Correlation	.313**	1	.241*	.228*	.209*	.068	-.374**	-.472**
	Sig. (2-tailed)	.002		.016	.023	.038	.504	.000	.000
Feet On Wall	Pearson Correlation	.156	.241*	1	.000	-.016	-.019	-.058	-.261**
	Sig. (2-tailed)	.124	.016		.997	.872	.848	.568	.009
Feet Off wall	Pearson Correlation	.425**	.228*	.000	1	.157	.159	-.115	-.532**
	Sig. (2-tailed)	.000	.023	.997		.120	.117	.256	.000
1st Kick	Pearson Correlation	.258**	.209*	-.016	.157	1	-.069	-.241*	-.226*
	Sig. (2-tailed)	.010	.038	.872	.120		.499	.016	.024
Max depth	Pearson Correlation	.082	.068	-.019	.159	-.069	1	-.196	-.137
	Sig. (2-tailed)	.417	.504	.848	.117	.499		.051	.178
Rotation time	Pearson Correlation	-.380**	-.374**	-.058	-.115	-.241*	-.196	1	.312**
	Sig. (2-tailed)	.000	.000	.568	.256	.016	.051		.002
5m RTT	Pearson Correlation	-.557**	-.472**	-.261**	-.532**	-.226*	-.137	.312**	1
	Sig. (2-tailed)	.000	.000	.009	.000	.024	.178	.002	

**. Correlation is significant at the 0.01 level (2-tailed).

*. Correlation is significant at the 0.05 level (2-tailed).

The descriptive statistics during the wall contact phase for the group are presented in Table 64 where the time that the feet were in contact with the wall was measured in seconds (s) while the width of the centre of the balls of the feet and the depth from the top of the pressure mat was measured in centimetres (cm).

Table 64 Descriptive statistics during the wall contact phase for a group of elite swimmers using a turn pressure mat

Descriptive Statistics

	N	Minimum	Maximum	Mean	Std. Deviation
Wall Contact Time (s)	99	0.16	0.40	0.31	0.06
Feet Width (cm)	98	-11.43	29.21	12.09	9.38
Orientation (°)	95	0.00	85.20	29.44	23.54
Left foot depth (cm)	99	3.81	43.18	22.63	8.82
Right foot depth (cm)	98	2.54	41.91	20.97	8.15
Valid N (listwise)	95				

Results from the testing showed that the wall contact time (WCT) ranged from 0.16 to 0.40s with a mean time of 0.31 ± 0.06s. Data presented a minimum feet width of -11.43cm and a maximum width of 29.21cm. A negative value in the feet width data is when the right foot if located to the left of the left foot and results from the feet contacting the wall with the toes towards the left wall of the pool. A positive feet width value occurs when the right foot is closer to the right side of the pressure mat than the left foot.

The orientation of the feet was measured in degrees where 0° reflects the toes pointing towards the surface of the water and 90° represents the toes pointing towards the side wall of the pool. Whilst the values ranged from 0-85.20° the standard deviation of 23.54° suggested a large variation of the feet position during the freestyle turns for this subject population. The values for the depth of the left and right foot from the top of the pressure mat also show a large variation within the group. The mean value was 22.63cm for the left foot and 20.97cm for the right foot with standard deviations of 8.82 and 8.15 respectively.

When performing an automatic forward stepwise regression analysis on the data the most important variable found to predict the criterion measure of the 5m RTT was the swimmer. The other two variables were the time that the feet were on the wall as well as the stroke. Data is presented in Figure 67 and included the anthropometric, video and pressure data.

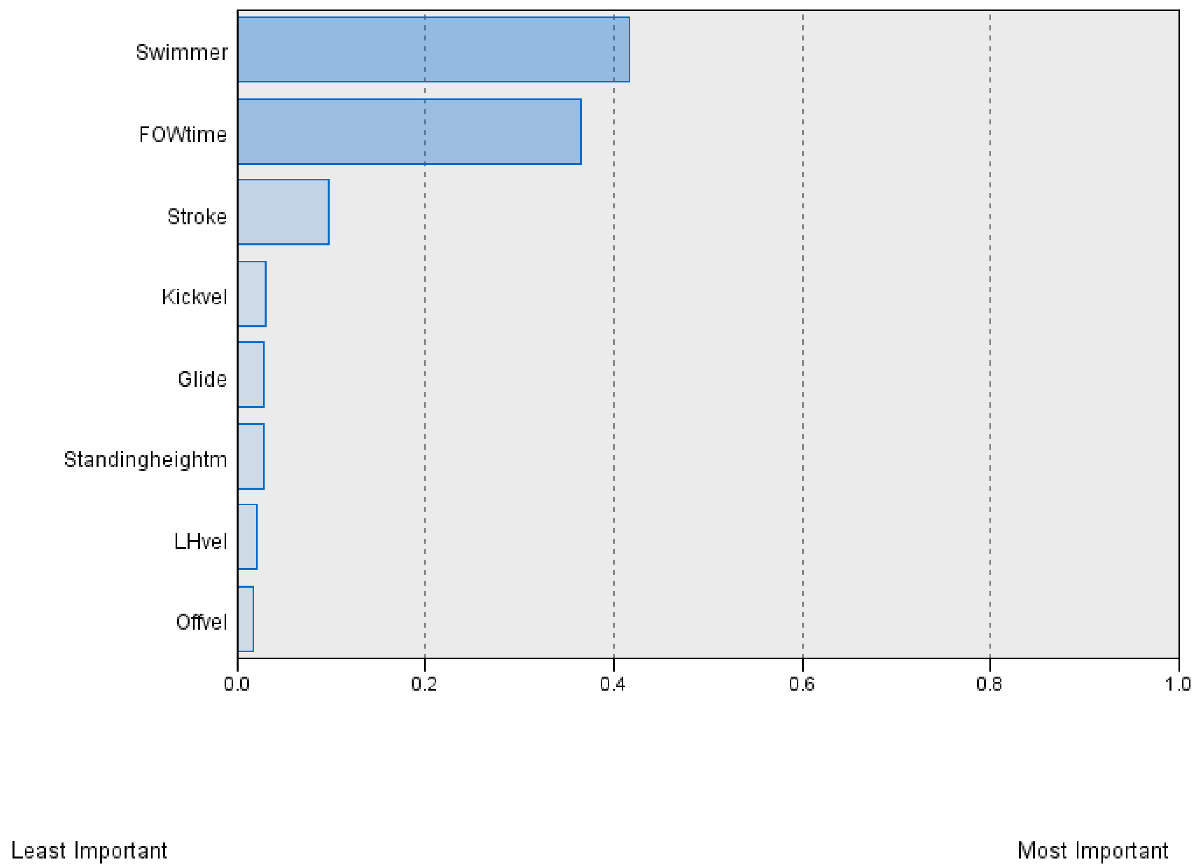


Figure 67: Regression analysis with the 5m RTT as the dependent variable

Correlations were also performed on the anthropometric data and the 5m RTT as displayed in Table 65. Negative significant correlations at the $p \leq 0.01$ level were observed with the standing height, trochanter height, tuck index and mass and the 5m RTT. Taller swimmers with longer legs had faster turn times than the shorter swimmers within the group. The heavier swimmers within the group also had faster 5m RTTs than the lighter swimmers within the group.

Tuck index was the only variable that produced a positive correlation with the 5m RTT indicating that those swimmers who contacted the wall in a more tucked position had a faster turn time than those swimmers contacting the wall with straighter legs.

Pearson correlations were performed on the data gathered during the wall contact phase and its impact on the criterion measure of the 5m RTT (Table 66). The time that the feet were in contact with the wall, distance between the centre of the two feet, orientation of the feet as well as the depth of the left and right foot were analysed.

There were no significant correlations with the criterion measure and each of the variables measured during the wall contact phase however there were significant positive correlations ($p \leq 0.05$) with the wall contact time and the width of the feet. Swimmers who spent longer with their feet contacting the wall placed their feet further apart than those swimmers with a smaller WCT.

Table 65 Correlations between the 5m RTT and anthropometric measures of the swimmers

		Standing height (cm)	Trochanter height (cm)	Tuck index	Mass (kg)	5m RTT (s)
Standing height (cm)	Pearson Correlation	1	.718**	-.306**	.862**	-.718**
	Sig. (2-tailed)		.000	.002	.000	.000
Trochanter height (cm)	Pearson Correlation	.718**	1	-.200*	.637**	-.567**
	Sig. (2-tailed)	.000		.047	.000	.000
Tuck index	Pearson Correlation	-.306**	-.200*	1	-.216*	.330**
	Sig. (2-tailed)	.002	.047		.032	.001
Mass (kg)	Pearson Correlation	.862**	.637**	-.216*	1	-.739**
	Sig. (2-tailed)	.000	.000	.032		.000
5m RTT (s)	Pearson Correlation	-.718**	-.567**	.330**	-.739**	1
	Sig. (2-tailed)	.000	.000	.001	.000	

**. Correlation is significant at the 0.01 level (2-tailed).

*. Correlation is significant at the 0.05 level (2-tailed).

Foot width was negatively correlated ($p \leq 0.01$) with the orientation angle and at the $p \leq 0.05$ level with the depth of the left foot. Swimmers who contacted the wall with their feet closer together tended to have a greater rotation of their feet so that their toes tended to point more towards the side of the pool than the surface of the water. The left foot depth was also positively correlated with the orientation and right foot depth ($p \leq 0.01$).

Table 66 Correlations between the 5m RTT and variables measured during the wall contact phase of the turn

		5m RTT	WCT	Foot Width	Orientation	Left foot depth	Right foot depth
5m RTT	Pearson Correlation	1	.136	-.034	.110	-.152	-.060
	Sig. (2-tailed)		.180	.742	.288	.133	.555
WCT	Pearson Correlation	.136	1	.211*	-.097	.023	.028
	Sig. (2-tailed)	.180		.037	.350	.820	.784
Foot Width	Pearson Correlation	-.034	.211*	1	-.787**	-.243*	-.121
	Sig. (2-tailed)	.742	.037		.000	.016	.237
Orientation	Pearson Correlation	.110	-.097	-.787**	1	.335**	.184
	Sig. (2-tailed)	.288	.350	.000		.001	.075
Left foot depth	Pearson Correlation	-.152	.023	-.243*	.335**	1	.462**
	Sig. (2-tailed)	.133	.820	.016	.001		.000
Right foot depth	Pearson Correlation	-.060	.028	-.121	.184	.462**	1
	Sig. (2-tailed)	.555	.784	.237	.075	.000	

*. Correlation is significant at the 0.05 level (2-tailed).

**. Correlation is significant at the 0.01 level (2-tailed).

6.3.6 Turn study 4

Not all of the swimmers used in the previous study were freestyle specialists so further data was gathered on the preferred stroke of the swimmers one month after the previous testing. During the final turn study 8 swimmers did butterfly turns, 3 swimmers did backstroke, 6 swimmers performed breaststroke turns and 13 swimmers were tested on freestyle.

Testing procedures were the same as the previous month where each swimmer performed three maximal effort turns with appropriate rest between each trial to ensure complete recovery. Times were measured as the head passed the 5m distance when approaching the wall until their head passed the same position after the turn. Data was gathered from the waterproofed pressure mat as well as visual systems associated with the SwimTrack© software. Results for the turns in each of the strokes is presented in Table 67 and included information on the number of subjects, anthropometric data and information from the wall contact phase of the turns.

Table 67 Turn data for each of the four swimming strokes

	Butterfly	Backstroke	Breaststroke	Freestyle
Standing height (cm)	180.00 ± 10.26	186.27 ± 9.38	183.77 ± 6.07	184.33 ± 8.23
Trochanter height (cm)	92.59 ± 3.51	96.70 ± 5.42	92.63 ± 2.34	94.11 ± 4.64
Mass (kg)	77.17 ± 7.34	86.07 ± 11.68	78.05 ± 7.83	78.10 ± 6.88
5m RTT	5.57 ± 0.39	5.15 ± 0.38	6.09 ± 0.39	5.06 ± 0.54
Max depth (m)	0.98 ± 0.17	1.18 ± 0.07	0.90 ± 0.08	0.89 ± 0.14
Rotation time (s)	0.86 ± 0.08	1.30 ± 0.14	0.87 ± 0.04	1.28 ± 0.20
WCT (s)	0.35 ± 0.07	0.30 ± 0.06	0.34 ± 0.03	0.30 ± 0.06
Left av. pressure (Pa)	54101.19 ± 15050.92	52674.41 ± 23460.93	62482.97 ± 16868.89	76870.45 ± 27997.20
Left area (cm)	23.50 ± 5.93	21.94 ± 4.47	21.24 ± 5.95	20.76 ± 5.51
Right av. pressure (Pa)	57814.51 ± 16360.69	53363.89 ± 23970.81	57722.50 ± 13779.39	57356.52 ± 22378.59
Right area (cm)	20.80 ± 6.28	25.54 ± 4.60	20.43 ± 6.28	22.57 ± 5.59
Foot width (cm)	7.57 ± 5.24	14.11 ± 5.37	13.82 ± 8.76	14.84 ±9.09
Foot height (cm)	0.66 ± 8.86	2.82 ± 5.07	3.06 ± 11.38	1.49 ± 8.10
Orientation (°)	46.32 ± 20.68	22.69 ± 16.14	35.22 ± 29.99	24.41 ± 22.85
Tuck index	0.91 ± 0.11	0.85 ± 0.09	0.91 ± .012	0.91 ± 0.14
Glide time (s)	0.92 ± 0.26	1.04 ± 0.39	1.81 ± 0.28	0.79 ± 0.32
1st kick velocity (m/s)	1.97 ± 0.30	1.47 ± .019	1.86 ± 0.39	2.11 ± 0.48
Subjects (n)	8	3	6	13

The tallest swimmers were the ones who performed the backstroke turns (186.27cm) followed by the freestylers (184.33cm), breaststrokers (183.77cm) and then the butterfly swimmers (180.00cm). The fastest 5m RTT were observed in freestyle (5.06s) followed by backstroke (5.15s), butterfly (5.57s) and breaststroke (6.09s).

Rotation time from the last hand entry until the feet contact the wall in freestyle and backstroke (average 1.29s) was slower than the times observed in the short axis strokes of butterfly and breaststroke (average 0.87s).

The mean tuck index was 0.91 for butterfly, breaststroke and freestyle and 0.85 for backstroke suggesting that the backstroke swimmers tended to have more of a tucked position when contacting the wall than observed in the other three strokes.

Glide time was shortest (0.79s) in freestyle when compared to the other three strokes. Swimmers paused for 0.92s in butterfly after pushing off the wall before commencing their underwater kick, 1.04s in backstroke and 1.81s in breaststroke before their first kick. Research into the optimal timing of the first kick suggested that the velocity of the swimmer should be between 1.9 and 2.2m/s (Lyttle et al., 2000) for all strokes other than breaststroke where the free swimming velocity is lower than the other strokes. The swimmers in this research were within this range for the butterfly and freestyle groups although the backstroke swimmers waited too long before commencing their first kick with a velocity of 1.47m/s. Surprisingly the velocity of the breaststroke swimmers when commencing their underwater kick was 1.86m/s which is likely to be too high compared to their swimming speed although there is currently no research to corroborate this assessment.

When examining the position of the feet on the wall the width between the centre of the left and right feet was 13.82cm for breaststroke, 14.11cm for backstroke and 14.84cm for freestyle. The only stroke that was different to this was butterfly where the feet were approximately 7.57cm apart when contacting the wall. In all four strokes there was a large standard deviation in the values observed for the vertical height difference between the left and right feet. Figure 68 shows the mean and standard deviations for each stroke in a box plot representation and highlights three outliers in the butterfly turn analysis. Breaststroke and freestyle had the largest range in foot width positions during the wall contact phase as seen in Table 67 and Figure 69.

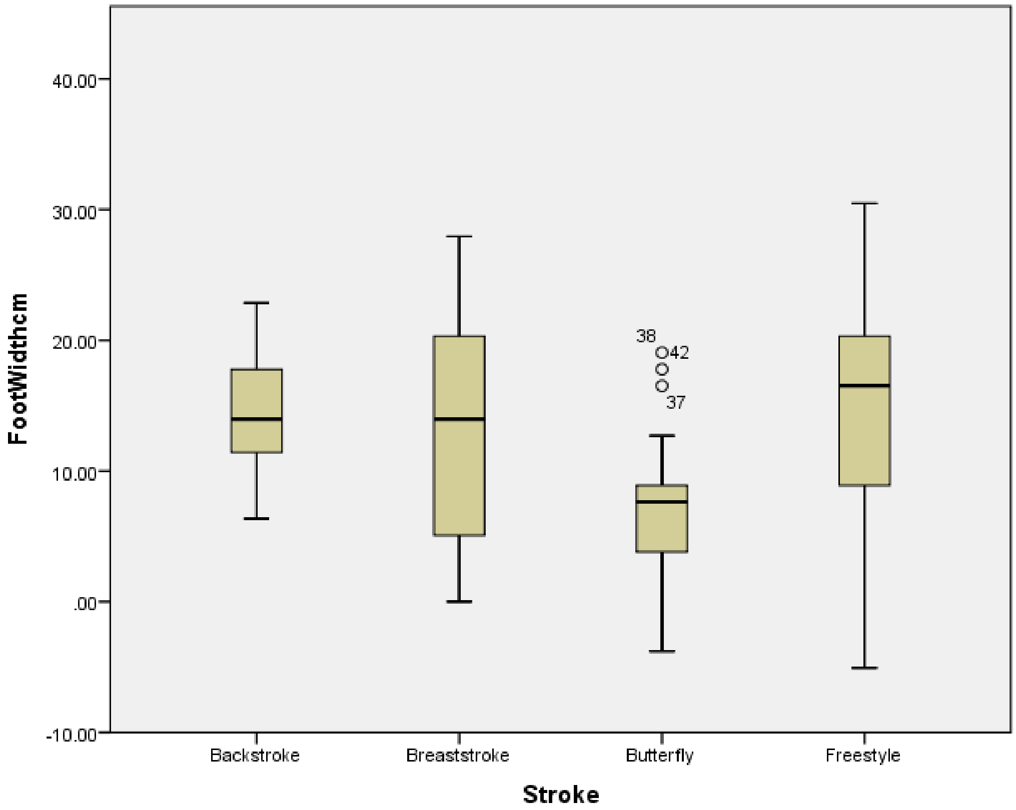


Figure 68 Box plot diagram representing the foot width (cm) for all four strokes during the wall contact phase of turns

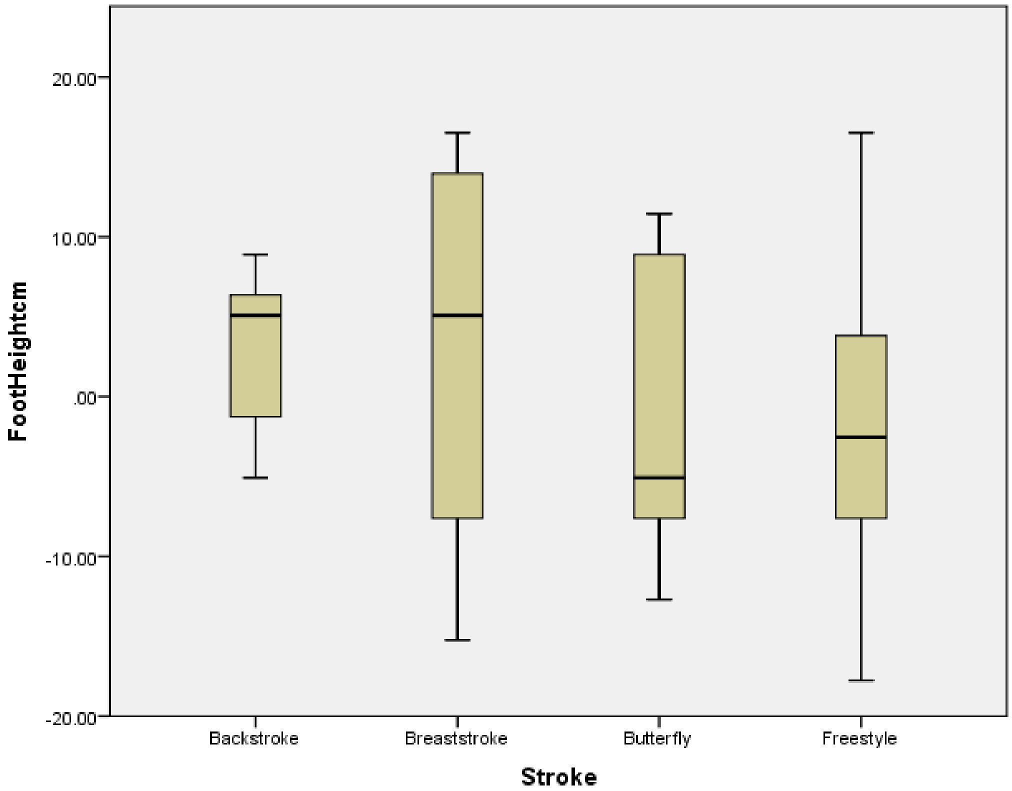


Figure 69: Box plot diagram representing the foot height (cm) for all four strokes during the wall contact phase of turns

Similar trends were observed when measuring the vertical height between the left and right feet during the wall contact phase of the turns (Figure 69). Breaststroke and freestyle were the two strokes that showed the largest range in height for the two feet when contacting the wall. The range was -5.08 to 8.09cm in backstroke, -15.24 to 16.51cm in breaststroke, -12.70 to 11.43cm in butterfly and -17.78 to 16.51cm in freestyle.

The values for the foot orientation varied between each of the four strokes and had relatively large standard deviations but these were smaller than the mean values. The mean feet orientation in butterfly was 46.32°, 22.69° in backstroke, 35.22° for breaststroke and 24.41° in freestyle. In backstroke there was a range of 10°, breaststroke and butterfly had a range of 19°, while there was a 75° difference in the rotation of the feet on the wall in freestyle as highlighted in Figure 70.

The box plot in Figure 70 clearly shows the different ranges of rotation used by the elite swimmers in different strokes. Backstroke had the smallest difference in orientation while freestyle has a large variation with the mean value approximately in the centre of these. The orientation of the feet on the wall was similar in freestyle and backstroke (long axis strokes) while the breaststroke and butterfly turns (short axis strokes) use more rotation when planting the feet on the wall. Further analysis is required to determine the effect of the orientation of the feet during the wall contact phase before recommendations can be made for improved turning performance.

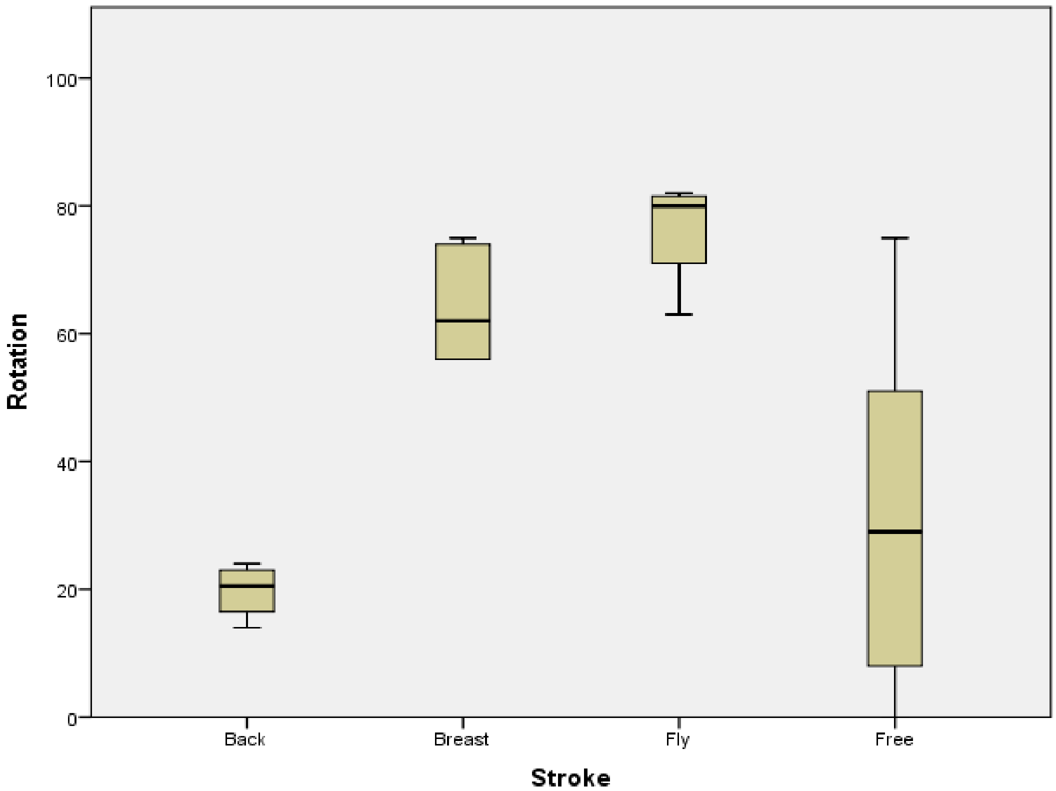


Figure 70: Box plot diagram on the orientation of the feet in degrees during the wall contact phase of the turn in all four strokes

More turns were conducted using freestyle which resulted in a greater variability within each of the measured parameters on the pressure mat. The wall contact time (WCT) ranged from 0.20-0.40s with an average WCT of 0.28s (Figure 71). An outlier within the freestyle data is noted above the box plot with a WCT of 0.44s.

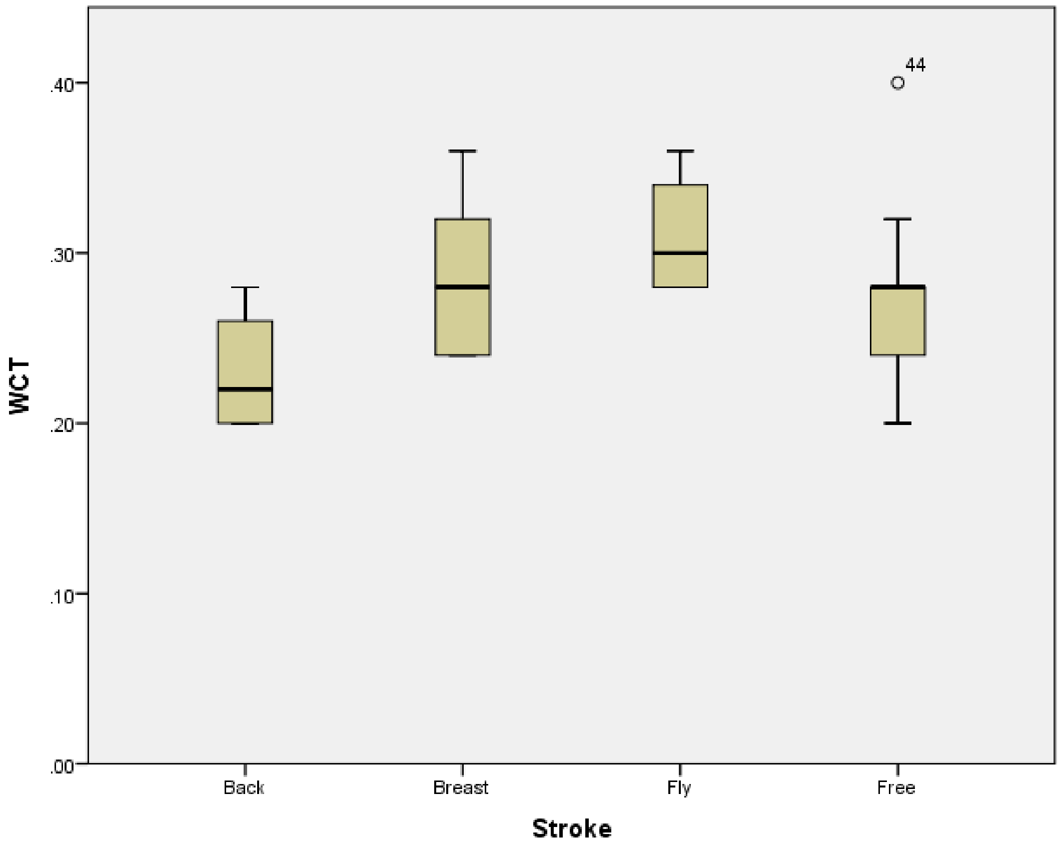


Figure 71: Cluster analysis on the wall contact times in seconds during turns conducted by elite swimmers separated by stroke

This research has highlighted the need to collect data on all four strokes in larger subject numbers in order to make accurate assessments of turning performances by elite and sub-elite swimmers.

6.4 Discussion

Total turn times measured during competition analysis showed that the turns were an important factor in the result of the race. The turns were then divided into a number of components for analysis in the competitive environment and included:

- Approach (in) – the head passing the 5m mark until the wall contact
- Rotation – hand to foot touch
- Wall contact phase

- Underwater phase – feet leaving the wall until the head breaks the surface of the water
- Out phase – feet leaving the wall until the head passes the 10m distance after the turn
- Free swimming – between the breakout and 10m distance after the turn

Investigations during both national and international competitions showed the times for each of the phases as well as the breakout distance for all swimmers competing at the major event for the year. This included the Commonwealth Games in 2010, World Championships in 2011, Olympic Games in 2012 and World Championships in 2013. These details were then compared with the winners of the same event so that strengths and weaknesses could be identified for each of the individuals. Information on each of the phases was monitored over the entire period of the research so that changes could be monitored for the 4 years.

Analysis of the British swimmers demonstrated that the phase of the turn where velocity can have the greatest improvement is during the push off the wall. They are able to travel faster in a streamlined position (approximately 3-4m/s) compared with the free swimming speed (2-2.2m/s in sprint freestyle). Swimmers were instructed to maintain this push off velocity before commencing their underwater kick when their velocity decreases to the range of 1.9-2.2m/s.

A portable pressure mat was developed to monitor turning performances in more detail than has been reported in previous literature. The unique feature of this system was the ability to determine the differences between the left and right feet as independent units during the wall contact phase of the swimming turns. Results from the start testing showed differences between the legs that were not related to leg dominance and these were anticipated during the turns.

The three main advantages to using a pressure mat for measuring the wall phase of the turn were:

1. Ability to measure the left and right feet independently
2. Portability of the equipment
3. Cost

Force platforms designed to measure swimming turns measure the horizontal and vertical force of the entire body, can weigh up to 180kg and cost up to £30,000. The pressure mat used in the current research was able to differentiate between the feet, determine the position on the wall in both the vertical and horizontal planes as well as the angle of orientation between the two feet. The system was portable at a combined weight of approximately 25kg and cost less than £10,000 to develop.

Pilot work on turns suggested the need to increase the size of the pressure mat to ensure that no changes in vertical position on the wall were required in order to test all of the swimming strokes. The height of the second pressure mat was the same as the width resulting in additional cells on the sensor which were the same dimensions as the previous pressure mat.

Through the development phase of the pressure mat it was determined that the data produced from the sensor mat was reliable and repeatable. Three swimmers were tested performing turns on their preferred stroke on two successive days with similar values produced.

Thirty-three university level swimmers were tested performing three maximal effort freestyle turns and were timed from their head passing the 5m distance in to the wall until their head passed the 10m distance after the turn. A multi component approach was used for the analysis with feedback provided to the coaches and swimmers from the vision and pressure systems.

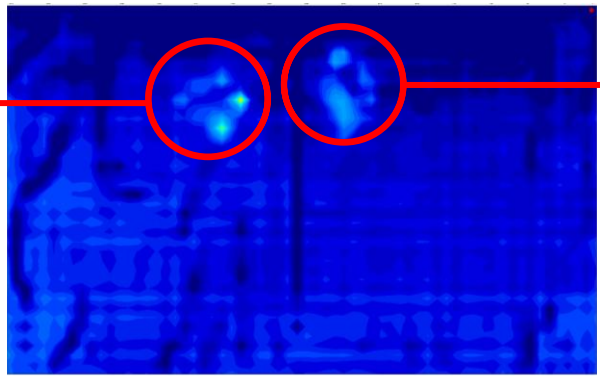
The data showed trends for the position that the feet contact the wall in each of the four strokes but there were not enough trials to make clear conclusions. Future research is required to determine the optimal foot position that will result in the fastest overall turn times.

6.4.1 Feedback to swimmers and coaches

The feedback to the coaches included information on each of the turn phases and the coaches then selected variables that they felt would be the most appropriate to feed back to the swimmers. An example of the report is shown in Figure 72 and included a screen shot of the foot placement on the wall for their fastest 5m RTT as well as the data for each trial on.

Verbal feedback was also provided to each swimmer during the video feedback session with each swimmer after the final turn study. This enabled biomechanical techniques to be employed during training so that the total turn time could be improved. A maximum of three key points were suggested to each swimmer along with the written reports.

The pressure mat was able to determine the foot positions and force generated during the contact phase of the turns. This information provided an indication of the positions that the group of swimmers used but future work should use larger subject numbers in all four of the strokes in order to make conclusive recommendations for elite swimmers.



Trial	5m RTT (s)	1st Kick dist. (m)	1st Kick velocity (m/s)	Max depth (m)	Rotation time (s)	Wall contact (s)	Glide time (s)	Left Av pressure (psi)	Left Area (inches)	Left foot vertical (cm)	Right Av pressure (psi)	Right Area (inches)	Right foot vertical (cm)	Foot Width (cm)	Foot Height (cm)	Orientation (degrees)	Tuck index
1	4.53	3.28	3.02	1.07	1.00	0.32	0.64	7.80	11.75	20.74	4.05	14.00	19.47	16.51	1.27	4.4	0.88
2	4.59	2.85	2.17	0.91	1.32	0.32	0.76	7.94	12.00	22.01	6.52	12.50	16.93	20.32	5.08	14.0	0.85
3	4.55	2.99	1.39	0.95	1.12	0.32	0.84	7.87	13.75	25.82	6.39	12.00	23.28	16.51	2.54	8.7	0.91

1st kick velocity should be between 1.9-2.2m/s
Rotation time aiming to be 1s or faster
Wall contact time aiming to be 0.32s or faster
Looking for similar pressure values between the left and right foot
Vertical position of each foot from the surface of the water
Horizontal distance between the centre of the ball of the left and right foot
Vertical distance between the centre of the ball of the left and right foot
Angle between the left and right foot - 0° represents the feet pointing directly up and 90° would represent the feet facing the side of the pool

Figure 72: Turn testing report provided to each swimmer after study 3 and 4 testing

6.4.2 Practical implications

The position of the feet on the wall may impact the overall turning performances of swimmers. Results suggested that swimmers should contact the wall with their feet approximately 20cm apart and with similar force.

Orientation of the feet was shown to be inconclusive within the present study but will impact on the underwater phase of the turn. Swimmers should continue to use the position (toes towards the surface of the water or pointing towards the side of the pool) until further analysis has been conducted.

Chapter 7 – Conclusions and future work

The purpose of the research presented within this thesis was to demonstrate how the use technology could enhance the performances of elite British swimmers. Research within the thesis was divided into three main components:

- Competition analysis
- Starts
- Turns

The work within all three of these components had clear objectives that were outlined within the introduction and were addressed as part of the research as noted below.

Competition analysis

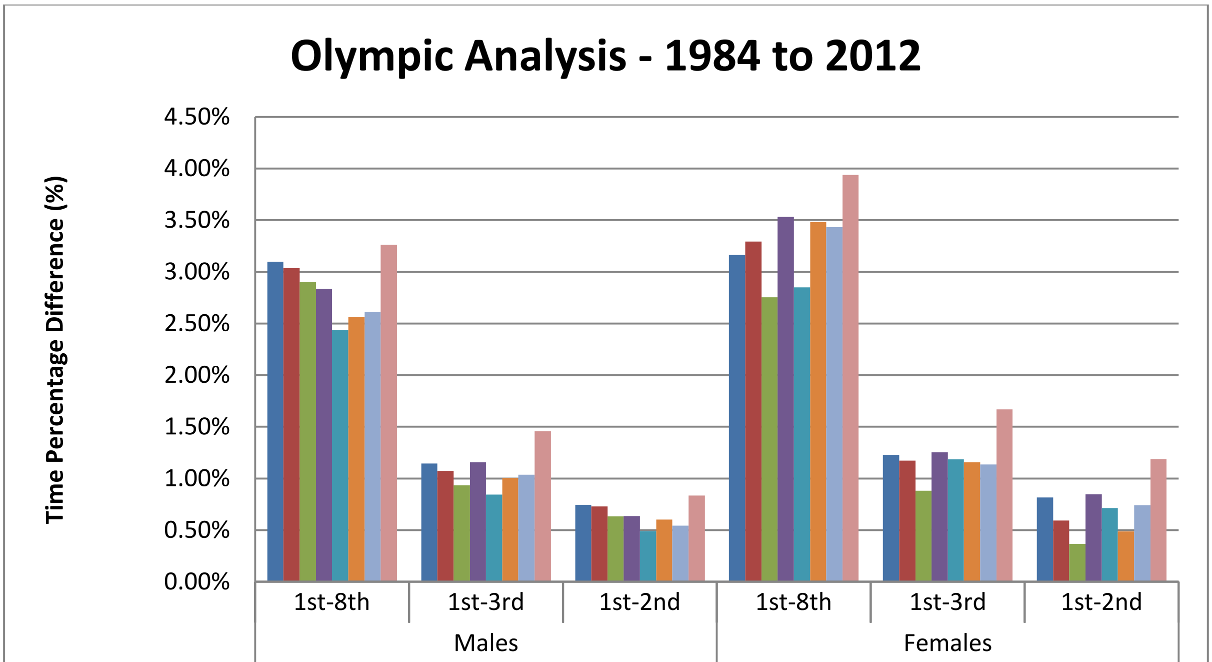
Objective 1

To measure the performances of swimmers during the major international competition each year. This would include comprehensive information on the skill phases (starts and turns) of the race which accounts for 30% of the 100m long course[28] events.

Work was presented throughout the chapter on competition analysis where data was gathered during the major international competitions from 2010-2013. When analysing the data from the 1984-2012 Olympic Games, the majority of the male events showed a 1-3% difference in time for the finalists while there was more than 3% difference in the female events. Trends were also observed between the time differences for the medallists (1^{st}-3^{rd} position) as well as the difference between the winner and second place in all events. As the number of swimmers compared decreased there was a similar decrease in the time percentage so that the majority of the races had a 1-3% difference when comparing the medallists and less than 1% difference between the first two places in each race. Average data for all events at each Olympic Games between 1984 and 2012 is presented in Figure 73 with the male and female events separated.

New knowledge gained throughout this research includes the development of new software that provides more detailed information on each of the components of the race. Analysis of this data has highlighted the strengths and weaknesses of the British swimmers so that changes in race strategies can be employed within the daily training environment.

[28] Races that occur in a 50m pool are referred to as long course events while those conducted in a 25m pool are short course events.



	Males 1st-8th	Males 1st-3rd	Males 1st-2nd	Females 1st-8th	Females 1st-3rd	Females 1st-2nd
2012 London	3.10%	1.15%	0.75%	3.16%	1.23%	0.82%
2008 Beijing	3.04%	1.07%	0.73%	3.29%	1.17%	0.59%
2004 Athens	2.90%	0.93%	0.63%	2.75%	0.88%	0.37%
2000 Sydney	2.83%	1.16%	0.64%	3.53%	1.25%	0.85%
1996 Atlanta	2.44%	0.84%	0.49%	2.85%	1.18%	0.71%
1992 Barcelona	2.56%	1.00%	0.60%	3.48%	1.16%	0.49%
1988 Seoul	2.61%	1.04%	0.54%	3.43%	1.13%	0.74%
1984 LA	3.26%	1.46%	0.83%	3.94%	1.67%	1.19%

Figure 73: Average time percentage difference for all events at the 1984-2012 Olympic Games for males and females

The differences in performances between competitions over a three year period for selected elite British swimmers were tracked for the first time and included more comprehensive analysis of the start and turn phases of the race. These skill components were also analysed for the winners and medallists at every major international competition (Commonwealth Games, World Championships, European Championships and Olympic Games) from 2010-2013. Data highlighted that the general trend was that the winners were faster in the starts and turns than the other competitors in the event although this was not always the case.

Throughout the duration of the research data was presented to the coaches and swimmers competing at the competitions. This was then used to improve race performances during the competition and then to make greater changes during the following training cycle.

Development on the new race analysis system (Nemo©) enabled the coaches to have greater detail for the skill components of the race as well as a format that was considered more “coach friendly”.

Starts

Objective 2

To determine the optimal starting position of elite level swimmers training at the five Intensive Training Centres (ITCs) based around the United Kingdom. Ongoing research would monitor the starting performances both within training and competitions.

With the introduction of a new design to the starting block used at major competitions it was important to determine the optimal starting position for those swimmers who were likely to compete for Great Britain in the 2012 Olympic Games. Vertical and horizontal forces were measured for the front and rear legs independently on the instrumented starting block developed at Loughborough University. The other parameters that were used to determine the optimal position for each swimmer were the horizontal velocity at take-off, flight distance, maximum depth and 15m start time using the SwimTrack© software developed at Sheffield Hallam University.

After the initial analysis of more than 1400 starts, some swimmers were filmed and analysed on a weekly basis within the training centres so that feedback could be provided on a more regular basis. This enabled the swimmers to determine the optimal distance to commence their underwater kick where the velocity from the block phase could be maintained for the optimal period of time.

The focus of the research within this thesis was on the block and flight phase of the start while some components of the underwater phase were examined. This included information on the maximum depth of the hip as well as the timing of the first kick which had been suggested to be optimal if the swimmer was travelling between 1.9 and 2.2m/s. Interestingly there has been very little research since the work presented by Lyttle and his colleagues during the late 1990's to support this information. Data was presented at the Biomechanics and Medicine in Swimming (BMS) conference in April 2014 to show that researchers are now looking into the underwater phase within backstroke (de Jesus et al., 2014). McCabe et al. (2012) examined the timing during the underwater phase in breaststroke although the optimal velocity for commencing the underwater kick in both of these strokes was not discussed.

A case study was presented in the chapter on starts for the swimmer who was asked to change the leg at the front of the block as well as to move the wedge towards the rear of the block by 3 positions compared to his preferred starting position. Over a 12 month period improvements were observed for his time between the starting signal and his head reaching the 15m mark from the wall. Recently this subject was selected to compete for the English team at the 2014 Commonwealth Games which will be his first international swimming experience.

Swimming start performance as measured from the starting signal until the swimmer's head passing the 15m distance from the wall improved both in training and during competition over the period of this research as presented within the chapter. The work that was analysed during this phase of the research was presented at the 2010 BMS conference in Oslo as well as the 2010 and 2011 International Society of Biomechanics in Sport conferences.

Turns

Objective 3

To determine the position of the feet on the wall that resulted in the fastest turn times as measured from the head passing the 5m distance in to the wall and back to the same position after the swimmer had completed the turning motion.

The various phases of the turn were discussed within the literature review section of the chapter and included the approach (in), rotation, wall contact, underwater and swimming segments. Lyttle and Benjanuvatra adapted Hay's model of turning (1992) as presented in Figure 74 to describe each of the phases and how they could be measured.

To date there has been no research on the effectiveness of one type of turning technique compared to another whilst many variations are observed during international swimming competitions. With so many contributing factors presented in Figure 74 it was not possible to measure all of the variables within the timeframe of this research.

Previous research on swimming turns has used force platforms to measure the force, velocity and impulse of the swimmer as an entire unit when contacting the wall. By utilising this technique it was impossible to determine any differences between the left and right legs or the position of the feet compared to each other as well as the surface of the water. Some additional limiting factors when using this form of technology included: the cost of the equipment, the weight for installation and removal around testing sessions, and the change to the distance of the wall from the "T" located on the bottom of the swimming pool.

Time was spent investigating the most appropriate alternative to these limitations and resulted in the development of a waterproofed pressure mat that could be attached quickly and easily to the end wall of a swimming pool. Software was developed to automatically determine the position and orientation of the feet during the wall contact phase of the turn.

The final version of the pressure mat for turn analysis was large enough to be used to evaluate the turns in all four swimming strokes as well as the turns used in medley events.

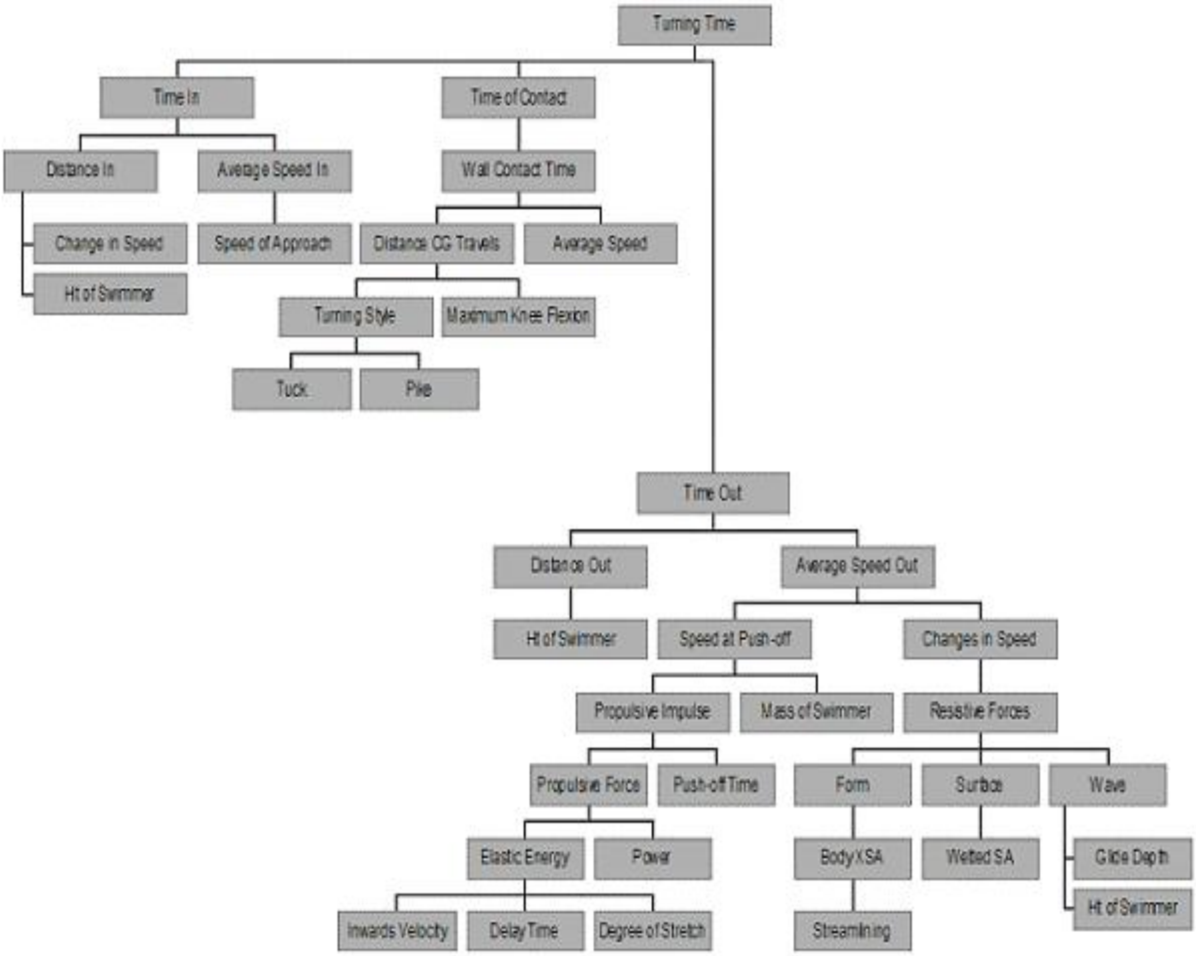


Figure 74: Contributing factors within a swimming turn presented by Lyttle and Benjanuvatra (2007) from Hay's 1992 model

The focus of this analysis was on the wall contact phase of the turn due to the ability to differentiate between the left and right feet for the first time in swimming turn research. After the pilot testing, a large study was performed on University swimmers completing 3 maximal freestyle turns and examined the effect on foot position in relation to the 5m RTT. Differences were noted for the males and females in total turn time and the parameters that were significantly correlated with this performance. This data was presented at the 2014 BMS conference in Canberra (Cossor et al., 2014).

The same group of swimmers were tested again the following month to confirm the reliability of the manual analysis of the pressure mat data and to enable swimmers to perform turns in their main stroke. Analysis of the data was divided in to the different strokes with comparisons made between the strokes. These included vertical and horizontal heights, wall contact times and orientation of the feet.

Whilst it was felt that the wall contact phase was an important contributor to the overall performance of the turn, it is likely that differences will be found in the amount of drag acting upon the body as the swimmer leaves the wall when contacting the wall utilising different foot placement and orientations.

Future work

The research presented within this thesis was able to provide current information on swimming performances at international level competitions. Enhancements were made to the software used to analyse these performances so that the data could be provided to the coaches and athletes in a shorter time frame after the completion of the race. Future work will continue to improve the analysis techniques so that the processing of the data will become automated. This will then allow the support staff to spend more time interpreting the data and providing this information to the coaches and swimmers which could potentially lead to improvements in performances both within the current competition as well as those to be held in the future.

Swimming start research has been performed over several decades and the new knowledge presented in this research was information on the left and right legs using the new OSB11 type starting blocks. Future research should look to include the arm force during the grab phase on the block and differentiating this from the front leg force data.

The greatest learning from this research was the understanding of the foot placement during the wall contact phase of the turn. In the future more data should be collected on each of the individual strokes to gain a more robust understanding of the wall contact phase. New research could also test more elite level swimmers although the majority of the swimmers used in the current research competed at the national championships.

There is still a great deal of work that needs to be done within the area of turn research and will benefit from the inclusion of a pressure mat within the analysis process. The current research has shown a difference between male and female orientation of the feet on the wall during freestyle turns and future work should include greater subject numbers as well as more elite level swimmers.

Visual observations of the pressure mat throughout the capture process showed no differences between the pressures at the top of the mat compared to the bottom of the mat although this should be measured in greater detail during future research.

Early work presented within this research also examined the turning technique of swimmers in all four strokes. Subject numbers were very low and future work should look to measure at least 10 males and 10 females performing their preferred stroke for comprehensive interpretation. This original work suggests that techniques are similar in the short axis strokes (breaststroke and butterfly) which tended to have a greater distance between the centre of the feet when compared to the freestyle and backstroke turns.

Whilst data was gathered on the velocity and position of the swimmer at different phases of the starts and turns, future research will benefit from an understanding of the drag components as the swimmer travels beneath the surface of the water. Swimmers travel at their fastest within swimming when leaving the wall in either a start or turn so it is important to maintain this velocity for as long as possible. When examining the push off the wall from a turn relationships should be examined between the positions of the feet on the wall with the direction that the body rotates when leaving the wall.

Future testing of the wall contact phase of turns should continue to use the pressure mat hardware with the dimensions of 81 x 81cm to ensure capture for all strokes in each trial but pressure range should be decreased from 10-200psi to 5-100psi. An increase in the number of sensors within the testing area will also ensure a greater representation of the foot. Currently the shape appears to have square edges due to the area of each cell (12.7mm squared) and this would be improved with smaller cells. The increase in the area of each foot would also ensure that the force values could be calculated more accurately than the data presented within this thesis.

Technology continues to improve at a rapid rate and while this research has shown the benefit of using the current technology to enhance swimming performance, it will not be long before the above points can be addressed.

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Appendices

Swimming Starts Utilising a Wedge Block

INFORMED CONSENT FORM
(to be completed after Participant Information Sheet has been read)

The purpose and details of this study have been explained to me. I understand that this study is designed to further scientific knowledge and that all procedures have been approved by the Loughborough University Ethical Advisory Committee.

I have read and understood the information sheet and this consent form.

I have had an opportunity to ask questions about my participation.

I understand that I am under no obligation to take part in the study.

I understand that I have the right to withdraw from this study at any stage for any reason, and that I will not be required to explain my reasons for withdrawing.

I understand that all the information I provide will be treated in strict confidence and will be kept anonymous and confidential to the researchers unless (under the statutory obligations of the agencies which the researchers are working with), it is judged that confidentiality will have to be breached for the safety of the participant or others.
I agree to participate in this study.

If you have any complaints, the University has a policy relating to Research Misconduct and Whistle Blowing which is available online at
http://www.lboro.ac.uk/admin/committees/ethical/Whistleblowing(2).htm.

Your name ______________________________

Your signature ______________________________

Signature of investigator ______________________________

Date ______________________________

Swimming Starts Utilising a Wedge Block
Participant Information Sheet

Jodi Cossor, EIS Pool Loughborough University, Epinal Way, Loughborough LE11 3TU
Email: Jodi.cossor@swimming.org Phone: 07748 322255
Andy West, Wolfson School of Mechanical and Manufacturing Engineering, Loughborough University, Epinal Way, Loughborough LE11 3TU
Email: A.A.West@lboro.ac.uk Phone: 01509 227550
Paul Conway, Wolfson School of Mechanical and Manufacturing Engineering, Loughborough University, Epinal Way, Loughborough LE11 3TU
Email: P.P.Conway@lboro.ac.uk Phone: 01509 227670

What is the purpose of the study?

The OSB11 starting blocks were introduced to international swimming competitions in 2008 and will be used in the London 2012 Olympic Games. The main differences to the OSB9 blocks include:

- the change from 5° to 10° pitch of the block
- the inclusion of a wedge at the rear of the block
- the ability to set the wedge in one of five positions

Early research using these blocks has indicated improvements in starting performance of up to 0.2s to 7.5m. The start itself is a complicated movement incorporating the block, flight and underwater phases and we will be measuring each of these to maximise your potential.

Who is doing this research and why?

Jodi Cossor will be leading this research under the supervision of Andy West and Paul Conway from the Wolfson School of Mechanical and Manufacturing Engineering. By determining your optimum position on the block, it will be possible to maximise the benefit of the starting phase in your race. At your level of swimming we anticipate that there will be differences for each swimmer and we would like to opportunity to provide you with quantitative feedback to enable you to have the best position to start in.

Once I take part, can I change my mind?

Yes! After you have read this information and asked any questions you may have we will ask you to complete an Informed Consent Form, however if at any time, before, during or after the sessions you wish to withdraw from the study please just contact Jodi Cossor on 07748 322255. You can withdraw at any time, for any reason and you will not be asked to explain your reasons for withdrawing.

Will I be required to attend any sessions and where will these be?

You will be required to attend two pool sessions on consecutive days and these may be part of your normal training schedule. Exact dates and times will be provided closer to the testing. Within your ITC you will also be asked to do some jumps in the gym on a force platform as part of your regular testing and a physiotherapy screening session. You may be asked to have some anthropometric measures taken if we do not already have these.

How long will it take?

This project will require you to perform tests both on land and in the water but will work around your normal training load. You will be asked to perform between 30 and 50 maximal starts over two days for the biomechanical data. The physiotherapy screening will take no longer than 60 minutes. The strength and conditioning jumps will be incorporated into your regular testing sessions and should take no longer than 20 minutes while the anthropometric measures will also take no longer than 20 minutes.

Is there anything I need to do before the sessions?

Nothing will be required of you prior to this testing.

Is there anything I need to bring with me?

You will not be required to bring anything with you that you don't already use in training.

What type of clothing should I wear?

During the pool testing sessions it is preferable that you were dark or brightly coloured swim suits if possible. Correct clothing for the gym will be required for the land tests and you will need to be in a swim suit and shorts for the physiotherapy and anthropometric tests.

What will I be asked to do?

Biomechanics – force will be measured on an instrumented starting block. Position and velocity will be calculated using the SwimTrack software and will be compared to acceleration data collected from the wireless node placed on your lower back. You will be requested to perform between 30 and 50 maximal starts to 15m over two consecutive days.

Physiotherapy – screening will measure eleven key positions looking at various ranges of movement that may affect your performance.

Strength and Conditioning – force will be measured in the gym and compared to those measured on the starting block. Counter movement jumps with your hands on your hips and feet in set positions will be assessed during a short testing session.

Nutrition – anthropometric measures will be taken to assess any relationships between limb lengths/girths with flight distances and peak forces.

What personal information will be required from me?

No personal information other than your anthropometric data will be required and this will be kept confidential within the investigation group.

Are there any risks in participating?

There are no anticipated risks involved in taking part in this study.

Will my taking part in this study be kept confidential?

The information collected as part of this research will be kept by the lead investigator but may be discussed within the investigation group. Results will be provided to yourself and you can choose if you would like to share these with your coach.

What will happen to the results of the study?

These tests will be used to determine the most suitable starting position for you to use from a multidisciplinary approach. A 0.1s improvement in your start time can be the difference between making a final or standing on the podium at the Olympic level.

Future tests will be available to monitor your progress but will only include relevant tests based on your initial testing.

What do I get for participating?

Whilst there is no financial reward for taking part in this study you will be provided with information that will have the potential to improve your start and hence your overall race performance.

I have some more questions who should I contact?

Please contact Jodi Cossor on 07748 322255 if you have any further questions.

What if I am not happy with how the research was conducted?

The University has a policy relating to Research Misconduct and Whistle Blowing which is available online at http://www.lboro.ac.uk/admin/committees/ethical/Whistleblowing(2).htm.

Ref No: R10-P108

LOUGHBOROUGH UNIVERSITY

ETHICAL ADVISORY SUB-COMMITTEE

RESEARCH PROPOSAL

INVOLVING HUMAN PARTICIPANTS

Title:	Swimming starts utilising a wedge block
Applicant:	Dr A West, J Cossor
Department:	Wolfson School of Mechanical and Manufacturing Engineering
Date of clearance:	24 August 2010

Comments of the Sub-Committee:

The Sub-Committee agreed to issue clearance to proceed subject to the following conditions:

- That the Participant Information Sheet was:
  - Checked for spelling and grammatical mistakes.
  - Amended to include that the Participants would be videoed during the swimming part of the study.
- That confirmation was provided as to where the study data would be stored.

Loughborough University

Swimming Turns Utilising a Pressure Mat

INFORMED CONSENT FORM
(to be completed after Participant Information Sheet has been read)

The purpose and details of this study have been explained to me. I understand that this study is designed to further scientific knowledge and that all procedures have been approved by the Loughborough University Ethical Advisory Committee.

I have read and understood the information sheet and this consent form.

I have had an opportunity to ask questions about my participation.

I understand that I am under no obligation to take part in the study.

I understand that I have the right to withdraw from this study at any stage for any reason, and that I will not be required to explain my reasons for withdrawing.

I understand that all the information I provide will be treated in strict confidence and will be kept anonymous and confidential to the researchers unless (under the statutory obligations of the agencies which the researchers are working with), it is judged that confidentiality will have to be breached for the safety of the participant or others.
I agree to participate in this study.

If you have any complaints, the University has a policy relating to Research Misconduct and Whistle Blowing which is available online at
http://www.lboro.ac.uk/admin/committees/ethical/Whistleblowing(2).htm.

Your name ______________________________

Your signature ______________________________

Signature of investigator ______________________________

Date ______________________________

Loughborough University

Swimming Turns Utilising a Pressure Mat
Participant Information Sheet

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What is the purpose of the study?

Research on swimming turns has focused on the mechanics of the turn along with peak forces generated when the swimmer contacts the wall. The benefit of a pressure mat compared with more traditional measuring tools is the ability to determine differences in peak pressure between the left and right legs as well as the position of the feet on the wall.

Measurements will also be recorded on the distance of the hip from the wall during the rotation phase as well as the time that it takes for the head to pass the 5 m distance after the turn so that comparisons can be made with previous research.

Who is doing this research and why?

Jodi Cossor will be leading this research under the supervision of Andy West and Paul Conway from the Wolfson School of Mechanical and Manufacturing Engineering. Results of research on swimming starts showed differences in peak force values between the left and right legs and this has not previously been tested during turns. At your level of swimming we anticipate that there will be differences for each swimmer and we would like the opportunity to provide you with quantitative feedback on your foot position during the wall contact phase of the turn as well as your total turn time from 5 m in to the wall and back to the same position.

Once I take part, can I change my mind?

Yes! After you have read this information and asked any questions you may have we will ask you to complete an Informed Consent Form, however if at any time, before, during or after the sessions you wish to withdraw from the study please just contact Jodi Cossor on

07748 322255. You can withdraw at any time, for any reason and you will not be asked to explain your reasons for withdrawing.

Will I be required to attend any sessions and where will these be?

Testing will take place during one of your scheduled training sessions where we will record three freestyle turns. Exact dates and times will be provided closer to the testing after consultation with your coach. Prior to entering the water a large circle will be marked on to your skin with a permanent marker at the position of the head of the femur. Standing height, seated height and weight will also be recorded for use within the analysis process. Some swimmers may be asked to attach a wireless sensor to their lower back during the pool testing.

How long will it take?

This project will require you to perform maximal freestyle turns within a training session that do not impact on your normal training load. You will be asked to perform three freestyle turns for the research project but it may be possible to film a few additional turns on your preferred stroke.

Is there anything I need to do before the sessions?

Nothing will be required of you prior to this testing.

Is there anything I need to bring with me?

You will not be required to bring anything with you that you don't already use in training.

What type of clothing should I wear?

During the pool testing sessions it is preferable that you wear dark or brightly coloured swim suits if possible.

What will I be asked to do?

Biomechanics – pressure and foot placement will be measured on a waterproof turning mat. Position and velocity of the hip will be calculated using the SwimTrack. You will be requested to perform all three freestyle turns at maximum effort during one training session. If you are wearing the wireless sensor you will need to climb out of the pool after each trial so that the information can be downloaded to the laptop.

What personal information will be required from me?

No personal information other than your anthropometric data will be required and this will be kept confidential within the investigation group.

Are there any risks in participating?

There are no anticipated risks involved in taking part in this study.

Will my taking part in this study be kept confidential?

The information collected as part of this research will be kept by the lead investigator but may be discussed within the investigation group. Results will be provided to yourself and you can choose if you would like to share these with your coach.

What will happen to the results of the study?

These tests will be used to determine foot position on the wall during a turn and if this has any impact on the time that it takes for you to reach the 5 m distance after turning. Differences in the peak pressure values between the feet *may* also be determined within the scope of this research.

All results will be kept by the lead researcher but may be shared with other investigators within the research group.

What do I get for participating?

Whilst there is no financial reward for taking part in this study you will be provided with information that will have the potential to improve your turn and hence your overall race performance.

I have some more questions who should I contact?

Please contact Jodi Cossor on 07748 322255 if you have any further questions.

What if I am not happy with how the research was conducted?

The University has a policy relating to Research Misconduct and Whistle Blowing which is available online at http://www.lboro.ac.uk/admin/committees/ethical/Whistleblowing(2).htm.

The Development of a Component Based Approach for Swim Start Analysis

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A component based system was developed to provide greater quantitative feedback of starts based on input from British Swim coaches. Currently the information provided by the system comprises integrated vision, force data from an instrumented starting platform and wireless three-axis acceleration data. Initial testing has demonstrated the reliability of the system and the direct impact of intervention with an elite athlete.

Key words: swimming, starts, vision system, force platform, wireless acceleration

INTRODUCTION

Swimming races are divided into the start, turn, and free swimming sections. The contribution of each phase to overall performance is dependent on race length. The start has a greater contribution to success in the sprint events compared with longer distances. Analysis of female freestyle sprint events at the Beijing Olympics, illustrates that a 1% reduction in start time would be larger than the time difference between the first and second places (Slawson, 2010).

Research on swimming starts has included information on the block, flight, underwater and free swimming phases. Block time has been the most measured parameter although forces and velocities leaving the block are generally discussed in relation to the block phase. Arellano et al. (2005) and Mason et al. (2007) suggested that increased horizontal force results in better starts. Flight time and distance are the main reported parameters associated with the flight phase although the angle of entry has been noted as being important to *overall* start performance (Ruschel et al., 2007). While it is noted that the underwater phase can be the longest in terms of time, the block and flight phases significantly influence the drag forces experienced by the swimmer in the glide phase (Mason et al., 2007). Transition into the break out and the free swimming sections also contribute to the overall start time and variations between swimmers are usually attributed to differences in underwater kicking skill.

The use of vision systems is still the most common analysis technique but it can be user intensive and costly. Force plate analysis has been successful utilised due to the reliability of the system along with the capability to provide real time measures. To date, the limitation of utilising force data has been in the interpretation of these data and the subsequent development of interventions for improved performance.

Accelerometers have been used in the understanding of human movement and performance in areas such as gait, sleep and healthcare. Research using accelerometers in swimming has included the derivation of information on stroke count, lap count and stroke type (James et al., 2004, Ohgi, 2006, and Davey et al., 2008). Acceleration systems can be characterised into either real-time data transmission or logging and download units. Only the latter system has been used in swimming research and only on a one to one basis. Although useful information on free swimming performance has been disseminated from these studies, a wireless networked solution would enable data to be collected real time from a pool of athletes. A system has been designed, implemented and evaluated in the current research that allows many wireless nodes to transmit in real-time to a co-ordinating receiving unit that acts as the interface to visualisation, analysis and storage on conventional personal computers.

This study was used to determine and evaluate the efficacy of performance variables that significantly contribute to the overall starting performance. In addition, in pool testing has demonstrated the reliability of the system and the impact of intervention strategies on the performance of elite athletes.

METHODS

A force platform incorporating four Kistler (9317B) transducers into a starting block with similar dimensions to the Omega OSB9 block has been designed at the Sports Technology Institute at Loughborough University. Three orthogonal axes of force data were synchronised with video output from a Photron SA1 high-speed camera set at 50fps with a resolution of 1024 x 1024 pixels. A wireless accelerometer node was placed at the small of the back of the swimmer in order to gain information on the accelerations generated during the start. A schematic of the testing set up is illustrated in Figure 1.

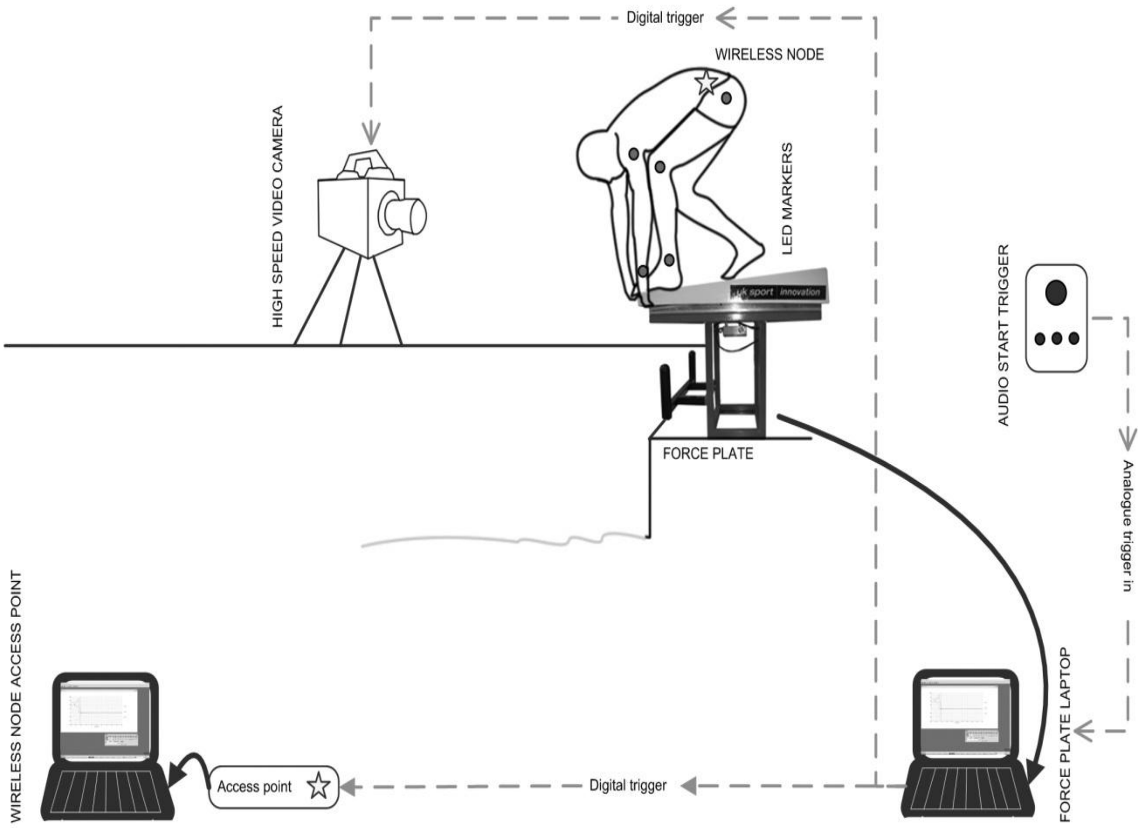

Figure 1. Set up incorporating a video, force platform and wireless accelerometer node.

A variety of tests were conducted using the instrumented block to capture force data on twenty male and female swimmers ranging from National to International level over a period of twelve months. Tests included swimmers performing a number of trials on one day, the same swimmers repeating trials one month later, as well as some swimmers testing the difference between grab and track starting techniques. An external analogue trigger synchronised the capture of data from the force platform and video camera whilst simultaneously generating an audio signal for the swimmer to start. Various parameters of the *block* and *flight* phases of the start were determined from the analysis of the force data and correlated with the images recorded via the vision system. During the *block* phase the *time to first movement*, *horizontal and vertical forces*, and *overall block time* were determined. Using the moments generated on the force platform, *centre of pressure* was examined. *Flight distance* and *time to 15m* were determined via the vision data whilst *flight time*s, time to the first stroke and number of strokes prior to 15m were determined from accelerometer data generated by the wireless node.

RESULTS

The initial focus of the research was on the validation of the data from the force platform. A number of University swimmers were tested using both grab and track starts. Unfortunately it was noted that this level of swimmer was unable to demonstrate a consistent enough dive force profile to enable performance improvements to be evident between different dives.

Further testing was undertaken with an International level swimmer where a significantly high degree of repeatability was evident in the force profiles (see Figure 2). Very little difference between the timing, amplitude and profile of the individual trials for the elite swimmer were observed compared with the significant variability in these parameters shown for the trials provided by an amateur swimmer as seen in Table 1. There was 0.7% difference in the impulse for the elite swimmer compared to 9.8% for the University swimmer. Likewise there were only 1.2% differences in timing and maximum forces in the horizontal and vertical planes for the elite athlete but 16.3% and 14% differences respectively for the University swimmer. Hence via the detailed examination of the characteristics of starting force profiles over repeated trials it is possible to determine relevant measures of athlete skill level (i.e. variance in timing, impulse, and number of peaks) without the aid of vision systems.

	Dive	Max y	Time	Max Z	Time	Unload time	Impulse y	Impulse z
Elite	1	414.72	0.75	725.17	0.73	0.92	151.67	444.28
	2	415.27	0.76	741.22	0.73	0.94	149.59	444.34
Uni	1	554.17	0.51	929.48	0.64	0.87	181.67	530.17
	2	454.62	0.70	857.96	0.70	0.94	159.31	565.67

Table 1. Horizontal and vertical force data for different levels of swimmers.

An intervention was designed for the International level swimmer in order to improve their starting performance. The force profiles for the new dive technique in both the horizontal and vertical components are illustrated in Figure 2. The standard dive technique profiles are provided for comparison. With the new dive technique, the timing of the first movement was observed to be earlier (0.1s) with the same peak force in the horizontal direction while there was a 6% reduction in peak vertical force compared to the traditional start. This type of quantitative feedback on measures of performance highlight the benefits of a system that is not labour or time intensive and allows for immediate feedback so that changes in technique can be observed.

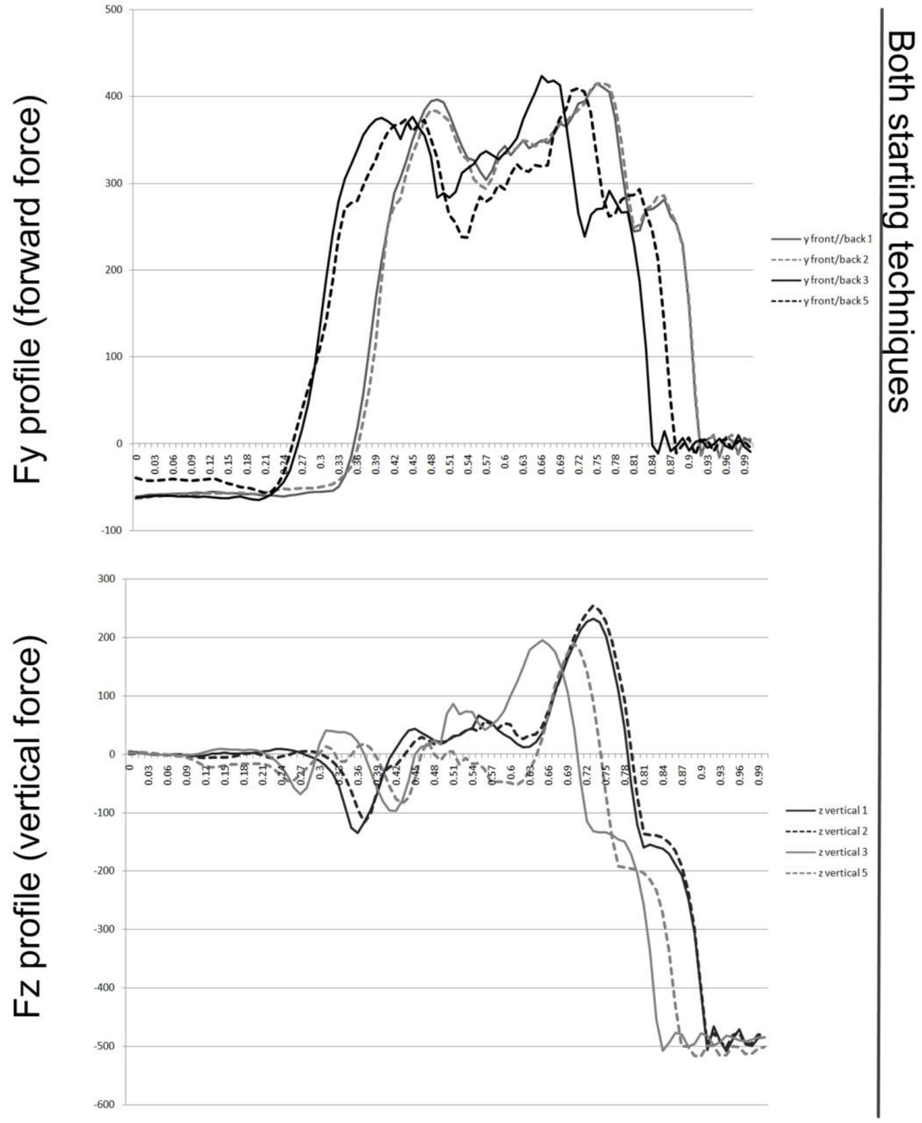

Figure 2. Comparison of force data an elite swimmer using different techniques.

In Figure 3 an example of the information provided to the coach and swimmer is illustrated. From the force data it is possible to determine the *block time*, the *time of first movement*, *peak horizontal and vertical forces* as well as *centre of pressure* information. The vision system information is used to provide information relevant to the flight phase of the start i.e. the *flight distance* and *flight time*. The *timing of the first stroke* as well as the *number of strokes* through to the 15m mark can be determined using the acceleration data.

The inclusion of the vision data in the report provides a detailed initial understanding of the force data collected during the *block* and *flight* phases.

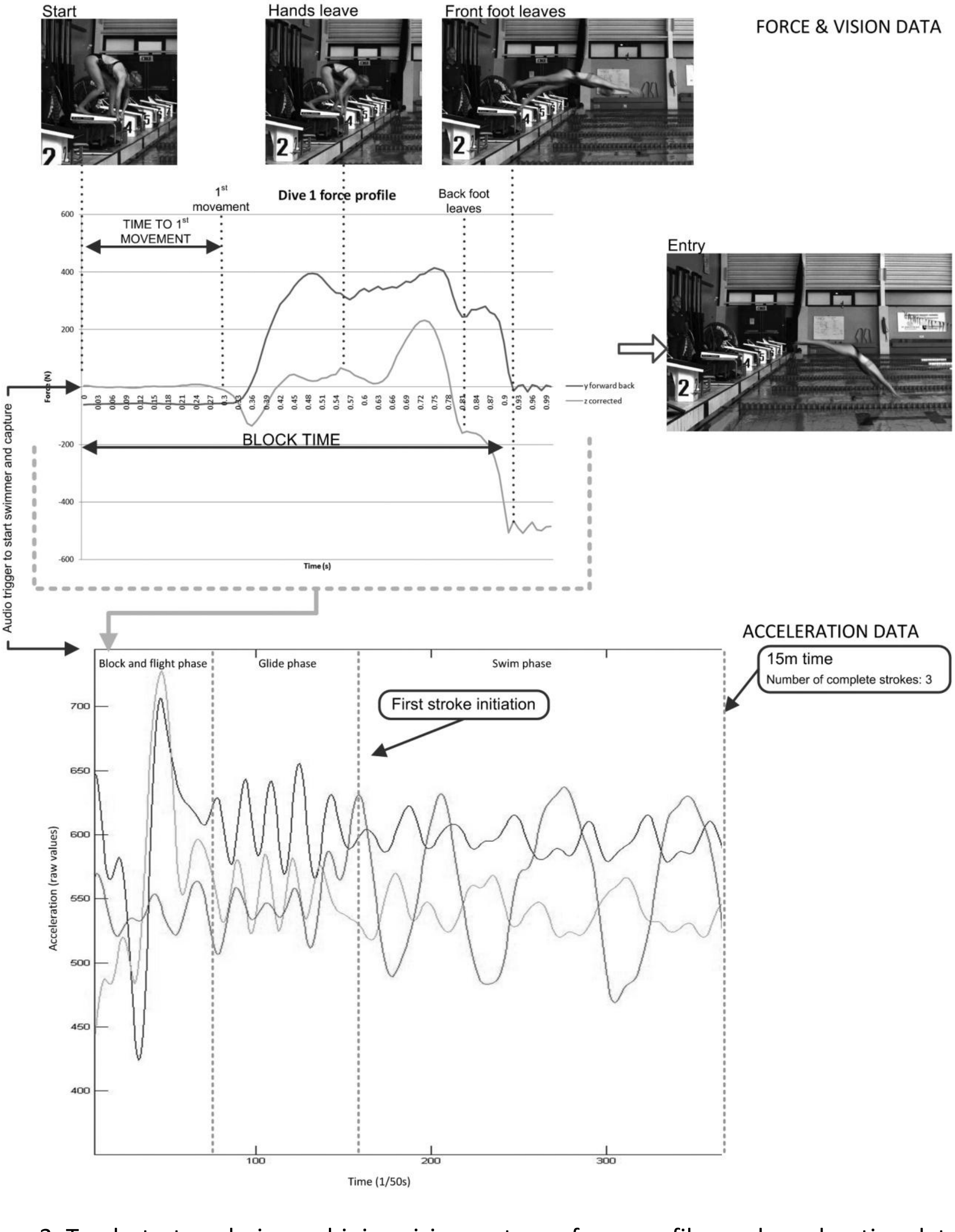

Figure 3. Track start analysis combining vision systems, force profiles and acceleration data.

DISCUSSION

Individual monitoring components have been developed that enable parameters relevant to the performance of various components of the start phase of swimming to be quantified. The three main monitoring components include vision information, force profiles and acceleration data through a network of distributed wireless nodes. Each of these components is able to provide feedback to the coaches and the athletes but it is the synchronisation and integration that allows a greater level of understanding to be obtained.

From the video images it is possible to provide qualitative feedback immediately after each start. By synchronising this with the force platform information, quantitative values during the block phase can be calculated and fed back to the coaches and swimmers. An example of this integrated analysis approach was shown with the elite level athlete whilst undergoing an intervention in their starting technique resulted in quantifiable visible differences in both the horizontal and vertical force components. The addition of wireless acceleration information is unique to this analysis of swimming starts where information on stroking and timing is included in the data analysis.

Results from a number of trials of the integrated system have highlighted the reliability of the data and the impact of interventions. The synchronisation of data from a number of monitoring modalities provides accurate, timely and relevant feedback to both the coaches and athletes supporting enhanced impact from testing. Future work will be focussed on the development of a more complete understanding of force and acceleration data and the implications for skill and performance improvement throughout the various phases of the start.

CONCLUSION

An integrated component-based system has been developed that allows swimming starts to be analysed in greater detail than possible with previous systems via integrated video, force and acceleration data. Feedback was provided to the coach and athlete for interventions in training to be made and the impacts to be quantified in detail. Future work will examine the impact on starting performance of the wedge included on the next generation Omega OSB11 starting blocks which are likely to be used in the London 2012 Olympic Games.

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ARE LAND TESTS A GOOD PREDICTOR OF SWIM START PERFORMANCE?

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The purpose of this study was to determine if there were any relationships between land tests and starting performance in swimmers. Results on six British international level male swimmers were collected and analysed independently to ensure no bias. Pearson correlations showed significant relationships between peak vertical forces on land with peak vertical forces on both the main plate and wedge components of the OSB11 style starting block. Correlations were also found with maximum depth and entry distance for both jump height and peak force indicating that land tests can be used as an alternative to instrumented blocks for accurate assessments of starting performance.

KEY WORDS: swimming, starts, jumps, OSB11.

INTRODUCTION: Swimming starts are explosive movements designed to propel athletes through the air as quickly and as far as possible in order to take advantage of the decreased resistance compared with water. Strength and conditioning coaches regularly monitor land tests throughout the swimming season but the relevance of these to actual swimming performance has not been examined in great detail. The swimming start can be divided into a number of phases including the block, flight, underwater and free swimming phases of which the block phase is hypothesised to be closely related to land conditions. Within a competition environment, starts can comprise up to 26.1% of the overall race time in sprint events (Cossor and Mason, 2001) and have been shown to have an impact on performance in nearly all strokes and distances (Mason and Cossor, 2000). At the 2009 World Swimming Championships in Rome, the average difference between the gold and bronze medal in all of the 50m events was 0.19s. That difference could be made or lost in the start phase of the race to 15m and highlights the importance of skills in overall race performance.

The three most common forms of start technique that have been used in swimming include the grab, track and swing starts. In a grab start the swimmer has both feet at the front of the block and the hands placed either between or outside the legs. For the track start technique, the swimmer places one foot at the front of the block and the other towards the rear of the block. A wedge has been introduced to the block design so that swimmers now have a fixed area to push against with their rear leg, similar to athletics track starts. Swing starts tend to be used in relay events where the arms swing in a backwards direction in order to generate momentum prior to the swimmer leaving the blocks. Traditionally, sprinters have tended to favour the track start technique with a mixed use between the grab and track starts for the other events. Observations at international competitions in 2010 suggest that most swimmers are now favouring the track start technique with the exception of some breaststrokers.

Previous research has looked at the effect of land training on swimming starts (Arellano et al., 2005, Benjanuvatra et al., 2007, (Breed and Young, 2003) and (West et al., 2010) with no significant results, but none have analysed the new OSB11 wedge type blocks. The purpose of this study was to determine if there were any relationships between dry land jump tests and swimming start performance utilising the OSB11 block with either the left or right legs at the front of the block.

While swimmers had a preferred foot in the forward position, tests were conducted with both the left and right foot forward as no scientific approach had previously been used to determine the best foot. In tests using land based athletes, Read and Bellamy (1990) found little difference between the preferred and non-preferred legs for strength and power measures. (Hardt et al., 2009) used the revised Waterloo Footedness Questionnaire (Elias et al., 1998) to assess foot preference but found that there was no relationship between the results of the questionnaire and preferred foot used in swimming starts. The group also found that the most effective starts were those using the preferred technique and it was suggested that this was due to a practice effect.

METHODS: Elite male swimmers from the British Swimming team were asked to perform eighteen swimming starts from an instrumented starting block with equivalent geometry to the Omega OSB11 block. An audio signal was used to start the each of the six swimmers after the “take your marks” command was given to replicate racing conditions and participants were instructed to swim maximally past the 15m mark. Times to 15m were measured (average of 6.37s) but are not included due to the focus on the block and flight phases of the start in this research.

Block time, peak horizontal and vertical forces and times were measured on both the main plate and the wedge component of the block with a sampling frequency of 100Hz. The SwimTrack software written by Sheffield Hallam University was used to determine position and velocity of the swimmers as they left the block and as their head entered the water. Details of the pool based testing set up are explained in Cossor et al. (2010).

Three trials were performed in each of the land based tests on a single axis force platform capturing data at 200Hz. Counter movement jumps (CMJ) were performed with the hands on the hips as were the left and right foot forward jumps. Markers were placed on the force platform to indicate the maximum size of the starting block (50 x 53cm) as well as the centre position to better represent positions during a swimming start.

Trials on both the land and in the water were randomised in order to minimise any effects of learning or muscular fatigue throughout the testing sessions.

RESULTS: Average information for each of the testing conditions was used for the analysis, see table 1 for results from the main plate and table 2 for results from the wedge. Data was subgrouped for left and right legs upon which comparisons were made. The peak vertical (Z) and horizontal (Y) forces and the time that they occurred after the starting signal can then be compared between the main plate and wedge platform. Vertical forces on the starting block could also be compared with vertical forces during the land jumping tests.

Table 1 Main force plate data in the vertical (Z) and horizontal (Y) directions for each leg

Front Leg	Block time (s)	Max Fz (N)	At time (s)	Max Fy (N)	At time (s)
Left	0.76 ± 0.06	813.39 ± 82.25	0.46 ± 0.03	380.12 ± 38.5	0.70 ± 0.01
Right	0.75 ± 0.06	833.83 ± 65.83	0.56 ± 0.05	407.76 ± 57.2	0.68 ± 0.01

Table 2 Wedge force plate data in the vertical (Z) and horizontal (Y) directions for each leg

Front Leg	Block time (s)	Max Fz (N)	At time (s)	Max Fy (N)	At time (s)
Left	0.66 ± 0.05	885.06 ± 111.8	0.50 ± 0.01	182.18 ± 22.0	0.56 ± 0.02
Right	0.64 ± 0.07	912.59 ± 99.3	0.46 ± 0.03	166.53 ± 38.1	0.55 ± 0.03

Table 3 Correlations between land and pool based tests

	Right Jump Height	Left Jump Height	Right Fz land	Left Fz land
Right Fz main			0.526	0.596
Left Fz main	-0.478	-0.515	0.647	0.636
Right Fz wedge			0.653	0.741
Left Fz wedge			0.792	0.830
Right dive depth			0.885	0.794
Left dive depth			0.765	0.771
Right entry distance				
Left entry distance	-0.694	-0.593	0.500	0.600

In order to determine any relationships between land and pool based tests, Pearson Product Moment Correlations were generated with significant values reported at the alpha level of 0.05 and are presented in table 3. Jump heights and peak vertical forces were measured for the left and right leg in the forward position. Peak forces on the main and wedge components as well as maximum depth and head entry distance with the left and right front in the forward position were used for the pool based measures.

Results showed significant positive correlations for all swimming based variables with the peak vertical jump forces except for the entry distance with the right leg in the forward position. Vertical jump height was also negatively, significantly correlated with the peak vertical forces with the left foot in the forward position on the starting block as well as the horizontal entry distance in the same position.

DISCUSSION: The start itself can be divided into a number of phases but the focus of the current study was on the block and flight phases. Research has previously attempted to examine relationships between starting performance and land tests using a variety of methods. These have included different types of starts – grab (Benjanuvatra et al., 2007), track (West et al., 2010) and swing (Breed and Young, 2003) with upper and lower body land tests (Arellano et al., 2005). The main aim of this research was to determine if there were any relationships between land tests and swimming starts using the new OSB11 style starting blocks.

Traditionally swimmers have chosen their preferred foot forward based on feel rather than scientific measures and while (Hardt et al., 2009) found that questionnaires showed no relation to start performance, the current study also attempted to look for differences between the left and right leg in the forward position. Galbraith et al. (2008) suggested that the strongest leg should be placed at the rear of the block while other swimming specific research suggested that the strongest leg should be at the front (Blanksby et al., 2002 and Hardt et al., 2009). All subjects were required to perform tests in both positions (left and right leg forward) on the land and in the water without the researchers' knowledge of preferred foot in order to minimise bias of the results. Though the results showed little differences in timing for the left and right leg, there were differences noted in peak forces. Future studies would need to determine if there were any significant differences between the left and right legs but with the small sample size in the current study it was felt that this would not be a true indicator.

Strong positive correlations within the group were found between the peak forces measured during the land tests and the peak forces measured on both the main and wedge plates of the starting block suggesting that land tests can be used as an alternative to pool based tests for peak force. It is has been suggested that the horizontal velocity at take-off is linked to improved starting performances (Galbraith et al., 2008), (Guimaraes and Hay, 1985) and (Houel et al., 2010a) but as the land tests were measured using a uni-directional force plate, it was felt that direct comparisons in the vertical component would be more beneficial.

Future research may examine the relationship between the vertical and horizontal components on the starting block and this resultant measure compared with the vertical forces measured during simple jumping tests on land.

The maximum depth that a swimmer travels after their dive can have an effect on velocity, drag and angle of ascent and this variable would also be strongly correlated to the peak forces measured on land. As the focus of this research was predominantly on the block and flight phases of the start, this relationship was not examined any further but it was interesting to note and will be explored further.

Whilst there was no correlation between the starts with the right leg at the front of the block and peak vertical jump forces, there was for the left leg. Greater peak forces measured on land were significantly related to longer flight phases with the head entering further from the blocks compared with lower peak forces. Head entry distance is likely to be closely related to the horizontal forces measured on the starting block but were not examined in this instance due to time constraints.

All of the peak jump forces were measured using a portable single axis force platform that is easy to locate in various venues making testing accessible to a large range of swimmers. Vertical height is another simple measure that showed significant negative correlations with the peak vertical forces on the main plate and the horizontal entry distance when the left leg was in the forward position. Interestingly there were no relationships with the right leg in the forward position for this group of elite male swimmers so further research will investigate the trends with a larger subject group.

CONCLUSION: The outcomes of this study show that simple jump tests measured on land do relate to swimming start performance and can be used by swimmers and coaches. Equipment used for the jumps on land was portable and would allow for testing to occur in a variety of locations including the poolside. Due to the ease of testing, these types of jumps could occur more frequently than testing with the inclusion of an instrumented starting block and at a fraction of the price. The jump height tests indicate that there may be a preference towards swimmers having the left leg at the front of the starting block but with the numbers quite small in the current study, this needs to be investigated further before conclusions can be made.

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AN INVESTIGATION IN THE USE OF A PRESSURE MAT TO MONITOR TURN PERFORMANCE IN SWIMMING

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A purpose built pressure mat was designed and developed by Loughborough University in order to characterise the wall contact phase of swimming turns. In-house software enabled information concerning horizontal and vertical foot locations as well as orientation of the feet, wall contact time and peak force data that was extracted automatically. Two elite male swimmers on two separate days performed three maximal effort turns that resulted in similar values for wall contact time, peak pressure, as well as vertical and horizontal locations on the wall. Subject two produced greater peak forces (1.69 and 1.76BW) than subject one (1.34 and 1.20BW). Future testing will use larger subject numbers to obtain the statistical significance of the measured values.

KEY WORDS: swimming, turns, pressure.

INTRODUCTION: Swimming turns can be divided into a number of different phases including the approach, rotation, wall contact, underwater and stroking phases (Lyttle & Benjanuvatra 2007) within the 15m distance measured during competitions. The approach phase is defined as the time from the head passing the 5m distance into the wall until the last hand entry in freestyle (FR) and backstroke (BK), or the hand touch in breaststroke (BR) and butterfly (BF). The rotation is defined as the period from the end of the approach phase until the feet touch the wall in all turns while the wall contact phase is the period of time that the hands and/or feet are in contact with the wall. As the swimmer leaves the wall after the turn they glide and kick in the underwater phase before commencing stroking through to the 10m mark from the wall. Improvements in any one of these phases can affect the overall race result during competition (Slawson, Conway, Justham, Le Sage & West 2010).

Turning technique in swimming has been measured extensively to date using *vision systems*, (Tourny-Chollet, Chollet, Hogie & Papparodopoulos 2001; Prins & Patz 2006; Slawson et al. 2010; Slawson, Conway, Justham & West 2010; Kishimoto, Takeda, Sugimoto, Tsubakimoto & Takagi 2010; Pereira, Ruschel, Souza, Araujo, Goncalves, Fernandes, Roesler & Vilas-Boas 2011) *force platforms* (Lyttle & Mason 1997; Blanksby, Simpson, Elliott & McElroy 1998; Cossor, Blanksby, & Elliott 1999; Lyttle, Blanksby, Elliott & Lloyd 1999; Blanksby, Skender, Elliott, McElroy & Landers 2004; Araujo, Pereira, Gatti, Freitas, Jacomel, Roesler & Vilas-Boas

2010; Puel, Morlier, Mesnard, Cid & Hellard 2010) and *tethered devices* (Lyttle et al. 1999; Lyttle & Blanksby 2000; Lyttle, Blanksby, Elliott & Lloyd 2000; Lyttle & Benjanuvatra 2007) but no testing results have been reported in the literature regarding the use of pressure mats in swim turn testing.

The benefits of using a pressure sensor mat rather than a force platform includes: cost, portability, protrusion of the sensor on the wall, and information available. Force platforms used in turn analysis can comprise single or multiple axis transducers in order to measure the overall force, impulse and centre of pressure during the wall contact phase. Pixelated pressure sensor mats enable forces to be measured for each leg individually to enable a greater understanding of their relative contribution to turn performance. Information on vertical depth from the water surface, horizontal distance between feet as well as the orientation angle between the two feet can be measured using this technology. The aim of the present study was to use a novel method of measuring swimming turns that enabled both individual and combined values from the left and right legs to be reported.

METHODS: A custom, high pressure sensor mat with flexible design (XSENSOR model IX500:40:64.02) with an active area of 51cm x 81cm was encased within a waterproof bag and then attached to a rigid polycarbonate backing for mounting on the pool wall. Velcro strips on the rear of the pressure mat allowed for changes in the position of the sensing area on the wall in relation to the surface of the water. The sensor array included 2,560 individual sensor elements with a resolution of 12.7mm in both the vertical and horizontal directions. Data were sampled at 40Hz with a pressure range of 10-200psi. Two elite male swimmers performed multiple swimming turns over consecutive days in order to evaluate the repeatability of the pressure mat data and associated analysis and visualisation software. Swimmers were required to conduct three maximal effort turns on their best stroke in each of the testing sessions to ensure that the data was consistent for each swimmer.

The measurement area of the pressure mat with two feet contacting the wall is seen in Figure I. The left foot vertical distance from the surface of the water is line A while the same distance for the right foot is represented by line B. The horizontal distance between the two feet is line C and the orientation angle between the feet is shown as α in figure 1. Peak pressure and wall contact time (WCT) were also measured while a fixed Sony HQ2 camera operating at 25Hz was also used to obtain the WCT results from the pressure system. Values derived from the pressure mat were used in the final analysis due to the higher capture rate compared to that of the camera.

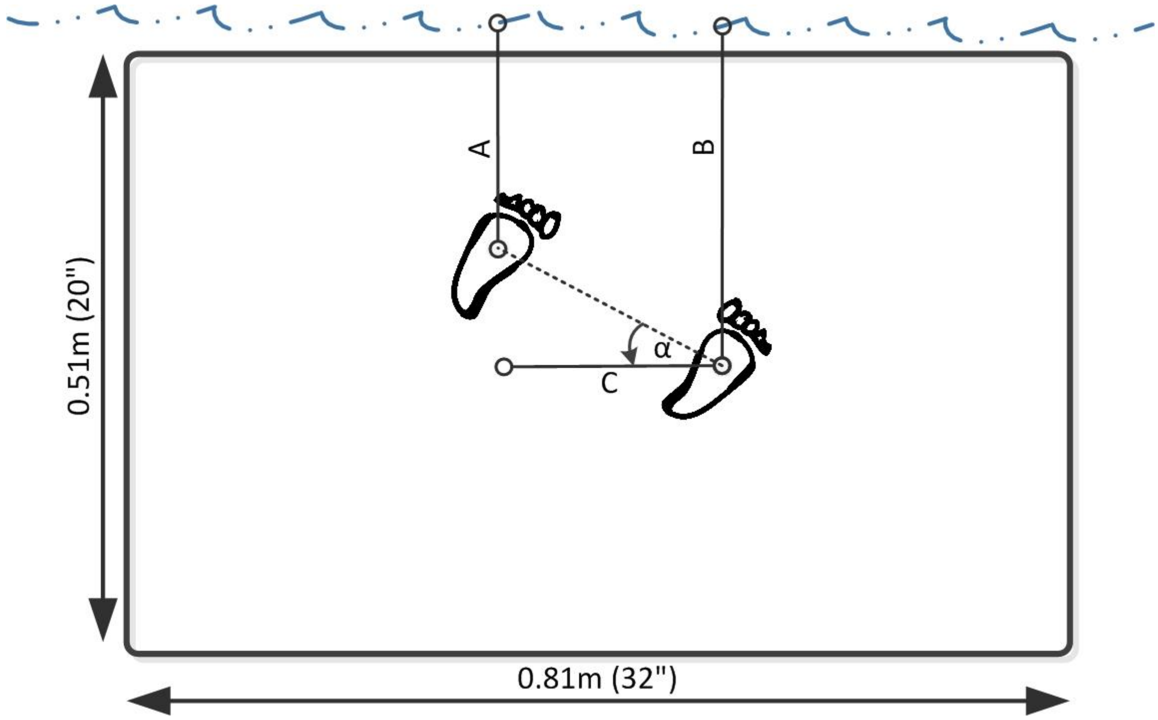

Figure 1: Schematic of the feet contacting the sensor area of the pressure mat.

Force was derived from the pressure data using the equation:

$$F = P.A \quad (1)$$

where *F* is force, *P* is pressure and *A* is the contact area. Details on the methodology used to calculate the distances and angles can be found elsewhere (Chakravorti, Slawson, Cossor, Conway & West 2012).

RESULTS: The mean and standard deviations of the three trials performed by each swimmer on both of the two testing sessions are shown in Table 1. The distance (in cm) from the surface of the water to the left and right feet is also noted along with the horizontal distance between the two feet at wall contact. The orientation angle in degrees provides an indication of the position of the two feet on the wall. Subject one performed freestyle turns while subject two performed backstroke turns as these were their preferred strokes. Subject one had a mean WCT of 0.25s on the first session and 0.30s on the second and subject two showed similar values (0.29s compared with 0.31s). The peak pressure values were similar between the two sessions for subject two (20.45psi and 19.59psi) while there was a much greater variation in the averages (i.e. 31.57psi and 43.85psi) and standard deviation (SD) values (12.51 and 10.42 SD) for subject one. The peak forces produced by subject one (1.34 and 1.20BW) were less than those produced by subject two (1.69 and 1.76BW) even though they were both performing the more traditional flip turns with only the feet contacting the wall. Values for depth and horizontal distance between the feet were similar on both testing occasions for both swimmers. The area with the greatest variation was the orientation of the feet with values of 6.47° and 26.90° for subject one and 31.40° compared with 24.37° for subject two over the two testing sessions.

Table I.

Descriptive statistics (means and standard deviations (in brackets)) for testing trials

Subject	Session	WCT (s)	Peak Pressure (psi)	Force (BW)	Left Foot (cm)	Right Foot (cm)	Horizontal (cm)	Orientation (°)
1	1	0.25 (0.06)	31.57 (12.51)	1.34 (0.10)	31.33 (3.52)	31.73 (2.14)	10.97(1.78)	6.47 (1.01)
	2	0.30 (0.02)	43.85 (10.42)	1.20 (0.28)	30.50 (6.93)	30.50 (0.00)	10.60 (4.95)	26.90 (11.03)
2	1	0.29 (0.02)	20.45 (2.50)	1.69(0.06)	21.57 (2.83)	26.57 (2.14)	13.33 (1.79)	31.40 (10.78)
	2	0.31 (0.05)	19.59 (7.59)	1.76 (0.23)	21.53 (4.60)	24.10 (2.08)	12.93 (2.35)	24.37 (13.09)

DISCUSSION: The pressure mat was designed specifically to ensure that there was a minimal protrusion from the wall of the testing equipment so that the swimmers did not need to alter their approach phase during the turn. The protrusion into the pool of wall mounted force platforms range from 4.5cm (Blanksby et al. 1998) to 20cm (Araujo et al., 2010) where the markings on the bottom of the pool needing to be adjusted for the swimmers. As well as only being 4mm thick, the pressure mat was painted yellow with a black cross to replicate the touchpads used during competitions. This was done after receiving feedback from the subjects following pilot testing.

Data from the turn pressure mat were able to provide information on the peak pressure which was then converted to force. Values from previous research varied due to the wide range of ages and strokes used. Age group swimmers from 10-13 years old produced 0.55BW (backstroke), 1.22BW (breaststroke) and 1.24BW (freestylers) (Blanksby et al. 1998; Cossor et al. 1999; Blanksby et al. 2004). Subject one in the current study was a senior elite male freestyler. As previous research reported values of 1.66-1.92BW (Lyttle & Mason 1997) and 1.60BW (Lyttle, Blanksby, et al. 1999) this swimmer needed to improve his force exerted on the wall during the contact phase of the turn when compared to the force exerted by swimmers in similar events. No data for elite male backstrokers were found in the literature for a comparison with subject two although they were comparable to the freestyle values.

One of the benefits in using the pressure mat is the ability to identify automatically the depth of each foot on the wall during the contact phase to highlight the differences between the two subjects. The freestyle swimmer (subject one) had his feet at approximately 10cm below the surface of the water which was deeper than subject two at an average depth of 1.5cm for the left foot and 5cm for the right foot. These results are consistent with unpublished data demonstrating greater maximum contact depths for backstroke swimmers when compared to freestylers. The values for both swimmers are less than the 30-40cm depth suggested by (Maglischo, 1993) and 40-60cm proposed by (Lyttle et al. 1998; Lyttle, Blanksby, et al. 1999; Lyttle, Lloyd, et al. 1999; Lyttle & Benjanuvatra 2007).

CONCLUSION: This study using two elite male swimmers has demonstrated the use of a pressure mat designed specifically to monitor swimming turns in real time. Results showed that it was possible to measure forces, wall contact time, vertical and horizontal distances of the feet as well as their orientation, through the use of the equipment. The advantages of using a pressure mat rather than a traditional force platform includes cost, portability and the ability to differentiate between the two legs during the contact phase of the turn. Future research will involve greater subject numbers and the use of all four strokes to completely evaluate the hardware and software capability.

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THE EFFECT OF FEET PLACEMENT DURING THE WALL CONTACT PHASE ON FREESTYLE TURNS

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ABSTRACT

A waterproofed pressure mat was used to analyse the wall contact phase of freestyle turns by 34 university swimmers to determine the variables on the wall that effect turning performance. Data was analysed as a group of athletes and then divided by gender to see if males and females used the same approach to turning technique with different anthropometry. Foot position and orientation with relation to the surface of the water, wall contact time and maximum depth were related to the criterion measure of 5m Round Trip Time (RTT). Within the group that was tested the only significant correlation ($p>0.05$) with turn performance during the wall contact phase was the tuck index (0.330). When the sample was divided by the gender of the swimmer the foot width and orientation were significantly related to the 5m RTT for the males while the Wall Contact Time (WCT), foot height, foot width and tuck index were related to female turn performance. Rotation time, height, mass and tuck index were related with successful turning while future testing should investigate the turning performance freestyle specialist swimmers to determine the impact of foot placement.

INTRODUCTION

Turn performance has been monitored both in a training and competition environment and includes various phases such as the approach, rotation, wall contact, push off, underwater and swimming segments (Lyttle and Benjanuvatra, 2007). Freestyle turns have been investigated by a number of researchers with the instrumentation during the wall contact phase limited to force platforms and video cameras (Blanksby et al., 1998, 1996, 1995; Cossor et al., 1999; Lyttle and Mason, 1997; Lyttle et al., 1999; Nicol and Kruger, 1979; Pereira et al., 2011; Prins and Patz, 2006; Puel et al., 2010, 2012; Takahashi et al., 1983).

A limitation with the use of force platforms for analysis is the inability to determine the position and contribution of individual legs to the overall turn performance. Previous research has discussed the development of turn analysis systems that incorporate the use of a pressure mat (Chakravorti et al., 2012a, 2012b; Cossor et al., 2012; Webster et al., 2011). Each of these studies proved the concept of pressure mats and bespoke software for turn analysis with a limited number of subjects.

Video at major international competitions has shown that there are two techniques that are used by elite swimmers when contacting the wall. The first includes a faster rotation around the transverse axis with the feet contacting the wall so that the toes are pointing towards the surface of the water where the orientation is referred to as 0°. The other technique includes an additional rotation of the body along the medial axis when approaching the wall so that the feet contact the wall when the toes are positioned towards the side walls creating an orientation of 90°. The purpose of this study was to evaluate foot orientation as a contributor of performance in freestyle turns.

METHODS

An integrated approach to the analysis of swimming turns was used that included the use of three underwater cameras (Sony HQ2) and a waterproofed flexible pressure sensor mat (XSENSOR model IX500:40:64:02). The design of the pressure mat has been discussed previously by Cossor et al. (2012) including the detail of the 2560 individual sensing elements within the active area of the mat.

The pressure mat was connected to a laptop that captured the pressure data at 100Hz for further analysis. One of the cameras was attached to a tripod and viewed the rotation phase of the turn above the water while the two other cameras were attached to poles that were 2m and 4m from the end of the pool and at a depth of 1m below the surface of the water. A representation of the testing set up is shown in Figure 1 with the approximate location of the equipment used.

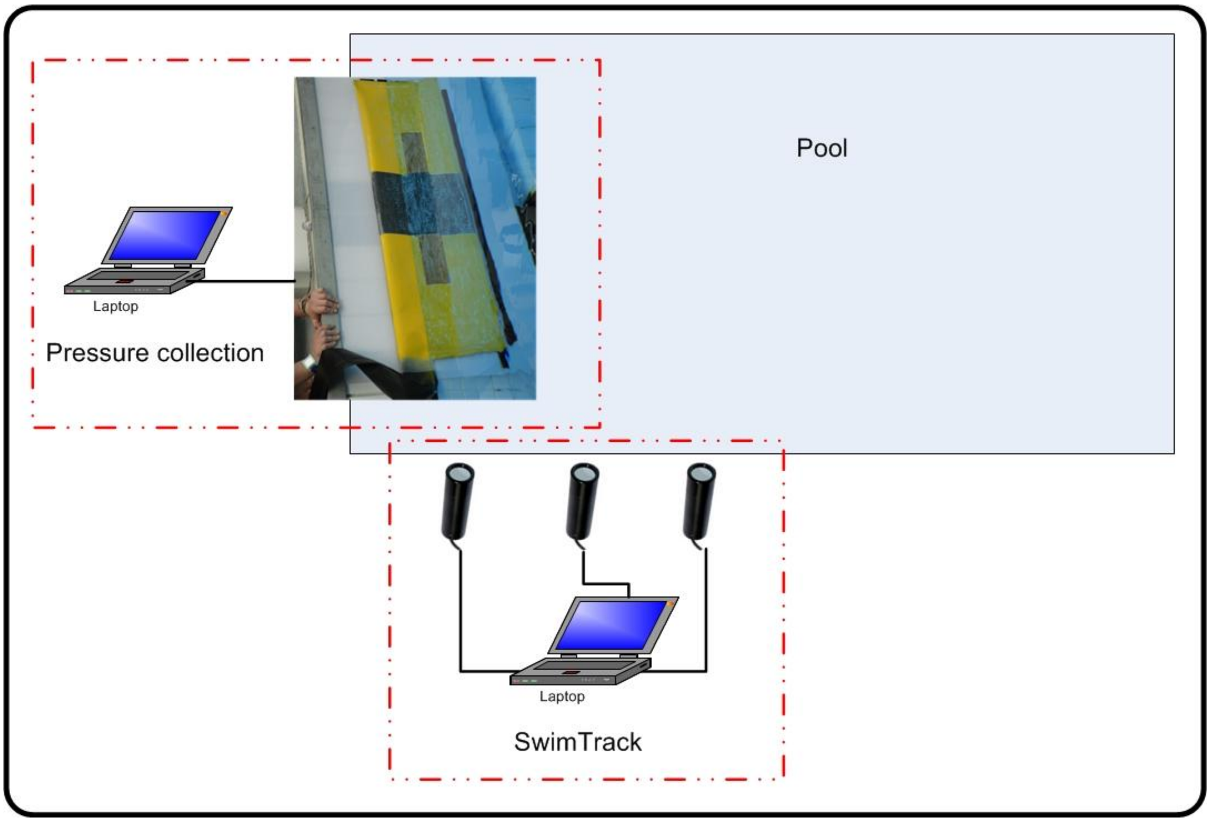

Figure 1. Turn testing set up with a pressure mat and three video cameras

Thirty-four university swimmers completed three maximal effort freestyle turns with sufficient rest between each trial to ensure a full recovery. The average mass was 81.16 ± 6.51kg for the males and 68.17 ± 4.60kg for the females. Standing height was 1.86 ± 0.06m for the males and 1.73 ± 0.05m for the females as displayed in Table 1.

Analysis measures included the 5m Round Trip Time (RTT), foot placement and orientation on the wall, peak pressure, Wall Contact Time (WCT), and maximum depth of the hip after leaving the wall. Time and velocity during the last hand entry, feet leaving the wall and the first underwater kick were also recorded using the SwimTrack© software as described by Cossor et al. (2012).

Table 1: Anthropometric data of the subjects used within the study

	Number of trials	Mass (kg)	Standing height (m)	Trochanter height (m)
Males	65	81.16 ± 6.51	1.86 ± 0.06	0.95 ± 0.04
Females	34	68.17 ± 4.60	1.73 ± 0.05	0.90 ± 0.02

The centre of the swimmer's head was used to calculate the RTT during the approach to the wall and return to the same 5m distance. It was possible to measure the horizontal and vertical position of each foot during the wall contact phase due to the large number of sensing elements within the mat so that each calculations could be made by multiplying the cell number for the sensing element where contact occurred by the size of the cell (12.7 x 12.7mm). The method used to calculate the orientation between the centre of each foot when contacting the wall was described in Cossor et al. (2012). Peak pressure and wall contact time was manually calculated using the XSensor software.

Instantaneous velocity at a set point was calculated using data from the previous two frames as well as the next two frames of video operating at 25 frames per second and known distances at each of these points using the calibration process prior to each testing session.

RESULTS

Only those trials where both feet came into contact with the sensing area on the pressure mat were used for analysis purposes, which resulted in 99 of the 102 turns being analysed. Mean and standard deviations for the 5m RTT, WCT, foot width, foot height, orientation and tuck index are presented in Table 2. The average turn time for males (4.66s) was much faster than for the females (5.39s) within the group whilst the wall contact time of 0.31s was the same for all participants. Standard deviations reported for the foot width and foot height showed large differences within the subject population as did the orientation of the feet on the wall.

Table 2: Mean and standard deviation data for variables during the wall contact phase and the 5m RTT

	5 m RTT (s)	WCT (s)	Foot width (cm)	Foot height (cm)	Orientation (°)	Tuck index
Males	4.66 ± 0.22	0.31 ± 0.06	12.28 ± 8.55	1.61 ± 8.12	28.60 ± 24.24	0.90 ± 0.09
Females	5.39 ± 0.23	0.31 ± 0.06	11.73 ± 10.89	1.83 ± 10.21	31.02 ± 22.45	1.01 ± 0.11
Combined	4.91 ± 0.41	0.31 ± 0.06	12.09 ± 9.38	1.68 ± 8.85	29.44 ± 23.54	0.94 ± 0.11

Tuck index is a measure reported in previous literature (Blanksby et al., 1996; Cossor et al., 1999; Prins and Patz, 2006) where the distance of the greater trochanter to the wall is measured during wall contact. This measure is then divided by the swimmer's trochanteric height to provide the tuck index value with smaller values indicating a bent knee position and larger values representing straighter legs when contacting the wall.

Pearson Product Moment Correlations showed significant (p<0.05) relationships between the criterion measure 5m RTT and (i) rotation time (0.312), (ii) height (-0.718), mass (-0.739), and (iv) tuck index (0.330). Wall contact time, foot width, foot height, orientation, and maximum depth did not significantly correlate with freestyle turn performance when the data was analysed as a complete group. Data was then separated by gender with the significant relationships (p<0.05) shown in Table 3.

Table 3: Significant (p<0.05) Pearson Product Moment Correlations with wall contact phase variables and the 5m RTT criterion measure

	WCT (s)	Foot width (cm)	Foot height (cm)	Orientation (°)	Tuck index
Males		-0.275		0.268	
Females	0.403	0.355	-0.586		-0.551
Combined					0.330

The only parameter that provided a significant correlation for the wall contact phase and the 5m RTT when the subjects were combined into one group was the tuck index. This would suggest that both the males and females use a similar knee angle position when contacting the wall so that the hips are at approximately the same distance from the wall relative to their height.

DISCUSSION

Observations of turning performance during the 2012 Olympic Games highlighted two different foot positions on the wall during the freestyle turn. The first was to have the toes of the feet pointing towards the surface of the water while the second had the feet rotated between 45 and 90° when contacting the wall. As such the purpose of the research was to determine if the placement of the feet on the wall impacted on the turning performance of elite swimmers. It was not possible to measure this information using traditional force platforms so a waterproofed pressure mat was developed that enabled each foot to be measured separately. Data from this research showed that the orientation of the feet was significantly related to the turning performance for the male subjects but not the females although the standard deviations were large for both genders.

Marinho et al. (2010) found an effect on the depth of the swimmer during the glide phase after turning to reduce drag although the maximum depth of the swimmers in this study did not impact on the total turn time. The position of the hips in relation to the feet during wall contact determines the depth of the swimmer during the underwater phase – if they are even then the body will be parallel to the surface of the water. When the feet are higher than the hips then the swimmer will travel towards the bottom of the pool whereas the opposite is true when the position of the hips and feet are reversed as the swimmer leaves the wall. There may also be individual differences observed within the elite population so case studies may be more appropriate in the future.

In research examining 8 elite female athletes performing freestyle turns where the 3m RTT was used as the criterion measure, Puel et al. (2010) suggested that the glide duration and maximal horizontal force were the variables related to improved turning performance. As the swimmers left the wall in the current study there was a positive correlation with the timing of the first kick (0.599) and negative correlation with the velocity at which this kick occurred (-0.226) with the 5m RTT. These results indicated that the swimmers with a faster 5m RTT held their streamlined position for a longer period of time prior to commencing the first kick in the underwater phase and this enabled their velocity to decrease to a level that was similar to their kicking speed.

More comprehensive measures of the body position and the drag acting on the body during this phase of the turn will provide a more detailed understanding of the underwater phase and should be investigated in future research.

Whilst the group of swimmers used within this study were experienced and trained for a minimum of 8 sessions per week, they were not all freestyle specialists and the results may have differed with a smaller sample size that competed in freestyle events on a regular basis. The large standard deviations observed in the foot width, foot height and orientation measures within the group suggest that there was not a consistent trend of foot placement during the wall contact phase of the turn.

There were also large standard deviations within the subject group used indicating large variations in turning technique. Future research could look to measure correlations for each individual where more trials were monitored (8-10) for an improved interpretation of the relationship between the wall contact phase and 5m RTT.

CONCLUSIONS

The group of swimmers used in the current study showed similar trends to previous research (Blanksby et al., 1998; Cossor et al., 1999) where turn time was related to the height and mass of the individual. There were no significant relationships with the placement and pressure of each foot during the wall contact phase and the 5m RTT when analysed as a complete group. Significant relationships during the wall contact phase of the freestyle turn were observed when the males and females were analysed separately.

Future research should examine the individual foot position on the wall during tumble turns for freestyle specialist swimmers to make a more accurate assessment of the impact of feet placement on successful turn performance as well as use case studies within the elite population.

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